Understanding local neuromuscular mechanisms that explain the efficacy of interventions for patellofemoral pain

Submitted in partial fulfilment of the requirements of the Degree of Doctor of Philosophy

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Statement of originality

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Abstract

Patellofemoral pain (PFP) is a common and persistent knee pain complaint among all age ranges, especially highly active people. Multiple approaches have been used to understand symptom persistence, including identifying a mechanism explaining intervention benefits (i.e. changes in specific deficits in groups that show symptoms' improvement). Research has been conducted to identify the characteristics associated with PFP, but uncertainty regarding local neuromuscular characteristics remain evident.

The thesis aimed to a) identify the local neuromuscular characteristics associated with PFP, b) develop an evidence informed laboratory protocol to detect those characteristics, c) establish protocol reliability and feasibility, and d) identify interventions that can target these neuromuscular characteristics.

A systematic review with meta-analysis was completed to identify the neuromuscular characteristics of all muscles that cross the knee in people with PFP compared to uninjured groups. Ten deficits within three neuromuscular domains were found. Within the electromyography (EMG) domain, a delay in Vastus medialis (VM) relative to Vastus lateralis (VL) excitation onset, a high Biceps femoris (BF) mean excitation amplitude, and a lower Hoffman-reflex amplitude of VM were identified. Within the muscle performance domain, lower isometric, concentric, and eccentric extensors peak torque and total work, lower concentric flexors peak torque, and lower rate of torque development (RTD) to reach 30%, 60% and 90% of extensors peak torque were identified. Hamstring tightness was identified within muscle flexibility domain. The systematic review was published and the results used to inform testing protocol development.

A second systematic review with meta-analysis was conducted to identify interventions that can target the local deficits associated with PFP. The results indicate that currently an intervention that effectively modifies EMG characteristics cannot be identified. Predominantly, exercise interventions have effects on strength and flexibility in PFP. Specifically, hip and knee targeted exercises are found to have a potential mechanism of benefit through both characteristics categories.

A unique approach was introduced within the thesis to develop a deficit-detection protocol based on systematic review results. This approach provided a comprehensive analysis of the protocols from the studies that were included in the meta-analysis. A battery of tests was developed and included; a) VM-VL excitation onset timing in step-up task, b) BF mean excitation amplitude in single-leg triple-hop test, c) isometric, d) concentric and e) eccentric extensors peak torque, f) RTD to 30%, 60% and 90% of isometric peak torque, and hamstrings flexibility.

Reliability testing of the deficit-detection protocol was conducted with both uninjured and participants with PFP over two phases. Phase one evaluated the original protocols adapted from the review. Phase two was performed on the EMG and RTD domains to explore the effects of signal processing parameters on reliability, such as; onset detection thresholds modification, unnormalised signals, and the addition of absolute RTD. For the PFP group: reliable results were demonstrated for concentric and eccentric extensors peak torque; RTD of the quadriceps at 25ms, 50ms and 90% of peak torque; and hamstrings flexibility. The uninjured group showed reliable results in: unnormalised BF mean excitation amplitude; all three peak torque tests; RTD to 30% of peak torque and at 150 and 175 milliseconds; and hamstrings flexibility.

To establish participant recruitment rate and retention, in addition to the acceptability of the test protocol, a preliminary feasibility study of the deficit-detection protocol was conducted. A sample of 14 participants with PFP were recruited and tested at the Mile-end campus of QMUL before and after a six weeks period. Feasibility results indicate that 25.5% were willing to participate following an online screening process (n=17/55) and 82% met the eligibility criteria following face-to-face assessment (n=14/17). Recruitment rate was 0.5 participants per week and drop-out rate was 35.2% (n=11/17). The results indicate that the protocol did not meet all a-priori feasibility criteria, but the results can inform future research planning.

The thesis has successfully identified local deficits associated with PFP, developed a test protocol that demonstrates reliability in evaluating these deficits and assessed the feasibility of the protocol in individuals with PFP. Interventions to cause change within these local deficits have been identified, with gap maps demonstrating where further research is required to better align the mechanisms of treatment effects with specific deficits associated with PFP.

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Thesis at a glance

topic	Aim(s)	Participants	Methods	Conclusions
Systematic Review (PFP-associated deficits)	To identify the deficits that are associated with patellofemoral pain (PFP).	67 studies, 38 meta-analysed	We searched 5 databases, PRISMA followed. Evidence gap-maps produced	10* deficits should be targeted as they show association with PFP
Systematic review (Interventional mechanisms)	To identify the interventional effects on local deficits associated with PFP.	46 studies were included. 23 RCTs and 23 non-randomised interventional studies. 25 studies were meta-analysed	We searched 5 databases; PRISMA followed, ROB, quality of exercise reporting and PFP inclusion criteria were assessed.	Exercises can show mechanisms of effects in PFP through muscle performance and flexibility, and targeting hip and knee can show a mechanism of benefit
Lab. protocol development	To produce a lab-protocol based on the results of the first meta-analysis	The meta-analysis results were used to identify reproducible protocols of specific local deficits	Assessment tools were developed and studies' protocols were assessed	A laboratory evidence-based protocol was developed
Reliability study	To establish the reliability of the testing protocol	25 participants (11 uninjured and 14 PFP) were recruited	Within-session and test-retest reliability were investigated. Participants were seen 2 sessions 1 week apart	The protocol that was developed based on the results of meta-analysis was partially reliable
Feasibility study	To establish the feasibility of the testing protocol in patients with PFP.	14 participants with PFP were recruited	Data were collected in 2 sessions 6 weeks apart to analyse feasibility and conduct secondary analyses of changes and correlations between knee condition and neuromuscular characteristics	Protocol was partially feasible. Obtained willingness-to-participate, eligibility, retention, and recruitment rates can inform future planning
A future study plan based on the outcomes of the thesis	This chapter presents a potential plan of a future interventional study based on the outcomes of the thesis			

Keys: PFP; patellofemoral pain. RCT; randomised clinical trials. EMG; electromyographic. ROB; risk of bias

*: 9 deficits after we published a corrigendum. Details in Chapter three.

List of abbreviations

PFP	Patellofemoral pain
ROM	Range of motion
VM	Vastus medialis
VMO	Vastus medialis obliques
VML	Vastus medialis longus
VL	Vastus Lateralis
VLO	Vastus lateralis obliques
VLL	Vastus lateralis longus
BF	Biceps femoris
NOS	Newcastle-Ottawa scale
SD	Standard deviation
EMG	Electromyography
CSA	Cross-sectional area
SMD	Standardised mean difference
TFL	Tensor fascia latae
ITB	Iliotibial-band
RFD	Rate of force development
RTD	Rate of torque development
H-reflex	Hoffman reflex
MVC	Maximum voluntary contraction
vGRF	Vertical ground-reaction force
SNR	Signal-to-noise ratio
ASIS	Anterior superior iliac spine
mV	Millie volt
N	Newtons
ms	Milliseconds
SLTHT	Single-leg triple-hop test
IKD	Isokinetic dynamometer
IPFRN	International patellofemoral research network
VAS	Visual analogue scale
ICC	Intra-class correlation coefficient
CI	Confidence interval
SEM	Standard error of measurement
CoV	Coefficient of variation
BMI	Body mass index
Nm	Newton-meter
MCID	Minimal clinically important difference
AKPS	Anterior knee pain scale
SLS	Single-leg squat
KOOS-PF	Knee injury and Osteoarthritis Outcome Score – Patellofemoral subscale
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
ROB	Risk of bias
RCT	Randomised control trial
ROBINS-I	Risk of bias for non-randomised interventional studies

CERT	Consensus on Exercise Reporting Template
KT	Kinesio tape
OKC	Open kinetic chain
CKC	Closed kinetic chain
PENS	Patterned electrical neuromuscular stimulation
PRP	Platelet-rich plasma
PROMS	Patient reported outcomes
ASEP	American Society of Exercise Physiologists

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1 Introduction

This Chapter comprises an overview section, followed by two sections that focus on (i) a comprehensive overview of patellofemoral pain (PFP), and (ii) rationale for the focus on local neuromuscular characteristics associated with PFP.

1.1 Overview

The knee joint is a major joint that plays an imperative role in human locomotion. Due to that role, high loads pass through the knee, and reports suggest that up to 50% of sports-related injuries involve the knee joint (1). Patellofemoral pain (PFP) represents up to 45% of all knee joint problems (2). It is estimated that one out of six adult patients seen by clinicians due to knee complaints get diagnosed with PFP (3). Patellofemoral pain is also highly prevalent in adolescents, with point-prevalence reaching 7.2%, and up to 16.3% in females only (2).

A large number of studies investigating different interventions can be found in the literature. A recent review of interventional studies included 65 studies with adequate quality, and removed 105 low quality studies (4). Despite the extensive investigations of interventions, more than 50% of patients show no recovery in the long term (5), and up to 70% of patients report recurrent pain (6). Positive interventional outcomes are inconsistent, and PFP remains a major knee condition that directly impacts physical activity levels in affected populations (7).

In a consensus statement published by the Patellofemoral Pain Retreat, Witvrouw et al. (8) noted that research should aim to define PFP subgroups to help classify patients for targeted interventions, which allows to minimise the inconsistency of interventional outcomes. In other attempts to define PFP subgroups, Näslund et al. (9) used changes in bone metabolism in comparison to clinical tests, and found that around half of the examined group can show increased bone remodelling in scintigraphy investigations. Dierks et al. (10) used motion capture to measure 3D kinematic variables, and indeed found three subgroups (knee valgus, hip abduction, and knee and hip adduction) within runners with PFP. Subgrouping research conducted by Selfe et al. (11) used physical screening of muscle strength, flexibility, patellar mobility, and foot posture. Three subgroups were identified through their TIPPS approach; strong; weak and tight; and weak and pronated. All these substantial approaches aimed to use deficits to create treatment targets.

In another consensus statement, Powers et al. (12) presented a framework that highlights potential biomechanical pathways that can be targeted to aid subgroups identification through multiple local (around the knee), proximal and distal factors.

Local neuromuscular deficits are frequently reported, but there is a lack of agreement between these reports (12). Therefore, distinct local neuromuscular deficits might exist in PFP, warranting a comprehensive exploration (8,13), which is provided through this thesis.

1.2 Background to patellofemoral pain

1.2.1 Epidemiology of patellofemoral pain

In 2007, Callaghan and Selfe (14) explored the reports that formed the knowledge about the incidence and prevalence of PFP, indicating that these outcomes were not properly investigated in the United Kingdom. In 2018, Smith et al. (2) conducted a systematic review to identify epidemiological data of PFP, and multiple outcomes were identified in specific populations. Findings indicated that PFP is a common problem across adolescents and general populations, especially people with high activity levels (e.g. athletes and military personnel). Within military personnel, point prevalence is 13.5%. Within amateur cyclists and female elite athletes, recorded point prevalence can reach 35%. Within adolescents, 28.9% was reported generally, 7.2% for mixed sex groups, and 22.7% for female amateur athletes. In general population, reported annual prevalence reached 22.7%, and 35.7% in professional cyclists (2). However, uncertainties due to paucity of evidence, differences in case-definition and replication of other reports, similar to what Callaghan and Selfe (14) highlighted, were found. Overall, most frequently reported prevalence is 25%, and PFP diagnosis acquires up to 7.3% of all patients seen in healthcare (15).

Incidence rates - the number of new cases in a population within a period of time (14) - were predominant within males in military populations, reaching approximately 57% of 1000 people per year (16), and only one included study reported mixed sex data of 3.3% and 1.5% in 1000 cases per year in female and male recruits, respectively (2,17). Within general female adults, a study reported incidence of 20.8% of 77 participants after a 10-week running programme in novice runners (18), and another reported 1.9% within 53 amateur collegiate hockey, basketball and athletic athletes (19). Differences in rates (1.9 and 20.8%) might be related to differences in populations. In adolescents, incidence rates reached as high as 4.2% over two seasons of physical education, 5.1% over one season in school runners (mixed sex), and 14.9% in 1000 over one season in female athletes (2).

The high proportion of affected populations are of concern, especially that multiple reports indicate evident recurrency and negative prognosis. In adolescents, multiple investigations reported high PFP persistence rates. Nimon et al. (20) followed a group of 63 female adolescents for a mean period of 16 years (range; 14-20 years), and indicated that 27% showed significant symptoms after ≤20 years follow-up. Rathleff et al. (21) found a persistence rate of 55% in adolescents after two years follow-up. Moreover, Rathleff et al. (21) found 71% to be significantly more susceptible to reduction or ceasing of sport participation, which is similar to a 74% rate that was found previously (22). Stathopolu and Baildam (23) followed 46 patients who were diagnosed with PFP at mean age of 10.5 years to identify PFP prognosis in adolescents. Although only 22 participants responded (46%) at mean age of 22.6 years, 20 out of 22 (91%) reported current experience of anterior knee pain, with 10 (45%) reporting that symptoms had effects on their physical activity levels. In adults, Lankhorst et al. (5) conducted a longitudinal study of adults with PFP, reporting 50% to have notable symptoms at follow-ups of five to eight years (24). Therefore, with reports of long-term follow-up periods ranging from two to 20 years, PFP is shown to be a persistent, self-debilitating condition.

1.2.2 History and definition of patellofemoral pain

In 1784, William Hey, a surgeon, used the expression “internal derangement of the knee” to be behind anterior knee pain in young people. This expression was rejected by Konrad Büdinger, associating the symptoms to articular degenerations (25). A differentiation between Patellofemoral pain and Chondromalacia Patellae was considered in 1960s as research failed to find connection, and in 1978, a study by Leslie and Bentley found 49% of a sample of 78 participants (aged between 10 to 40 years) had negative arthroscopic investigations, although presenting with similar anterior knee complaints as the rest of the group (25,26). The overlap of terminologies to describe PFP is still seen today. Therefore, PFP implicates patellofemoral instability and/or overloading, without subluxations, dislocations or obvious articular cartilage damage (27).

Multiple synonyms have been used in the literature to describe PFP (28). Näslund et al. (9) presented a table showing the different synonyms of PFP used in the literature, with “patellofemoral pain” being most frequently used to describe the condition,

followed by “anterior knee pain”, “chondromalacia patellae”, “patellofemoral malalignment”, “idiopathic anterior knee pain”, and others. Runner’s knee, patellofemoral joint dysfunction, patellar arthralgia, retropatellar pain, peripatellar pain, and others were also used in the literature (28). This clearly shows the inconsistency in describing the condition. Although named variably within the literature, the definition of PFP have seen better consensus as most studies aim to exclude participants with other knee pathologies, showing agreement on it being a diagnosis of exclusion (9,28). Patellofemoral pain can be described as pain in or around the patella that develops insidiously (without trauma), felt during activities that load the knee during flexion (29–32) and is frequently reported after sudden over-activity relative to usual activity (33). A brief description of the function of the patellofemoral joint is needed to efficiently describe the condition and the diagnosis approach.

1.2.3 The patellofemoral joint

The patellofemoral joint is a joint formed between the patella; a sesamoid bone incapsulated by the quadriceps tendon, and the distal end of the femur. The patella adjusts length and direction of forces passing between quadriceps tendon and patellar tendon during knee motion (34). Contact area of the patella against the femoral condyles changes through the range of motion (ROM) of the knee. The joint action is represented as a gliding motion over the femoral condyles for around seven centimetres, and after 90° of flexion, the patella starts rotating outward (35). The patella elongates the lever arm of the quadriceps tendon of up to 30% during the whole ROM (35). During knee loading, the forces passing through the patellofemoral joint rise with increases in knee flexion angles. Reports indicate that the magnitude of the reaction forces at 90° of knee flexion reach more than twice the forces at 5° (25).

1.2.4 Diagnosis of Patellofemoral Pain

The recent clinical practice guidelines of PFP by Willy et al. (15) was a result of a thorough overview of the literature, producing summarised recommendations on examination and interventions. Within the literature, studies seem to agree on an aim to exclude any injuries or abnormalities that could cause the pain (36,37). Consequently, the guidelines suggestions are to examine for the presence of pain and exclude any other possible causes of pain. Patients with PFP should be examined for a reproducible retro-patellar or peripatellar pain with tasks that involve loading a flexed

knee (squats, stair negotiations, prolonged sitting or others), and a positive patellar tilt test (15).

1.2.5 Patellofemoral pathologies and differential diagnoses

Multiple patellofemoral pathologies can cause anterior knee pain. Amongst those are ligament and meniscus injuries, patellofemoral joint instability, quadriceps and patellar tendinopathies, Sinding-Larsen-Johansson syndrome and Osgood-Schlatter disease (15). An issue with PFP diagnosis is that it is a poorly defined pain commonly reported insidiously by people without structural abnormalities (38). Therefore, differential diagnoses seem to be very important, especially when researching risk and associated factors, to allow optimal identification of what PFP exhibits in investigational results. For example, degenerative changes develop in the knee with age advance (39,40). According to the American College of Rheumatology (41), at 38 years old, degenerative changes might start to cause clinical symptoms, and at 40 years or older, changes can be found radiographically. This was supported by a recent systematic review by Culvenor et al. (42), stating a prevalence of osteoarthritic changes among asymptomatic uninjured knees to be 19-43% in adults ≥40 years of age. This is mainly the reason why multiple case-control studies investigating factors associated with PFP included populations aged ≤ 40 years (43–48). Alongside osteoarthritis, chondromalacia patellae, characterised by softening, blistering, swelling, fissuring or fragmentation of patellofemoral joint cartilage, can be misinterpreted as PFP as it could cause similar pain representation (49). Patellofemoral joint morphology investigations can be optimally achieved with arthroscopy to diagnose chondromalacia patellae, therefore, clinical assessment might face differentiation difficulties (50). To summarise, PFP can be present with or without structural damage within the patellofemoral joint (38), and the exclusion of other conditions is important, especially in exploratory research that aim to identify factors causing the onset or persistence of PFP. Nevertheless, the differential diagnoses process does not identify the pathophysiological origins of symptoms.

1.2.6 Pathogenesis of patellofemoral pain

Multiple theories have been proposed to identify PFP pathogenesis; the “origination and development of the disease” (51). Elevated patellofemoral joint stress is a common theory found in PFP literature (12,52). Loading forces of the patellofemoral

joint are found to be greater in individuals with PFP when compared to controls (53). Besier et al. (54) modelled the forces generated by the muscles around the knee and found that elevated forces within the patellofemoral joint could be due to an increased muscle co-contraction in PFP. Farrokhi et al. (55) investigated patellar and femoral articular cartilage stress via two variables; uniform cartilage compression, or hydrostatic pressure, and tissue-distorting "octahedral" shear stress. When compared to controls , their findings indicate that people with PFP exhibited 35% and 66% more patellar hydrostatic pressure and octahedral stress, respectively. Similar findings were identified for the femoral cartilage (55). Other reports of peak shear within the femur show differences between PFP and controls of up to 28% (53). Patellar bone strain was higher in PFP, as an increase of 118% was seen compared to controls (56). Within the patellofemoral stress theory, pain nociception is attributed to subchondral bone tissue due to the elevated stress seen in these reports. Pain nociception is a process involving the transmission and perception of painful stimuli (57). Nociceptors are free nerve endings that can be stimulated by biological, electrical, thermal, mechanical, and chemical stimuli, which is perceived as pain in the brain (57). Being highly innervated, subchondral bone is thought to be the origin of pain in PFP (58). However, the evidence identifying the structural sources of nociception is still limited (8).

Another theory is the abnormal thermoregulation in PFP that is suspected to cause ischemia that elicits pain (59). This theory is proposed due to reports of differences in pulsatile blood flow and cold-knee sensations in individuals with PFP (60,61). Other research link the source of pain in PFP to thickening and neovascularisation of the retinacula (62), increased pain neurotransmitters in infrapatellar fat-pad and synovium (63), poor knee proprioception (64) and heightened peripheral sensitisation (65). These theories represent abnormal physiological processes. Therefore, Dye (66) suggested a possible disruption in tissue homeostasis that could be a result of an overlap of some or all of these descriptions. Current understanding of PFP pathogenesis directly informs the recommendation to clinicians to treat PFP as a multifactorial condition (67).

1.2.7 Factors related to patellofemoral pain

Evaluating the effects of targeted interventions on specific factors, or characteristics, of PFP is recommended (8). In order to identify those effects, the association between

these characteristics and PFP is needed. Research were conducted on people prior to developing PFP to identify risk factors (68–74). Many other investigations have been conducted to identify the deficits that are associated with the presence of PFP symptoms (46,47,75–79). These investigations reported characteristics that are local, proximal or distal to the knee (13,15). Despite the multifactorial nature of PFP that requires incorporating different types of characteristics, the local neuromuscular characteristics remain unclear. In their framework paper, Powers et al. (12) summarised these findings. However, the frequent inconsistency or contradictions that are mentioned within the statements in that paper are noteworthy (12). Callaghan wrote a chapter around patients' subgrouping based on PFP characteristics, and stated in the conclusion that the paucity and lack of extensive preliminary testing could be a reason for the uncertainty in the field (80).

The most recent synthesis of prospective studies was undertaken by Neal et al. (31). Their meta-analysis indicated that weak quadriceps in military recruits and strong hip muscles in adolescents predispose the corresponding populations to PFP. These findings were similar to a prior systematic review by Lankhorst et al. (29), indicating a general weakness in quadriceps to be a risk factor for PFP. Neal et al. (31) indicated that concentric peak torque of the quadriceps, not isometric, is a possible risk to developing PFP in military recruits.

Interestingly, there were differences in the 'weakness' expressed by studies when they were synthesised. Within the quadriceps, concentric peak torque was deemed a risk factor by Neal et al. (31) and isometric peak torque was highlighted as an associated factor by Lankhorst et al. (81). This indicates a need to specify the type of force expression that can be used to monitor deficits like weakness in the quadriceps. There are other local factors comprising of differences in muscle activation timing, specifically between Vastus medialis (VM) and Vastus lateralis (VL), thigh muscle tightness (within the quadriceps, hamstrings and iliotibial band), and patellar morphological and biomechanical abnormalities (12,13,81–83). Research is needed for the ascertainment of how these deficits can be reliably detected and targeted by interventions.

1.2.8 Current interventions of patellofemoral pain

Multiple conservative interventions have been proposed to treat PFP. These interventions consist of stretching and strengthening exercise therapy, patellar taping and mobilisation, the use of foot orthoses, gait retraining and patient education (15).

Exercise therapy targeting hip and knee are supported widely within published evidence (15,84–86) and remain the intervention of choice (4,87). Patellar taping was proposed by McConnell (88), and until today is still showing good immediate outcomes in alleviating pain. Foot orthoses, as an adjunct to exercise programmes, and gait retraining are recommended for patient groups with specific foot and gait mechanics for short term benefits (15). Patient education is recommended as part of intervention programmes as it can enhance adherence, self-management, and due to the unlikelihood of causing adverse events (15). The frequent recommendation of combining the aforementioned interventions into a multimodal protocol seems to be under wide agreement (15,87). Yet, dosage is still lacking a definite guideline (15), probably due to poor reporting (89) and lack of patient involvement in exercise programmes development (87). Inadequate studies of medium (3 to 12 months) and long-term investigations (>12 months) are also evident (4), which contributes to the lack of understanding around medium and long-term outcomes.

1.3 Background to local neuromuscular characteristics of patellofemoral pain

1.3.1 Definition of local neuromuscular characteristics

A definition of “local neuromuscular characteristics” in PFP can be constructed from Miriam-Webster dictionary to incorporate characteristics involving the nerves and muscles that are, due to knee involvement, local to the knee (90). The term “deficit” will be used whenever a characteristic is related to PFP, as they would be disadvantages or deficiencies (91) found in this patient group. So, any characteristic related to how muscles are controlled peripherally, as well as the physiological and anatomical status of muscles that cross the knee joint would be investigated. A study by Wu et al. (92) presented a detailed subclassification of such properties, based on two classes; mechanical and neuromuscular, and both are incorporated into representing strength, power, control and fatigability properties. As there is no definite agreement on the term, a clear start-point for the thesis will be set by using the term “neuro-muscular” to include muscle EMG activity, strength, morphology

(structure properties like cross-sectional areas, fascicle lengths and pinnation angles), and flexibility, similar to previous work within the knee joint (93) and PFP (94–96). Therefore, the muscles involved are the Quadriceps (Vastus medialis (VM), Vastus lateralis (VL), Vastus intermedius (VIM) and Rectus femoris (RF)), Hamstrings (Biceps femoris (BF), Semitendinosus (ST) and Semimembranosus (SM)), Gastrocnemii (Gastrocnemius medialis (Gast. M.) and Gastrocnemius lateralis (Gast. L.), Sartorius, Gracilis, Popliteus, and Tensor fascia latae (TFL), due to being connected to a structure that crosses the knee (Iliotibial-band (ITB)).

1.3.2 Conducting a thesis about local neuromuscular characteristics, their association with PFP and the changes that can occur to them after interventions

1.3.2.1 Why was the area of local neuromuscular characteristics chosen?

It is known as a concept to segment biomechanical investigations in PFP into local, distal and proximal fields, and all these segments underwent extensive research (6). However, the local neuromuscular segment still shows substantial inconsistency. The consensus statements that continue to be published by experts in PFP (8,12,87,97,98), had an essential role in developing the understanding of all research findings related to the goal of the thesis. Although these statements aim to provide best practice guidelines for PFP research, diagnosis and management, they frequently highlight the inconsistency about local deficits. In 2010, Davis et al. (13) stated that the impaired function of VM is frequently reported, yet inconsistent. This notion carried over to the consensus statement published by the same group, seven years later (in 2017) (12).

Generally, almost all statements in that consensus paper (12) were highlighting the inconsistent or inconclusive findings related to each characteristic, and this created a necessity to conduct a meta-analysis to identify local neuromuscular deficits that are associated with PFP.

1.3.2.2 Why a meta-analysis to identify the local neuromuscular characteristics that are associated with PFP is needed?

There are a plethora of studies exploring deficits in PFP, and the only viable solution to provide a solid justification for tests to be included in a deficits-detection protocol is to conduct a meta-analysis. The first reason is that meta-analyses form the highest levels of evidence in research (99). The second reason is that meta-analyses provide knowledge about empirical similarities in findings (99) which can indicate that a deficit

is, or is not, regularly found in PFP. Such a review would not include prospective studies, as the factors to be identified should be, theoretically, associated with the active presence of the condition to be identified as 'associated with PFP', rather than a 'risk' leading to the development of the condition.

Multiple systematic reviews were conducted to identify the deficits associated with PFP by synthesising such studies (81–83). However, there were no clear answers from these reviews about local neuromuscular deficits, with substantial association to PFP, that should be subsequently investigated to identify treatment effects. We will take VM-VL timing as an example; is it associated with PFP, and therefore should be included in a deficits'-detection protocol to identify interventions' effects?

In the 2017 consensus paper, Powers et al. (12) presented a framework of potential biomechanical pathways associated with PFP with multiple statements to address these pathways. Statement 1.1a.1 addresses Vasti EMG timing difference to be inconsistently found in PFP. This is understandable, as if we look at the literature, a decision to include or exclude VM-VL timing could be justified using studies that found delays (72,75,100–103), or studies that did not find delays (76,104–108). Chester et al. (83) meta-analysed the evidence around VM-VL excitation timing imbalances, and highlighted their findings to be inconclusive. Wong et al. (109) was a literature review around the same topic, and clearly stated that there is substantial diversity in the methods used to detect VM-VL timing, with inconclusive findings as well. Lankhorst et al. (81) was an essential piece of work that guided the knowledge required to conduct the thesis. Lankhorst et al. (81) had a broader area of synthesis as they included all biomechanical characteristics collected in PFP compared to uninjured groups, with no meta-analyses of local EMG deficits produced. This unclarity can be easily acknowledged once we look at the methods used in such studies individually.

To capture VM and VL excitation onset and identify timing differences, Voight et al. (103) and Witvrouw et al. (75) used knee jerk reflex, Mellor and Hodges (102) used resisted seated extension, Cowan et al. (100) used step-up task, Van Tiggelen et al. (72) used sudden rise on heels (rock task), Ng et al. (101) used three voluntary tasks (semi-squatting, tip-toeing and heel standing), and postero-anterior knee perturbations in three positions (standing (normal, on heels and on toes)), and all these studies found significant differences. For the same outcome measure (VM-VL timing), Brindle et al.

(76) used stair ascent, McClinton et al. (104) used step-up task with five different step heights, Pal et al. (105) used walking and running, Cavazutti et al. (106) used five different tasks (sit-to-stand, stand-to-sit, squat, step-up, step-down), Sheehy et al. (107) used steps ascent and descent, Karst and Willet (110) used voluntary knee extension and knee jerk reflex, Powers et al. (108) used level walking and stair ascent and descent, and none found significant delays. So, it seems that published work is yet to offer a clear answer on whether we can consider VM-VL timing as a local deficit associated with PFP, thus included in a protocol that targets such deficits. A focused meta-analysis can, hopefully, present an answer.

A better example can be exhibited with muscle weakness. Quadriceps weakness was highlighted as a risk factor by Neal et al. (31) when measured concentrically, but not isometrically. Lankhorst et al. performed two reviews about risk and associated factors (29,81). They reported that weakness measured concentrically is found in prospective "risk-factors" studies (29), but measured isometrically was the finding of their "associated-factors" review (81). The clinical importance in exploring multiple muscle performance properties is evident. Willy et al. (15) indicated that clinicians must explore muscle performance aspects in each patient for better exercise tailoring. Functional movements require different types of muscle contraction, and considering patients' needs is required for successful treatment (111). The last thorough review in this area by Lankhorst et al. (81) only produced one meta-analysis (of two studies of a local deficit) that showed a significant pooled effect for isometric knee extension peak torque at 60° to be lower in PFP.

Looking at studies individually, quadriceps performance in general can be found investigated in PFP isometrically (112–114), concentrically (44,115), and eccentrically (43,116,117). The same can be found for the hamstrings (44,45,116,118). Some studies investigated rate of torque development (79,116,119) that have not been meta-analysed previously. This begs the question; which type of force production should be incorporated in a deficits-detection protocol that can be used to identify a change in such muscle performance deficits in PFP? This will have direct implications on the decisions needed to build an exercise programme. For example, patients showing specific deficits within a test that targets power (force produced / unit of time) would

require specific modifications to an exercise programme that usually targets strength (the ability of a muscle to exert force at a specified velocity) (120).

In another statement (1.2c), Powers et al. (12) addressed muscle tightness in PFP. In that statement, three studies were cited to support the notion that 'hamstrings tightness is associated with PFP'; White et al. (121), Smith et al. (122) and Piva et al. (123). One study used straight leg raise (SLR) (123), one used a combination between popliteal angle and SLR (122), and one used a special method to conduct popliteal angle test, using a horizontal bar to fixate the hip at 90° of flexion (121). However, there are multiple aspects that render the assumption of associating hamstrings tightness to PFP inconclusive. Piva et al. (123) only excluded people without knee surgeries in the past two years. Types of surgeries were not specified, and some knee surgeries might lead to hamstrings tightness (124). Smith et al. (122) had a group of 46 adolescent skaters, with 14 having anterior knee pain, and only a subgroup of five participants being diagnosed with non-traumatic PFP. White et al. (121) had a sample that fits the criteria chosen for this thesis (discussed in sections 1.2.2 and 1.2.5), but their reliability was conducted on a group of nine uninjured participants. The same can be said about quadriceps tightness. Powers et al. (12) cited four studies associating quadriceps tightness to PFP (44,122,123,125). One of these studies was a study by Duffey et al. (44), which measured knee range of motion, in supine with a flexed hip, a different method to the other studies (122,123) (Kibler's (125) paper was not available). In their systematic review around potential risk factors, Waryasz and McDermott (82) cited the same studies in addition to Witvrouw et al. (69), which was a prospective study that aimed to identify deficits prior to the development of PFP in students (17 to 21 years old).

Within the literature that aimed to identify local neuromuscular deficits associated with PFP, the variety and breadth of what these deficits are, and how they can be detected, are evident. Syntheses that prioritise deficit types and their methods of detection are required, so that the tests that produced frequent findings of local neuromuscular deficits in PFP groups against uninjured groups can be identified.

Published research and guidelines are important in supplementing clinical-decision making (126). Within PFP, Greaves et al. (127) used published guidelines and consensuses specifically to build an intervention. In a different approach to classify

sub-groups of PFP, Selfe et al. (11) used a literature review and consensus statements to identify the clinical signs within potential subgroups of PFP, and the methods needed to assess these signs. Therefore, using published guidelines and consensuses to build research elements is not unusual in PFP. However, no previous work built a testing protocol by identifying the association between any type of deficits (including local neuromuscular deficits) with PFP through meta-analysis, and afterwards; objectively assessed the meta-analyses results.

1.3.2.3 Why a meta-analysis of interventions targeting such characteristics is needed?

Generally, several consensus statements, reviews and guideline papers summarised the interventional literature in PFP. In 2015, the International Patellofemoral Pain Research Retreat was held and in 2016, their outcomes around the best available interventional approaches to treat PFP were published. Hip and knee targeted exercises, combined interventions (two or more of exercises, patellar taping, mobilisation or orthoses) and foot orthoses were recommended (97). In 2017, the retreat was held again to update the recommendations, and those recommendations were the same. However, multiple other interventions were highlighted as uncertain (patellar taping or bracing, acupuncture or dry needling, manual soft tissue therapy, blood flow restriction and running retraining) or not recommended to be used in isolation (knee or lumbar mobilisations and electrophysical agents) (87).

In a mixed-methods guidelines paper by Barton et al. (128), three key factors were highlighted as determinants of interventional success in PFP; multimodal interventions combined with patient education and activity modification. In that paper, specifics of interventions were also highlighted. Immediate pain relief was highlighted as an essential aspect of any PFP intervention, and was recommended to be provided by patellar taping and bracing. Despite addressing a conflict between three systematic reviews that investigated patellar taping (129–131), Barton et al. (128) recommended medially directed patellar taping on the short term (four weeks) combined with exercise, as it improves adherence by providing early pain relief. Braces that limit lateral patellar translation were also recommended for the same reasons, on immediate term as an adjunct to exercise. These treatment options were supported by level one evidence (high-quality systematic reviews) (128). The most supported

treatment option was exercise intervention. Specifically, open kinetic chain (OKC) and closed kinetic chain (CKC) exercises were both recommended. Although it was strongly recommended by experts' opinion (128), VMO targeted exercise through biofeedback was not supported by Collins et al. (131) which was deemed as a high quality systematic review (128).

The most recent guidelines were published in 2019 by Willy et al. (15) and agreed on the choice of combining hip and knee targeted exercise to be in early stages of intervention, with a preference of targeting posterolateral hip muscles. To target knee muscles, Willy et al. (15) also equally recommended CKC and OKC exercises. Tailored taping was recommended with a goal to provide early pain relief, but choosing an aim of enhancing muscle function through taping was not recommended (15). Pre-fabricated orthoses were also recommended for a short term (for people with increased foot pronation), only in combination with exercise. However, Willy et al. (15) did not recommend using knee bracing or straps, nor VMO biofeedback-based exercises to treat PFP. Moreover, Willy et al. (15) highlighted that some interventions, like running retraining (to induce fore-foot strike, higher cadence and less hip adduction), blood-flow restrictions, and patient education (targeting load and body-weight management to promote to minimise patellofemoral joint overload) can be used to treat PFP.

Overall, the recommendation that was agreed upon in all these papers was maintaining exercise as an essential component in a combined interventions programme.

The effects of interventions through changes of deficits (a mechanism of effects (132)) require identifying interventions that are evidently able to cause a change in such deficits. With a similar reasoning of the section above, various interventions can be found being investigated in PFP, with an unclear knowledge about the feasible interventions that can target local neuromuscular deficits in PFP groups.

1.3.2.4 Is there a lack of knowledge of how interventions can change specific local neuromuscular deficits that are associated with PFP?

Despite the abundance of interventional studies in PFP, we suspect that there is a lack of knowledge about the specific changes that interventions can cause to local neuromuscular deficits that are associated with PFP. The main reason could be the lack

of clarity around deficits that are associated with PFP in the first place (highlighted in section 1.3.2.2). Subsequently, the second reason is the lack of studies that investigated the changes that occur after intervention in deficits that are evidently associated with PFP.

With that goal, a systematic review by Fagan and Delahunt (95) had an objective to identify interventions' effects on specific local neuromuscular characteristics. That systematic review gathered 11 studies and had four separate aims, including two aims related to local muscle EMG. One aim was to identify physiotherapy treatments that can restore VM and VL timing and activation magnitude imbalances. The authors identified two RCTs that used two different tasks in VM-VL timing data collection; stair ascent and rock and rise task (rising on toes and rocking back on heels following a visual que). Both studies were investigating the same six-weeks combined intervention (experimental group) against placebo taping with sham ultrasound (control group). Findings were indicating that the combined intervention of medial glide patellar taping with hip and knee targeted exercises changed VM-VL timing from VL having an excitation onset before VM (pre-treatment) to being detected to be after VM (post-treatment), regardless of the task used during data collection. Reduction of symptoms was also found in the experimental group only. However, it is important to note that both studies were performed by the same group (Cowan et al. (133,134)) and published in the same period (both published 2002), with the only apparent difference to be in sample size (total n=65 and n=40, respectively). However, their results indicate that VM-VL timing can show alteration in onset ratio in (at least one) improved PFP group, whether it is detected during stair ascent or a rock task.

In another study, Lima et al. (135) used a 90-days programme that consisted of OKC hip abduction exercise three-days a week. Opposed to free squatting, Lima et al. (135) only found a significant change in VM-VL onsets when signals were collected during squatting with isometric hip abduction. Mostamand et al. (136) conducted the test for VM-VL onsets in single leg squat in three conditions; before taping, with taping, and after six weeks of daily taping of the knee. Significant change in VM-VL onset was found in both the second and third conditions. After lumbopelvic manipulation given to the experimental group, Motealleh et al. (137) found no change in Vasti timing difference, but their results show significant changes in earlier onset of VM excitation

alone, and significant changes in Vasti excitation amplitudes, in a rock task. Also, pain was significantly lower after the manipulation, so, Motealleh et al. (137) showed that an intervention that is not recommended by recent guidelines (15) caused various significant changes in multiple local EMG characteristics within the Vasti, with associated improvement in pain. Witvrouw et al. (138) used knee jerk reflex to identify any alteration in VM-VL onsets, and found no significant changes although both recruited PFP groups showed significant pain reduction after five weeks of either OKC or CKC exercise programmes that targeted the quadriceps.

For any reader of biomechanics literature in PFP, it is easy to realise that Vasti timing differences are one of the most frequently investigated characteristics, and was chosen as an example in this paragraph due to that fact. The variability in findings and methods used to study VM-VL timing in PFP is evident, even in interventional studies (similar to the case-control investigations mentioned in the previous section).

With a careful look into other EMG studies of PFP, many interventional studies can be found, but the interventions and the methods of analysing EMG are highly heterogenous across these studies. For example, two interventional studies investigated VM excitation amplitude in maximal isometric contraction, at 90° after CKC and OKC exercise (139), and at 60° with medial patellar glide taping (140). Keet et al. (140) found a decrease in VM excitation amplitude without improvement in symptoms, but Cabral (139) did not have the same findings (no significant changes in VM) and only the group receiving OKC exercise showed decrease in pain. Other studies can be found using different data collection methods to investigate interventions' effects on VM excitation amplitude (135,137,141–147). The same example can be exhibited with multiple other characteristics, like VM-VL excitation onset (135–138), VM/VL excitation amplitude (135,140,141,148), VL excitation amplitude (135,142,143,145–147,149), VL excitation duration (135,144), RF excitation amplitude (149,150) or BF excitation amplitude (144,149). These studies used a variety of tasks during data collection, like anterior-posterior sway (141), single-leg squat (143), squatting with isometric hip abduction (135), step-up (140,146), side step-up (144), step down (145,147), rock task (137), walking (144) and running (149).

The same can be said about characteristics related to muscle performance. Within isometric peak torque of knee extension, studies can be found using different angles

like 30°, 60° and 90° to monitor changes in quadriceps 'weakness' pre-post interventions (151–155). Other studies used peak concentric torque for the same purpose, but at different speeds, like 60°, 180°, 240° and 300° per second (45,86,156–161). For knee flexors, studies can be found with similar diversity in isometric (162–164) and concentric peak torque tests (45,86,157,159).

All these investigations were used in interventional studies suspecting that the characteristics measured are associated with PFP. Without a succinct synthesis, and pre-identification of local neuromuscular deficits associated with PFP, it is very difficult to subjectively draw a clear picture about interventions and their effects on such deficits. Therefore, to identify a mechanism of effects of such interventions through local neuromuscular deficits, studies that investigated interventions' effects need to be synthesised based on their methods and interventions used for a clear answer.

1.3.2.5 Meta-analyses require methodological homogeneity, which can be provided by creating methodological domains

The goal of conducting a systematic review is to provide an overview of a specific research area by gathering relevant studies in a reproducible systematic method (165). However, there are multiple challenges in producing single conclusions from multiple studies, including sample sizes, study quality and methodological differences between included studies, which affect the interpretation and generalisability of the results (166). Thus, a meta-analysis is required. Meta-analysis is a process that produces an overall measure of the effects from studies in a systematic review by statistically combining and analysing their data (167,168).

Variability between studies can be termed heterogeneity, which refers to the differences between studies that are not due to chance (167). There are three types of heterogeneity (167); clinical heterogeneity, methodological heterogeneity and statistical heterogeneity. In clinical heterogeneity, the variations lie within samples, interventions and outcome measures. If differences exist between studies due to their design and bias risks, it is considered a methodological heterogeneity. When the effects of the interventions are different, it can be referred to as statistical heterogeneity. In any systematic review, the included studies should be sufficiently homogenous for a meta-analysis to be conducted (167).

To minimise these sources of heterogeneity, the meta-analyses will be conducted by categorising the gathered studies and extracted data into major domains, which will include categories and sub-categories based on availability of investigations. We explored a variety of published investigations within EMG in sections 1.3.2.3 to 1.3.2.4. So, for example, an EMG domain would be created if sufficient EMG studies are found, like studies of muscle excitation onset (of an 'EMG timing' category under the EMG domain), and so would be a muscle mean excitation amplitude (under 'EMG excitation amplitude' category under the same domain). The terms 'domains' and 'categories' and 'sub-categories' will be used to present a classification system that allows for an easy interpretation of the results.

1.3.2.6 Meta-analyses results may not be sufficient to identify a mechanism of effects of interventions through local neuromuscular characteristics in PFP

In 2012, Callaghan (80) discussed the limitations preventing accurate sub-classification of people with PFP, based on deficits that are frequently suspected to be associated with PFP. While this thesis is not directed towards sub-classifying people with this condition, multiple relevant points were raised in that paper. The author recommended re-examining the evidence that leads clinicians to subgroup people with PFP (i.e., the literature around deficits). The author also noted that the absence of sufficient reliability and validity possibly led clinicians to randomly choose what should and what should not be included in clinical examination. Moreover, evaluating treatments that target such deficits was a recommended step to make sure that targeting these deficits is worthwhile. This can be performed by conducting RCTs, to compare such interventions with generalised interventions in terms of superiority, thus being able to ascertain that targeting such deficits is worthwhile. Callaghan (80) concluded this paper by warning about problems that are potentially rendering such efforts inconclusive. Namely, the author highlighted that the systems used to sub-classify PFP lack preliminary research (reliability and validity), and improving these aspects would prevent a generalised random approach of the treatment of PFP.

As we demonstrated in the previous sections in this chapter, a solid knowledge about deficits associated with PFP and interventions that can target these deficits is initially required. In relevance to what Callaghan (80) addressed, the thesis will approach the

issue around local neuromuscular characteristics associated with PFP by synthesising the literature using meta-analyses, to empirically identify the characteristics that are frequently found in PFP groups when compared to uninjured people. Similarly, an intervention would be developed by synthesising interventional studies that targeted such deficits. To correctly progress into laboratory testing, a novel process will be used to extract the methods needed to detect these deficits from the meta-analyses that should identify the local neuromuscular characteristics associated with PFP. Finally, and to address the points mentioned by Callaghan (80), reliability and feasibility work will be conducted to fulfil the thesis aim.

1.4 Gaps of knowledge targeted in this PhD project

This PhD project aims to provide an understanding of interventional mechanisms of effects by providing evidence-based means of identifying local neuromuscular characteristics associated with PFP to aid detection of changes due to intervention. However, a gradual approach, comprising extensive literature synthesis and preliminary lab studies, to fulfil that aim is needed as current evidence is still unclear on some aspects discussed below.

1.4.1 The lack of consensus on evident local neuromuscular deficits associated with patellofemoral pain

Multiple factors are hypothesized to be causing onset and/or persistence of PFP. Few published systematic reviews were able to empirically find agreement among the research to present evident factors frequently reported within PFP investigations (31,81,169). These factors represent possible interventional targets. Nevertheless, a clear consensus on definite local neuromuscular deficits found in PFP is still absent (12,83). This could be due to multiple reasons. First, the methodologies used in exploratory research aiming to find these deficits are extensively variable. These differences are within the tasks during which deficits were found to significantly differ in PFP, and the specifications and preparations of modalities and measurement tools used (83,170). Secondly, the poor reporting of these methodologies, whether it was testing (170) or interventional protocols (89). This probably requires a different approach investigating available literature, prioritising these methods during research process and synthesis.

1.4.2 The overlap between interventional research and exploratory research that aimed to identify deficits associated with patellofemoral pain

Current literature, including Cochrane reviews, thoroughly explored beneficial interventions in PFP (129,171–174) and a recent paper was published in 2019 presenting clinical practice guidelines for healthcare settings (15). However, to identify the mechanisms of effects of interventions through local neuromuscular characteristics, an overlap between interventional and exploratory research on deficits 'associated' with PFP is needed. A possible gap is present within investigated local neuromuscular deficits between studies that aimed to identify deficits and studies that investigated interventions' effects on these deficits in PFP. This is similar to what is seen in prospective studies (31) compared to cross-sectional case-controls (81), as there is a clear difference in the (number and types of) investigated variables. This is probably due to the lack of methodological agreement mentioned earlier, thoroughly discussed by Witvrouw et al. (8), in a PFP research retreat statement highlighting important research gaps. By synthesising interventional studies that explored changes in local deficits, and identify the overlap of investigated variables with what have been undertaken in case-controls (175), this gap can be addressed.

2 Aims, objectives, impacts, hypotheses, and difficulties encountered by COVID-19

The overarching aim of this thesis is to provide an understanding of the local neuromuscular mechanisms that can explain improvement of PFP symptoms. This incorporates identifying the local deficits that are associated with PFP, and the potential effects of interventions on these deficits. Therefore, the approach adopted to reach that aim entailed merging the outcomes of a systematic review with laboratory research, then testing the resultant protocol's feasibility and reliability in a group of people with and without PFP. Interventions' effects on local neuromuscular characteristics were synthesised, aiding robust future planning using the outcomes of the thesis.

2.1 Research question of the thesis:

How can we identify and measure local neuromuscular characteristics associated with PFP, in order to investigate mechanisms of effects for specific interventions?

2.2 Specific aims, objectives, hypotheses, and impacts

2.2.1 Chapter 1; Introduction

The aim of this chapter was to highlight the origins from which a gap in the literature exists regarding the mechanisms of effects of interventions within local neuromuscular characteristics.

2.2.2 Chapter 3; Systematic review and meta-analysis (patients vs uninjured)

The first project of the PhD was a systematic review and meta-analysis of all PFP case-control studies that aimed to identify local neuromuscular deficits.

2.2.2.1 Aim

The aim was to identify the local neuromuscular characteristics that are associated with PFP.

2.2.2.2 Objective

To synthesise current literature investigating local neuromuscular characteristics in people with PFP compared to uninjured groups.

2.2.2.3 Hypotheses

- Null hypothesis
    - Local neuromuscular deficits that are associated with PFP cannot be identified through a systematic review and meta-analysis of current literature.
- Alternative hypothesis
    - Multiple local neuromuscular deficits that are associated with PFP can be identified through a systematic review and meta-analysis of current literature.

2.2.2.4 Impact on thesis progression

The outcomes of this review allowed the identification of local neuromuscular deficits that are associated with PFP. The testing protocol of the thesis should be built based on the results of this chapter.

2.2.3 Chapter 4; Systematic review and meta-analysis (changes of local deficits after interventions in people with PFP)

In this chapter, the goal is to highlight interventional methods that can change the local neuromuscular deficits of PFP.

2.2.3.1 Aims

To identify the effects of interventions on the local neuromuscular characteristics that are associated with PFP.

2.2.3.2 Objective

To synthesise current literature investigating the changes of local neuromuscular characteristics in people with PFP after intervention.

2.2.3.3 Hypotheses

- Null hypothesis
    - Interventional effects on local neuromuscular characteristics that are associated with PFP cannot be identified based on available literature.
- Alternative hypothesis
    - Interventional effects on local neuromuscular characteristics that are associated with PFP can be identified based on available literature.

2.2.3.4 Impact on thesis progression

This chapter identified the effects of interventions on local neuromuscular characteristics that were investigated within interventional research in the field. It also highlighted multiple important aspects (provided by the produced gap-maps) of variability in current research in terms of interventions' types and investigated characteristics.

2.2.4 Chapter 5; Building a local neuromuscular deficits' detection laboratory protocol

This chapter aimed to provide the thesis with a laboratory protocol that targets specific local neuromuscular deficits in PFP.

2.2.4.1 Aim

The aim was to identify the methods that can detect the deficits that have been identified to be associated with PFP.

2.2.4.2 Objectives

1. Extract detection methods from the results of the meta-analysis.
2. Build a detailed laboratory protocol out of the extracted methods.

2.2.4.3 Hypotheses

- As this chapter was a methods development chapter, it is not appropriate to present hypotheses as no statistical analyses were conducted to accurately test a hypothesis.

2.2.4.4 Impact on thesis progression

We produced a lab protocol that is based on meta-analyses of all available studies in the field. With this chapter, the thesis obtained evidence-based local deficits (the what (Chapter three)) and testing protocol (the how (Chapter five)) that can be used to identify a mechanism of interventional effects in PFP.

2.2.5 Chapter 6; Reliability of a detection protocol of local neuromuscular deficits in PFP

2.2.5.1 Aim

The aim in this chapter was to establish intra-rater reliability of the resultant testing protocol.

2.2.5.2 Objective

The objective was to recruit a PFP and uninjured cohorts to establish intra-rater reliability of the test protocol.

2.2.5.3 Hypotheses

- Null hypothesis
  - The reliability of a protocol to detect the local neuromuscular deficits associated with PFP that is derived from meta-analyses cannot be established.
- Alternative Hypothesis
  - The reliability of a protocol to detect the local neuromuscular deficits associated with PFP that is derived from meta-analyses can be established.

2.2.5.4 Impact on thesis progression

This chapter allowed a successful transition into feasibility and analyses testing in a PFP cohort.

2.2.6 Chapter 7; The preliminary feasibility study of the testing protocol

This chapter aims to identify the feasibility of the testing protocol in a PFP group.

2.2.6.1 Aim

To identify the feasibility of a protocol that comprises a battery of tests of local neuromuscular deficits associated with PFP, and conduct analyses that identify the changes in these deficits in relation to PFP symptoms, that would be used in a larger-scale future study.

2.2.6.2 Objectives

1. To assess the feasibility of the testing protocol in people with PFP.
2. To assess the changes in local neuromuscular deficits in relation to changes in PFP symptoms.

2.2.6.3 Hypotheses

- Null hypotheses
  - The deficits-detection protocol is not feasible in a group of people with PFP.
  - There are no significant correlations between local deficits and levels of pain and function.

- Alternative hypothesis
    - The deficits-detection protocol is feasible in a group of people with PFP.
    - There are significant correlations between local deficits and levels of pain and function.

2.2.6.4 Impact on thesis progression

Although the protocol showed partial feasibility, the feasibility outcomes aid planning for future work.

2.2.7 Chapter 8; a future plan based on the outcomes of the thesis

This chapter presents an overview of a potential future plan for an interventional study that can identify a mechanism of effects of interventions through local neuromuscular deficits associated with patellofemoral pain, which is built using the outcomes of the thesis.

2.3 COVID-19 related difficulties that impacted the process of the thesis

The COVID-19 pandemic significantly disrupted my PhD research, especially my lab work and reliability study. I began collecting data in February 2020 but had to stop abruptly in March after collecting data from eight participants, conducting two sessions for each. Outside of my studies, I faced personal challenges like having to move twice, evacuating with my family on a military plane, and re-joining the Kuwaiti army to set up and manage COVID-19 checking stations and quarantine zones.

These events had a big impact on my PhD work. Firstly, I couldn't meet participants for data collection due to health restrictions, so despite labs reopening, recruitment was difficult. Also, applying to the NHS to get ethical approval for my feasibility study took longer than normal. I started a new application to QMUL to conduct my last study using only the laboratory as I was not able to use the clinic within Mile-end hospital. On December 8th 2021, I obtained the ethical approval to conduct the reliability and feasibility work, of which the last participant was recruited at end of May 2022. Additionally, a major conference I planned to attend in Copenhagen (February 3rd to 5th, 2022) was cancelled, where I was set to present my work.

Because of these issues, I had to do my data analysis much later than planned, during the final writing phase of my thesis from June to December 2022. Given these disruptions, I've included this section to explain how my research process had to

change. Initially, my plan was to identify specific deficits in the field, find the best methods to detect them, establish reliability and conduct an interventional study. Despite the challenges, the core goals of my thesis were achieved, setting the stage for more extensive research in the future, possibly in post-doctoral studies.

3 Local neuromuscular characteristics associated with patellofemoral pain: A systematic review and meta-analysis

As a first project of the PhD, a systematic review and meta-analysis was conducted. It was a review of all studies of non-traumatic PFP that had uninjured and PFP groups being tested for local neuromuscular characteristics. This chapter established a major framework within the thesis as it formed a basis for all subsequent projects. It was presented in the PFP retreat (ipfrn.com) in 2019, published in the Journal of Clinical Biomechanics (176), and was accepted as an oral presentation in SportsKongres 2022 conference (which was cancelled due to COVID-19; abstract published in British Medical Journal (BMJ) in 2022 (177)). This review provided the thesis with a list of deficits to be tested in a protocol designed to detect mechanisms of interventions in people with PFP. It is important to note that a corrigendum was recently published regarding the Biceps Femoris pooled data ((178); Appendix 1.4). However, the thesis was systematically conducted based on the results mentioned in the chapter, showing pre-corrigendum outcomes.

3.1 Introduction

Patellofemoral pain (PFP) is one of the most common diagnoses within clinical musculoskeletal settings, with multiple possible kinematic and neuromuscular factors associated with the presence and development evident in the literature (31,81). Individuals with PFP experience different responses to similar interventions (8). Up to 50% of patients do not consider themselves recovered in the long-term, and around 70% have recurrent or chronic pain (5,6). Although psychosocial factors and personal beliefs about pain play an important role (179), symptom persistence is also purported to relate to unclear and under-reported modification of specific deficits following rehabilitative interventions (12,180). Providing researchers with the proper detection methods and clinicians with clearly defined local deficits that may need to be modified with treatment represents a basis to understand the mechanisms of benefit and deliver patient-centred interventions.

Multiple systematic reviews investigating the factors related to PFP can be found in the literature (29,31,37,81–83,181–183) These systematic reviews investigated both prognostic risk and neuromuscular factors associated with PFP. Although the work to date is substantial, no conclusive results on the local neuromuscular characteristics of the muscles crossing the knee have been reported as only single studies were found for some local characteristics (81) and due to unexplained heterogeneity (83). Consensus statements from the International Patellofemoral Pain Retreat recommend future research to seek understanding the deficits underpinning rehabilitation interventions directed locally, proximal and distal to the patellofemoral joint, such that interventions can be better targeted to the individuals' specific deficits (12,97).

The overarching aim of this systematic review was to guide future research and clinical practice by synthesizing findings about the local neuromuscular deficits associated with PFP. A secondary aim was to identify the evidence gaps amongst studies investigating local neuromuscular characteristics.

3.2 Methods

This section highlights the methodology used to perform this systematic review and meta-analysis. Any methodological deviations we used to analyse and present the data, including deficit categorisation and highlighted evidence gaps are mentioned below.

3.2.1 Protocol and registration

For this systematic review, we followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) with the protocol being registered with PROSPERO (CRD42019116841).

3.2.2 Data sources and search strategy

Pubmed, Embase, Cochrane Library, SportDiscus and Web of Science research databases were searched from inception to July 2021 by two reviewers (S.A. and N.M). Reference lists of similar previous systematic reviews were checked for further inclusion (S.A.). We only included studies in English and on human subjects. Medical Sub-Headings (MeSH) were searched for each category (PFP and related musculature) using the Pubmed MeSH terms searching tool (Table 3.1).

Table 3.1: Keywords used to perform literature search:

<table>
<tr><td rowspan="7">Keywords</td><td rowspan="3">Keywords group 1</td><td>In all text</td><td>retropatellar OR 'retro patellar' OR peripatellar OR 'peri patellar' OR parapatellar OR 'para patellar' OR patellofemoral OR 'patello femoral' OR femoropatellar OR 'femoro patellar' OR 'knee anterior' OR 'anterior knee' OR chondromalacia OR runner*</td></tr>
<tr><td colspan="2">AND</td></tr>
<tr><td>in all text</td><td>pain OR painful OR discomfort OR syndrom* OR dysfunction* OR patellae OR knee</td></tr>
<tr><td colspan="3">AND</td></tr>
<tr><td>Keywords group 2</td><td>In all text</td><td>quadricep* OR vmo OR vl OR vasti OR vastus OR 'rectus AND femoris' OR hamstring* OR semimembranosus OR semitendinosus OR 'bicep* AND femoris' OR popliteus OR gastrocnem* OR calf OR 'knee AND flexor*' OR 'knee AND extensor*' OR tfl OR itb OR 'iliotibial band' OR 'tensor fasciae latae' OR 'tensor fascia lata' OR sartorius OR gracilis</td></tr>
<tr><td colspan="3">AND NOT</td></tr>
<tr><td>Keywords group 3</td><td>In titles only</td><td>surg* OR reconstruct* OR arthroplast* OR 'anterior AND cruciate' OR 'posterior AND cruciate' OR acl OR pcl</td></tr>
</table>

3.2.3 Review process

Two reviewers (S.A. and N.M.) independently performed the literature search and screening, in which results were imported, and duplicates removed using Mendeley Reference Management Software (Mendeley Ltd. Elsevier, Version 1.19.3). Studies were screened for eligibility using the Rayyan application for systematic reviews (184).

3.2.4 Study eligibility

Due to the key involvement of the knee joint in PFP, we focused our approach on the muscles that cross the knee (quadriceps, hamstrings, gastrocnemii, gracilis, sartorius

and popliteus) to identify any local deficits in symptomatic compared to uninjured groups. However, we acknowledge the existence of other neuromuscular deficits proximal and distal to the knee.

To maximise the ability of identifying deficits that are associated with PFP and not degenerative patellofemoral joint diseases, this review focused on populations ≤ 40 years of age. This decision was supported by a recent systematic review by Culvenor et al. (42), stating a prevalence of osteoarthritic changes among asymptomatic uninjured knees to be 19-43% in adults ≥ 40 years of age. Males and females were included, in case-control studies with data of PFP and uninjured groups. The included studies should have at least one local neuromuscular characteristic investigated in individuals with PFP. Muscles that do not cross the knee were excluded. Populations with a history of surgeries or other knee pathologies, as well as subjects over 40 years of age were excluded.

3.2.5 Quality assessment

A modified version of the case-control Newcastle-Ottawa Quality Assessment Scale (NOS) was used (Appendix 3). The NOS consists of eight items, focusing on three main topics (selection, comparability, and exposure) with a maximum score of nine. Questions were modified to be relevant to case-control studies. The first question of the exposure section was removed as it was not applicable. Therefore, scores for each quality ranking were set as follows; LQ=0-2, MQ=3-5, and HQ=6-8. Studies having less than 10 subjects in either group had the quality assessment results decreased by one score, as results of small samples affect generalisability (99). Two reviewers (S.A. and N.M.) assessed the quality of the studies using the NOS independently. Any disagreements were resolved by discussions and consultation with a third reviewer (S.L.) and differences in scores were assessed by calculating agreement percentages (Table 3.4). Meta-analysis only included MQ and HQ studies to present results with a higher level of evidence.

3.2.6 Data extraction

Included studies' data and participants demographics were extracted by the first reviewer (S.A) except for the muscle performance investigations, which were extracted by the second reviewer (N.M), and collectively checked by both. All data sets containing the mean and standard deviation (SD) of each neuromuscular characteristic

were extracted from included studies. The tasks used to collect these characteristics within the included studies were used to divide them into two main categories (i) functional tasks; in which multiple joints work to perform the task, and (ii) isolated; involving the knee joint alone. This was undertaken to enhance the future guidance on which task to choose to detect each deficit and introduce possible explanations to the differences seen in deficit presence between different tasks. Under each category, the studies were further sub-categorised into four separate outcome measure domains (electromyographic (EMG), muscle performance, flexibility and cross-sectional area (CSA) data), with EMG having two sub-domains (excitation timing and amplitude). Studies with data presented in graphs were extracted using WebPlotDigitizer; Version 4.2 (185).

3.2.7 Evidence gap map

After data extraction, all investigations within the categories and sub-categories mentioned previously were combined to build an evidence gap map. The map was built based on the type of task used to detect each neuromuscular characteristic, within each muscle crossing the knee. The task categories are; stepping and stair negotiations, squatting and leg-presses, jumping, balance, walking and running tasks. This provides an overview of the investigations used to detect the local neuromuscular factors associated with PFP in populations under 40 years of age (Tables 3.5 to 3.7). Presenting the evidence gap map also allows for a better interpretation of the results, as it shows the missing investigations for which this review cannot provide evidence due to unavailability in the literature. Moreover, a summary of the meta-analyses outcomes is added to identify the differences between the number of the meta-analysed results and total reported investigations.

3.2.8 Data analysis

Similar outcome measures within each domain were pooled. Studies reporting the same task category but different tasks (e.g., both up and down stair negotiation), were pooled but not combined. Data from the same task category and task, but of differing intensities (e.g., different heights for step-up task) were combined using the RevMan calculator before being pooled, to avoid over-inflation of the effect size (186). Other data that were not eligible for pooling, were presented in tables in Appendix 3. The

forest plots are presented according to our approach of main categories (functional and isolated tasks) then the domains of neuromuscular investigations.

Review Manager (RevMan5) was used to perform the meta-analyses. Random-effects models were used in the meta-analyses as studies were not assumed to have a common effect size or direction (187). Standardised mean differences (SMDs) were calculated, using Hedges adjusted *g* (188), and *P*-values of <0.05 are considered significant pooled effects.

Detecting and quantifying statistical heterogeneity of data was performed using the chi^2 and I^2 tests (167). In heterogeneity testing, data with chi^2 *P*-value of < 0.05 and I^2 results of > 50%, were considered statistically heterogenous (189). Standardised mean differences of ≤0.59 were considered of small effect size, 0.60–1.19 were medium, and SMDs ≥1.20 were considered large. Levels of evidence were categorised as shown in Table 3.2, and are derived from Van Tulder et al. (190). For comparability, and to set a rigorous range to avoid over-sizing the magnitude of the overall effects, effect size ranges and evidence level decision rules were adapted from recent systematic reviews investigating similar topics (31,169,180).

Table 3.2: Ranking level of evidence using modified guidelines of Van Tulder et al. (190).

Strong evidence	Statistically significant and homogenous pooled effect from ≥3 studies including ≥ 2 HQ studies.
Moderate evidence	Statistically significant and heterogenous (I^2 > 50%) pooled effect from multiple studies with at least 1 high quality study.
	Statistically significant and homogenous (I^2≤ 50%) pooled effect from multiple MQ or LQ studies.
Limited evidence	Results from 1 HQ study; or multiple MQ or LQ studies that are statistically significant and heterogenous (I^2 > 50%).
Very limited evidence	Results from 1 MQ or 1 LQ study.
Conflicting evidence	Insignificant and heterogenous (I^2 > 50%) findings pooled from multiple studies, regardless of quality.

3.3 Results

The literature search, undertaken in July 2021, yielded 13657 studies. After removing duplicates and screening, 67 case-control studies (19 HQ, 39 MQ, nine LQ) were included (Figure 3.1 and Tables 3.3 and 3.4). A total sample size of n=1552 PFP (27.2% males) and n=1508 uninjured subjects (29.3% males) was included. Findings are summarised in the main text, with Appendix three containing complete data.

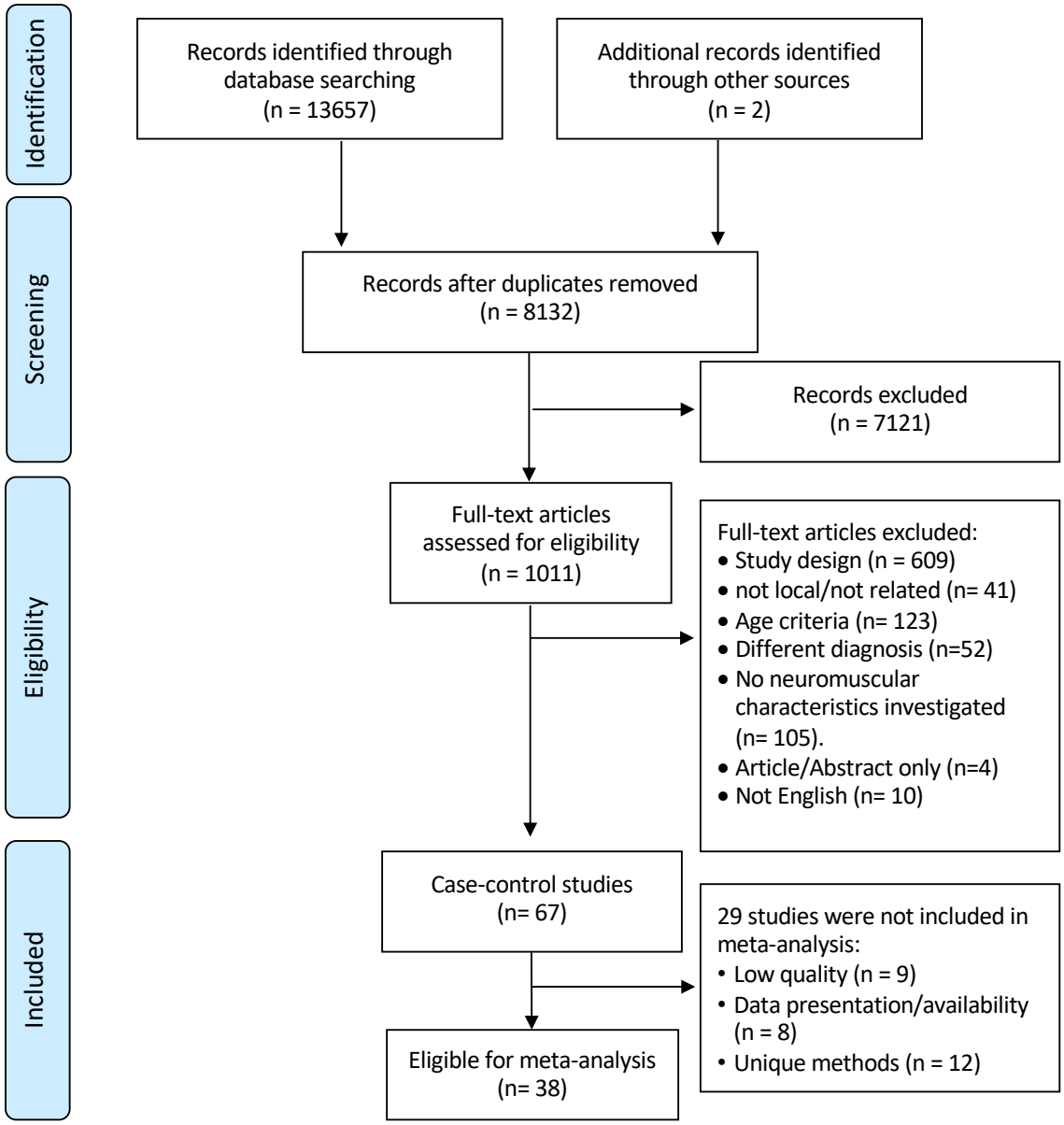


Figure 3.1: PRISMA flow-chart of the search and screening phase. Data presentation/availability; if data presented in a way that cannot be used in meta-analysis (e.g. median and interquartile). Unique methods; when the outcome measure is conducted by a single study.

Table 3.3: Studies' Characteristics

	Study (chronological order)	Sample size total (males)		Functional task (multiple joint contribution)	Isolated task/procedure (only knee joint involved)	Investigated domains							
						EMG					Non-EMG		
		PFP	Control			Type	Quadriceps	Hamstrings	Gastrocnemii	TFL	Muscle performance	Flexibility	CSA
1	**Voight et al. 1991**	16 (10)	41 (17)		knee jerk reflex	Timing	VMO, VL						
2	**Boucher et al. 1992**	9 (0)	9 (0)		OKC strength test	Amplitude	VMO, VML, VL				Extensors		
3	**MacIntyre and Robertson 1992**	8 (0)	12 (0)	Running		Amplitude	VM, RF, VL						
4	**Thomeé et al. 1995**	40 (0)	20 (0)		OKC strength test	Amplitude	VM, RF				Extensors		
5	**Thomeé et al. 1996**	11 (0)	9 (0)	Isometric squat against resistance	OKC strength test	Amplitude	VM, RF				Extensors		
6	**Witvrouw et al. 1996**	19 (8)	80 (37)		knee jerk reflex	Timing	VMO, VL						
7	**Miller et al. 1997**	6 (0)	9 (0)	Stepping task (up/down) and modified wall slides		Amplitude	VMO, VL						
8	**Laprade et al. 1998**	8 (0)	19 (0)		Seated resisted extension	Amplitude	VMO, VL						
9	**Cesarelli et al. 1999**	11 (11)	30 (30)		Seated resisted extension	Both	VM, RF, VL						
10	**Cesarelli et al. 2000**	12 (12)	30 (30)		Seated resisted extension	Both	VM, RF, VL						
11	**Duffey et al. 2000**	99 (59)	70 (53)		OKC strength test						Extensors + flexors		
12	**Brindle et al. 2003**	16 (4)	12 (5)	stair negotiation (up)		Timing	VMO, VL						
13	**Crossley et al. 2004**	48 (17)	18 (9)	stair negotiation (up/down)		Timing	VMO, VL						
14	**Christou 2004**	15 (0)	15 (0)	leg press	Flexibility tests	Amplitude	VMO, VL					Hamstrings + Gastrocs	
15	**Coqueiro et al. 2005**	10 (0)	10 (0)	Semi-squat		Amplitude	VMO, VLL						
16	**Earl et al. 2005**	16 (3)	16 (3)	Stepping task	Flexibility test	Timing	VMO, VL			TFL		Hamstrings + ITB	
17	**Hazneci et al. 2005**	24 (24)	24 (24)		OKC strength test						Extensors + flexors		
18	**Mellor et al. 2005**	10 (3)	10 (4)		Seated resisted extension	Timing	VMO, VL						
19	**Sacco et al. 2006**	6 (NA)	5 (NA)	stair negotiation (up/down)		Amplitude	VM, VL						
20	**Keet et al. 2007**	15 (4)	20 (7)	Stepping task (up /down)	OKC strength test	Amplitude	VMO, VL				Extensors		
21	**McClinton et al. 2007**	20 (11)	20 (10)	Stepping task (up)		Both	VMO, VL						
22	**Stensdotter et al. 2007**	17 (0)	17 (0)	leg press	OKC strength test	Both	VMO, VML, RF, VL				Extensors		
23	**Bevilaqua-Grossi et al. 2008**	12 (0)	12 (0)		knee jerk reflex	Timing	VMO, VLL, VLO						
24	**Santos et al. 2008**	10 (0)	10 (0)	single leg squat, stepping(up/down), sit-to-stand, single leg jump, tip-toeing and balance on heels	Seated resisted extension	Both	VMO, VLL, VLO						
25	**Liebensteiner et al. 2008**	19 (8)	19 (8)	leg press (against stable/unstable foot plate)		Amplitude	VMO, VL	BF, ST	Gast. M.				
26	**Stensdotter et al. 2008**	17 (0)	17 (0)	sudden standing perturbation on movable platform		Both	VMO, VML, RF, VL						
27	**White et al. 2009**	11 (6)	25 (13)		Flexibility test							Hamstrings	
28	**Bevilaqua-Grossi et al. 2009**	12 (0)	10 (0)	leg press	Seated resisted extension	Timing	VMO, VLL, VLO						
29	**Patil et al. 2010**	34 (14)	34 (14)		Flexibility test							Hamstrings	
30	**Felicio et al. 2011**	19 (0)	20 (0)	leg press	Seated resisted extension	Amplitude	VMO, VLL, VLO						
31	**Bolgla et al. 2011**	18 (0)	18 (0)	stair negotiation (descent)	Seated resisted extension	Both	VMO, VL						
32	**Dionisio *et al.*, 2011**	8 (4)	8 (4)	semi-squat		Amplitude	VMO, VML, RF, VL	BF, ST	Gast. L.				
33	**Mostamand et al. 2011**	18 (11)	18 (11)	single leg squat		Both	VMO, VL						

34	**Patil et al. 2011**	20 (8)	17 (7)		Seated resisted extension/flexion	Timing	VMO, VL	BF, ST (LH, MH)					
35	**Pal et al. 2011**	40 (21)	15 (7)	walking and running		Timing	VM, VL						
36	**Aminaka *et al.*, 2011**	20 (7)	20 (7)	stair negotiation (ascent and descent)		Timing	VMO						
37	**Chen *et al.*, 2012**	26 (5)	26 (5)		stimulation in supine lying position (electromechanical delay)	Timing	VMO, VL						
38	**Kim and Song, 2012**	10 (NA)	10 (NA)	stair negotiation (ascent and descent)		Both	VMO, VL						
39	**Rathleff *et al.*, 2013**	57 (0)	29 (0)	stair negotiation (descent)	OKC strength test	Both	VM, VL				Extensors		
40	**Bley et al. 2014**	20 (0)	20 (0)	single leg triple hop test		Amplitude	VL	BF					
41	**Giles et al. 2015**	35 (15)	35 (15)		muscle CSA measurements in supine position								Quadriceps (VM, RF, VL,VIM)
42	**Bolgla et al. 2015**	66 (66)	36 (36)		OKC strength test						Extensors		
43	**Song et al. 2015**	16 (0)	8 (0)	single leg squat		Amplitude	RF						
44	**Briani et al. 2016**	43 (0)	38 (0)	stair negotiation (ascent)		Timing	VM, VL						
45	**Kalytczak et al. 2016**	14 (0)	14 (0)	single leg triple hop test		Amplitude	VL	BF					
46	**de Oliveira Silva et al. 2016**	15 (0)	15 (0)		measuring H-reflex in supine position	Amplitude	VM						
47	**Carvalho et al. 2016**	25 (0)	25 (0)		OKC strength test						Extensors		
48	**Freddolini et al. 2017**	40 (40)	40 (40)	Walking		Timing	VM, RF, VL						
49	**Santos et al. 2017**	12 (0)	15 (0)	walking on treadmill (flat and inclined)		Amplitude	VMO, VLL, VLO						
50	**Goto et al. 2018**	14 (4)	14 (4)	star excursion balance test		Amplitude	VM						
51	**Chavez and Rebolledo 2018**	24 (0)	24 (0)	single leg squat		Timing	VM, RF, VL	BF					
52	**de Oliveira Silva et al. 2018**	65 (0)	51 (0)		OKC strength test						Extensors		
53	**Kalytczak et al. 2018**	14 (0)	14 (0)	single leg triple hop test		Amplitude	VL	BF					
54	**Briani et al. 2018**	19 (0)	19 (0)	stair negotiation (ascent)	OKC strength test	Amplitude	VM, VL				Extensors		
55	**Felicio et al 2019**	24 (0)	22 (0)	Squats and side-lying hip abduction	OKC strength test	Amplitude	VMO, VLL, VLO				Extensors		
56	**Ferreira et al. 2019a**	30 (0)	30 (0)		OKC strength test						Extensors		
57	**Ferreira et al. 2019b**	38 (0)	38 (0)		OKC strength test						Extensors		
58	**Gallina et al. 2019**	36 (0)	20 (0)		OKC strength test	Amplitude	VM, VL				Extensors		
59	**Gawda et al. 2019**	20 (15)	15 (10)	semi-squat		Amplitude	VMO, RF						
60	**Pazzinatto et al. 2019**	30 (0)	30 (0)		measuring H-reflex in supine position + knee jerk reflex	Amplitude	VM						
61	**Baellow et al. 2020**	15 (0)	15 (0)	Drop-vertical jump	OKC strength test	Amplitude	VMO, VL	BF			Extensors + flexors		
62	**Briani et al. 2020**	56 (0)	46 (0)		OKC strength test + Rate of force development						Extensors + flexors		
63	**El Sawy et al. 2020**	20 (20)	20 (20)		muscle CSA measurements in supine position								VMO
64	**Nunes et al. 2020**	26 (0)	26 (0)		OKC strength test + Rate of force development						Extensors		
65	**Peng et al. 2020**	10 (0)	25 (13)*		Seated resisted extension	Both	VM, VMO, VL, RF						
66	**de Albuquerque et al. 2021**	26 (0)	24 (0)		OKC strength test						Extensors		
67	**de Almeida Britto et al. 2021**	12 (12)	20 (20)	Running		Both	VMO, VL						
	Totals	**1552 (27.2%)**	**1508 (29.3 %)**	**39**	**42**	**53**	**53**	**8**	**2**	**1**	**20**	**4**	**2**

** Peng et al. 2020 had 13 uninjured male participants. However, all neuromuscular comparisons with PFP group (n=10) were from the 12 females in uninjured group.*

Table 3.4: Quality assessment of Case-control studies using a modified Newcastle-Ottawa scale (Check= yes, Blank= no, SA=first reviewer, NM=second reviewer).

	Study (Alphabetical order)	Selection								Comparability				Exposure				Total score	
		adequate case definition		Representativeness of cases		selection of controls		definition of controls		Controls for sex		controls for other factors		same method of ascertainment		non-response rate			
		NM	SA	NM	SA	NM	SA	NM	SA	NM	SA	NM	SA	NM	SA	NM	SA		
1	**Aminaka et al. 2011** (191)			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	6	HQ
2	**Baellow et al. 2020** (118)	✓	✓						✓	✓	✓			✓	✓	✓	✓	5	MQ
3	**Bevilaqua-Grossi et al. 2008** (192)									✓	✓	✓	✓	✓	✓	✓	✓	4	MQ
4	**Bevilaqua-Grossi et al. 2009** (193)	✓								✓	✓			✓	✓			2	LQ
5	**Bley et al. 2014** (194)			✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	5	MQ
6	**Bolgla et al. 2011** (195)	✓	✓					✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
7	**Bolgla et al. 2015** (47)	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓			6	HQ
8	**Boucher et al. 1992** (114)									✓	✓			✓	✓			1*	LQ
9	**Briani et al. 2016** (196)			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓			6	HQ
10	**Briani et al. 2018** (197)			✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	6	HQ
11	**Briani et al. 2021** (116)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓			6	HQ
12	**Brindle et al. 2003** (76)			✓	✓	✓		✓	✓					✓	✓	✓	✓	4	MQ
13	**Carvalho et al. 2016** (198)			✓	✓			✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
14	**Cesarelli et al. 1999** (199)									✓	✓	✓	✓	✓	✓	✓	✓	4	MQ
15	**Cesarelli et al. 2000** (115)									✓	✓	✓	✓	✓	✓	✓	✓	4	MQ
16	**Chen et al. 2012** (200)									✓	✓			✓	✓	✓	✓	3	MQ
17	**Christou 2004** (201)									✓	✓			✓	✓	✓	✓	3	MQ
18	**Coquiro et al. 2005** (202)	✓	✓					✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
19	**Crossley et al. 2004** (203)			✓	✓			✓					✓	✓	✓			3	MQ
20	**de Albuquerque et al. 2021** (113)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓			6	HQ
21	**de Almeida Britto et al. 2021** (204)			✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	6	HQ
22	**De Oliveira Silva et al. 2016** (205)			✓	✓			✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
23	**De Oliveira Silva et al. 2018** (117)			✓	✓			✓	✓	✓	✓			✓	✓			4	MQ
24	**Dionisio et al. 2011** (206)							✓		✓	✓			✓	✓	✓	✓	2*	LQ
25	**Duffey et al. 2000** (44)			✓	✓	✓	✓	✓	✓			✓	✓	✓	✓			5	MQ
26	**Earl et al. 2005** (77)			✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	6	HQ
27	**Sawy et al. 2020** (207)	✓	✓	✓	✓			✓	✓	✓	✓					✓	✓	5	MQ
28	**Felicio et al. 2011** (208)	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	6	HQ
29	**Felicio et al. 2019** (209)	✓	✓						✓	✓	✓	✓	✓	✓	✓			5	MQ
30	**Ferreira et al. 2019a** (210)	✓	✓			✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	7	HQ
31	**Ferreira et al. 2019b** (79)	✓	✓			✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	7	HQ
32	**Freddolini et al. 2017** (211)									✓	✓	✓	✓	✓	✓	✓	✓	4	MQ
33	**Gallina et al. 2019** (48)			✓	✓					✓	✓	✓		✓	✓			3	MQ
34	**Gawda et al. 2019** (212)							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	5	MQ
35	**Giles et al. 2015** (213)			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	7	HQ
36	**Goto et al. 2018** (214)			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	7	HQ
37	**Hazneci et al. 2005** (45)							✓	✓	✓	✓			✓	✓	✓	✓	4	MQ
38	**Kalytczak et al. 2016** (215)		✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	6	HQ
39	**Kalytczak et al. 2018** (216)							✓	✓	✓	✓			✓	✓	✓	✓	4	MQ
40	**Keet et al. 2007** (140)			✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	6	HQ
41	**Kim and Song 2012** (217)													✓	✓	✓	✓	2	LQ
42	**Laprade et al. 1998** (218)							✓		✓	✓			✓	✓	✓	✓	2*	LQ
43	**Liebensteiner et al. 2008** (219)			✓	✓			✓	✓	✓	✓	✓		✓	✓	✓	✓	5	MQ
44	**MacIntyre and Robrtson 1992** (220)			✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	5*	MQ
45	**McClinton et al. 2007** (104)	✓	✓					✓	✓					✓	✓	✓	✓	4	MQ
46	**Mellor et al. 2005** (102)	✓	✓											✓	✓	✓	✓	3	MQ

47	**Miller et al. 1997** (221)			✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	4*	MQ
48	**Mostamand et al. 2011** (136)			✓	✓			✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
49	**Nunes et al. 2020** (119)	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	7	HQ
50	**Chavez and Rebolledo 2018** (222)							✓	✓	✓	✓			✓	✓	✓	✓	4	MQ
51	**Pal et al. 2011** (105)			✓	✓			✓	✓					✓	✓			3	MQ
52	**Patil et al. 2010** (46)			✓	✓			✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
53	**Patil et al. 2011** (223)			✓	✓			✓		✓	✓			✓	✓		✓	4	MQ
54	**Pazzinatto et al. 2019** (224)	✓	✓	✓	✓	✓		✓	✓	✓	✓			✓	✓	✓	✓	6	HQ
55	**Peng et al. 2020** (225)	✓	✓									✓	✓	✓	✓	✓	✓	4	MQ
56	**Rathleff et al. 2013** (78)			✓	✓	✓	✓	✓	✓	✓	✓			✓	✓			5	MQ
57	**de Sacco et al. 2006** (226)													✓	✓			0*	LQ
58	**Santos et al. 2008** (227)	✓	✓	✓	✓			✓	✓	✓	✓	✓		✓	✓	✓	✓	6	HQ
59	**Santos et al. 2017** (228)							✓	✓	✓	✓			✓	✓	✓	✓	4	MQ
60	**Song et al. 2015** (150)			✓	✓	✓	✓	✓		✓	✓			✓	✓			4	MQ
61	**Stensdotter et al. 2007** (112)			✓	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓	6	HQ
62	**Stensdotter et al. 2008** (229)			✓	✓			✓	✓	✓	✓			✓	✓	✓	✓	5	MQ
63	**Thomee et al. 1995** (43)							✓		✓	✓			✓	✓	✓		2	LQ
64	**Thomee et al. 1996** (230)									✓	✓	✓	✓	✓	✓			2*	LQ
65	**Voight et al. 1991** (103)				✓			✓	✓	✓				✓	✓	✓	✓	4	MQ
66	**White et al. 2009** (121)			✓	✓			✓	✓					✓	✓	✓	✓	4	MQ
67	**Witvrouw et al. 1996** (75)			✓										✓	✓	✓	✓	2	LQ
	Agreement %	**97%**		**95%**		**94%**		**83%**		**98%**		**92%**		**100%**		**97%**			

**: score was decreased by one due to sample sizes (if either group had less than 10 participant).*

3.3.1 Evidence gap map

The map represents the current gaps in literature within investigations of local neuromuscular characteristics associated with PFP (Tables 3.5 to 3.7). Most investigations were focusing on quadriceps, and few or no investigations were found within other muscles crossing the knee. No studies were found with data related to gracilis, sartorius or popliteus muscles. Only one eligible study reported iliotibial band (ITB) flexibility data and tensor fascia latae (TFL) EMG data (77). Appendix three contains a gap map with citations, to allow the reader to quickly find the studies for each investigation.

Table 3.5: The gap map shows the total investigations performed using FUNCTIONAL TASKS to capture EMG timing (left side) and amplitude (right side). The bottom half summarises the results following meta-analysis:

Electromyographic Activity Domain (***Functional Tasks***)																		
Muscles / Tasks	**VM**	**VL**	**RF**	**BF**	**ST**	**GRA SAR POP**	**TFL**	**Gast. M**	**Gast. L**	**VM**	**VL**	**RF**	**BF**	**ST**	**GRA SAR POP**	**TFL**	**Gast. M**	**Gast. L**
Total Excitation **Timing** investigations										Total Excitation **Amplitude** Investigations								
Stepping and stair negotiation	❹ ⑤1	❸ ⑤1					❶			❸ ④2	❸ ④2							
Squatting and leg presses	❷ ②1	❷ ②1	❶ ①	①						❸ ⑦2	❸ ⑥1	❶ ② 2	①1	①1			①	1
Jumping tasks	❶	❶								❶ ①	❷ ③		❶ ③					
balance during standing	❶ ①	❶ ①	①							❷ ①	❶ ①	①						
Gait (walking)	②	②								①	①	①						
Gait (running)	②	②								①	①	①						
Meta-analysis results (**Timing** investigations)										**Meta-analysis** results (**Amplitude** investigations)								
Stepping and stair negotiation	EO ↔	EO ↔								MEA	MEA							
	ED									MEA-R ↔								
	EO-R ⇧																	
Squatting and leg presses										MEA	MEA (VL)							
											MEA(VLO) ↔							
Single-leg triple-hop test											MEA		MEA ⇧					

Pooled effect	⇧⇩ Small effect	↑↓ Medium effect	↔ No difference	Study numbers	**Example: ❹ ⑤1** **4 HQ, 5 MQ and 1 LQ** studies investigated VM timing EMG in stepping and stair negotiation	Evidence Level	Strong evidence	Moderate evidence	Conflicting evidence	No pooled data

EO: Excitation Onset. EO-R: Excitation Onset Ratio. ED: Excitation Duration. MEA: Mean Excitation Amplitude. MEA-R: Mean Excitation Amplitude Ratio. VM: Vastus medialis. VL: Vastus lateralis. VLO: Vastus lateralis longus. RF: Rectus femoris. BF: Biceps femoris. ST: Semitendinosus. GRA: Gracilis. SAR: Sartorius. POP: Popliteus. TFL: Tensor facia latae. Gast. M: Gastrocnemius medialis. Gast. L: Gastrocnemius lateralis. Arrow-up: higher. Arrow-down: lower. This gap-map was amended in the corrigendum by removing BF and VL data (178).

Table 3.6: The gap map shows the total investigations performed using ISOLATED TASKS to capture EMG timing (left side) and amplitude (right side). The bottom part summarises the results following meta-analyses:

Electromyographic Activity Domain (***Isolated Tasks***)																		
Muscles / Tasks	**VM**	**VL**	**RF**	**BF**	**ST**	**GRA SAR POP**	**TFL**	**Gast. M**	**Gast. L**	**VM**	**VL**	**RF**	**BF**	**ST**	**GRA SAR POP**	**TFL**	**Gast. M**	**Gast. L**
Total Excitation **Timing** investigations										Total Excitation **Amplitude** Investigations								
Isometric contraction	❷③ 1	❷③ 1	❶①	①	①					❹③ 3	❹③ 2	❶① 1						
Concentric contraction	❶②	❶②	②							❷② 1	❷②	② 1						
Eccentric contraction										❶ 1	❶	1						
Knee Jerk Reflex	① 2	① 2								❶								
H-Reflex										❶①								
Electro-mechanical Delay	①	①								Not applicable								
Meta-analysis results (**Timing** investigations)										**Meta-analysis** results (**Amplitude** investigations)								
H-Reflex										**MEA ↓**								
Seated knee extension										**MEA**	**MEA (VL)** / **MEA (VLO)**							

Pooled effect	⇧⇩ Small effect	↑↓ Medium effect	←→ No difference	Study numbers	**Example: ❷③ 1** **2 HQ, 3 MQ and 1 LQ** studies investigated VM EMG timing in isometric contractions	Evidence Level	Strong evidence	Moderate evidence	Conflicting evidence	No pooled data

MEA: Mean Excitation Amplitude. VM: Vastus medialis. VL: Vastus lateralis. VLO: Vastus lateralis longus. RF: Rectus femoris. BF: Biceps femoris. ST: Semitendinosus. GRA: Gracilis. SAR: Sartorius. POP: Popliteus. TFL: Tensor facia latae. Gast. M: Gastrocnemius medialis. Gast. L: Gastrocnemius lateralis. Arrow-up: higher. Arrow-down: lower.

Table 3.7: The gap map shows the total investigations of the Muscle performance, Flexibility and Cross-sectional area domains within each muscle / muscle group. The bottom part summarises the results following meta-analyses:

Muscle performance, Flexibility and Cross-sectional area domains						
Domains	**Muscles**	**Quadriceps**	**Hamstrings**	**Gastrocnemii**	**Gracilis, Sartorius & Popliteus**	**Iliotibial band**
Total investigations						
Muscle performance	**Isometric torque**	❾ ⑧ 2	❶ ①			
	Concentric torque	❹ ④ 1	❶ ②			
	Eccentric torque	❹ ① 1	❶			
Flexibility			❶ ③	①		❶
Cross-sectional area		❶ ①				
Meta-analysis results						
Muscle performance	**Isometric torque**	↓				
	Concentric torque	↓	⇩			
	Eccentric torque	⇩				
	Total work	⇩				
	Rate of force development (isometric) – **30% MVC**	⇩				
	60% MVC	⇩				
	90% MVC	↓				
Flexibility			⇩			
Cross-sectional area						

Pooled effect	⇧⇩ Small effect	↑↓ Medium effect	←→ No difference	Study numbers	**Example:** ❽ ⑧ 2 **8 HQ, 8 MQ and 2 LQ** studies investigated isometric quadriceps (extension) torque	Evidence Level	Strong evidence	Moderate evidence	Conflicting evidence	No pooled data

3.3.2 Results of meta-analyses

Multiple local neuromuscular factors were found to be associated with PFP; two in functional tasks and eight in isolated tasks (significant overall pooled effects (P<0.05)). Findings also indicate that characteristics in ten functional and four isolated tasks showed no association with PFP (P≥0.05).

3.3.2.1 Functional tasks

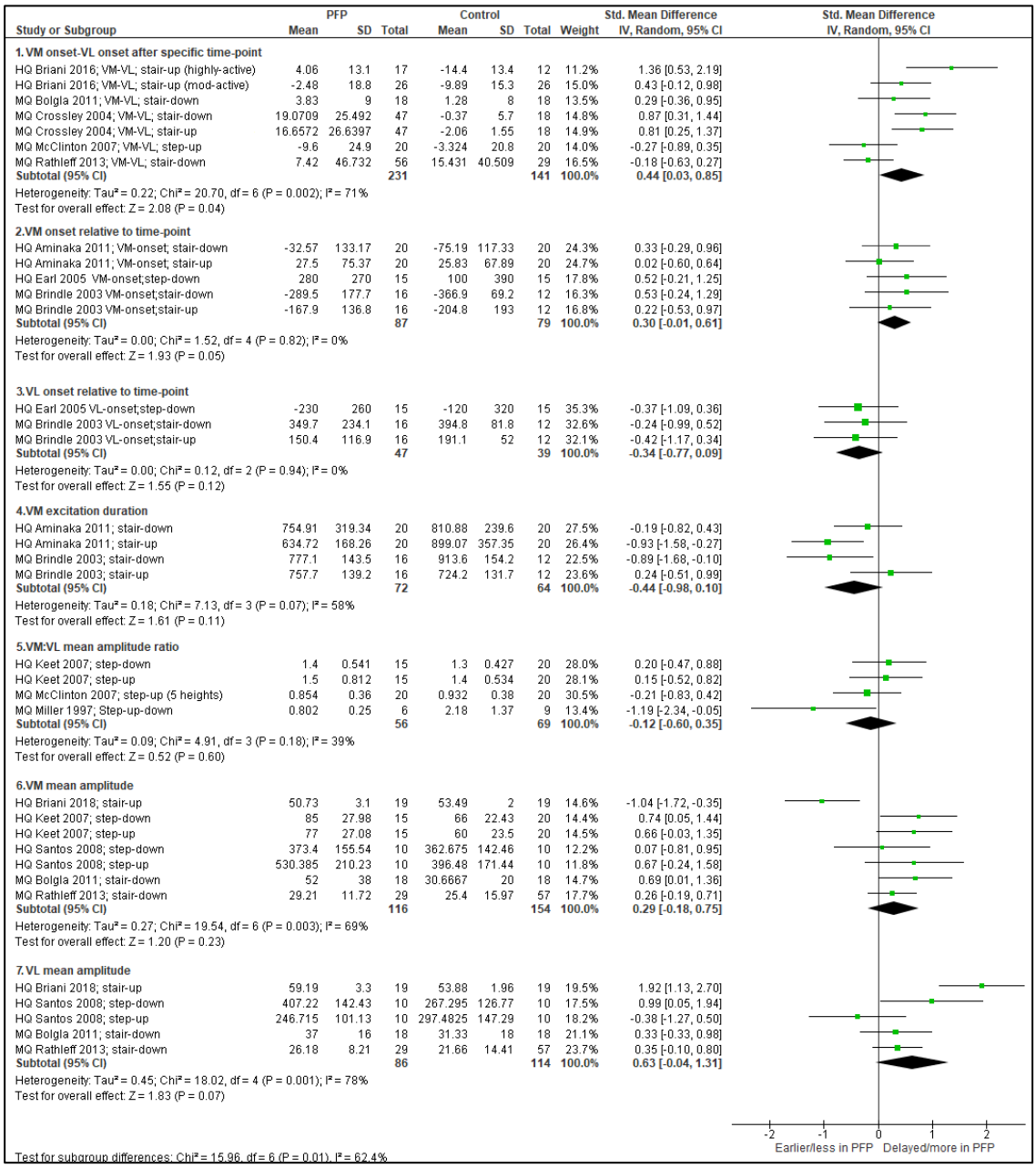


Figure 3.2: EMG investigations of stepping and stair negotiations.

Figure 3.2 shows meta-analyses results of EMG investigations during stepping and stair negotiation. With the timing sub-domain, moderate evidence (one HQ and four MQ) of small effect indicates a delayed VM to VL excitation onset in PFP. Strong evidence (two HQ and one MQ) indicates that VM and VL excitation onsets show no differences in

PFP, if measured individually from a time-point during the task. Conflicting evidence was found for VM excitation duration. Within investigations of mean excitation amplitudes; moderate evidence shows no difference in VM to VL ratio, while evidence is conflicting regarding VM and VL.

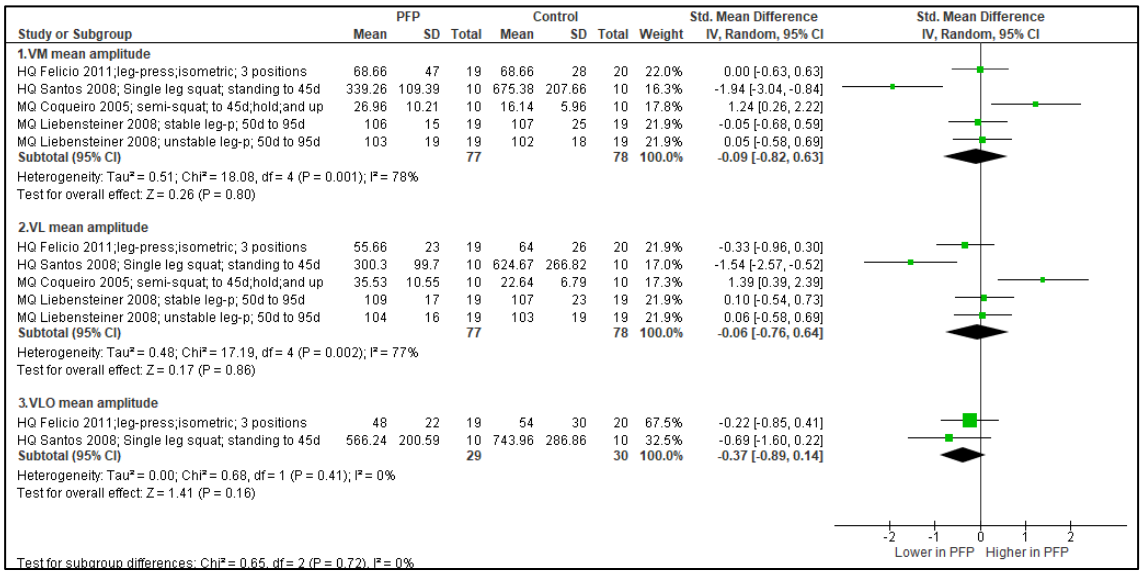


Figure 3.3: EMG investigations during squatting and leg presses.

Figure 3.3 shows conflicting evidence during squatting and leg-presses for VM and VL mean excitation amplitudes. For VLO, moderate evidence (two HQ) indicates no differences in PFP.

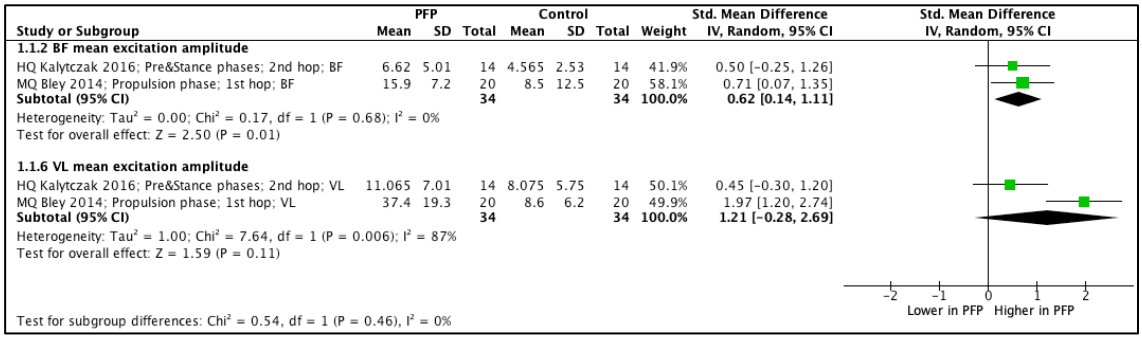


Figure 3.4: EMG investigations during single-leg triple-hop test (SLTHT).

During SLTHT (Figure 3.4), moderate evidence (one HQ and one MQ) of small effect indicates higher BF mean excitation amplitudes. Evidence is conflicting regarding VL mean excitation amplitude. This plot was later amended in the corrigendum, with all discussions regarding this result (178).

3.3.2.2 Isolated tasks

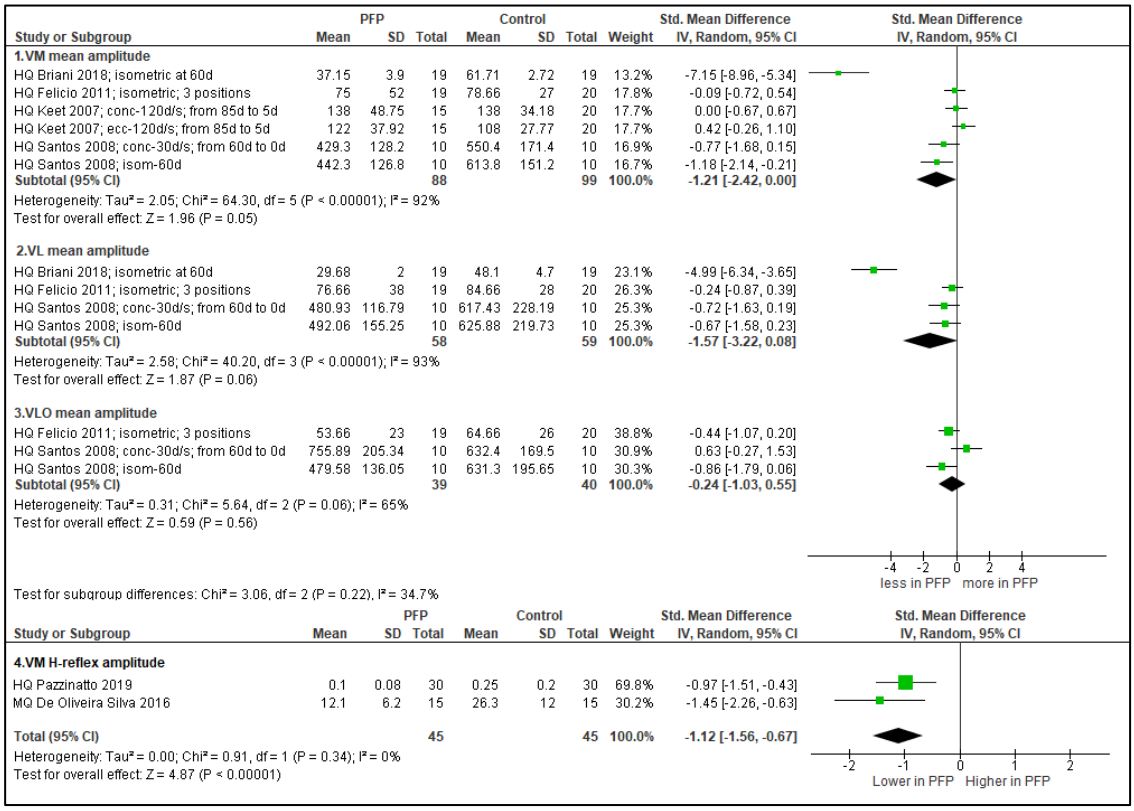


Figure 3.5: EMG investigations in isolated tasks.

Figure 3.5 shows investigations of mean excitation amplitudes during open kinetic chain exercise and Hoffman reflex test (H-reflex). Pooled data show conflicting evidence for VM, VL and VLO mean excitation amplitudes, and moderate evidence (one HQ and one MQ) of medium effect indicating lower VM H-Reflex peak amplitudes (% of maximum M-wave) to be associated with PFP.

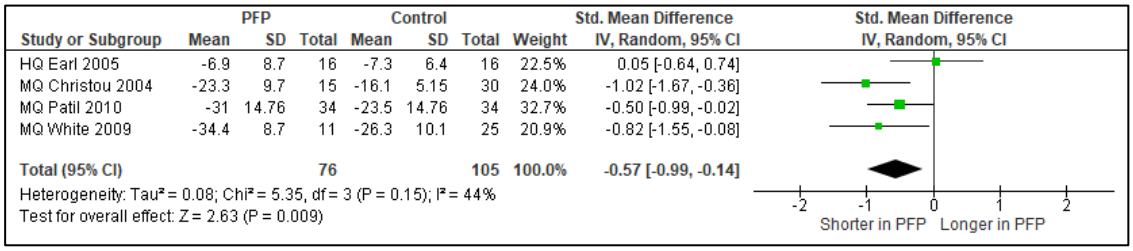


Figure 3.6: Hamstring flexibility investigation. Appendix three shows original reported data.

Figure 3.6 shows moderate evidence (one HQ and three MQ) of a small effect suggesting less flexibility in the hamstrings to be associated with PFP.

Study or Subgroup	PFP Mean	PFP SD	PFP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
1. Isometric knee extension peak torque								
HQ Bolgla 2015; 60deg; HHD; Bmass	44.5	15.4	66	51.9	13.4	36	7.8%	-0.50 [-0.91, -0.09]
HQ Briani 2018; 60deg; ForceTransducer; Bmass	19.4	6.1	19	19.1	5.9	19	5.7%	0.05 [-0.59, 0.68]
HQ Briani 2020; 60deg; IKD; Bmass	219.7	65.5	56	269.5	60.9	46	7.9%	-0.78 [-1.18, -0.37]
HQ de Albuquerque 2021; NA; HHD; Bmass	0.31	0.08	26	0.31	0.07	24	6.4%	0.00 [-0.55, 0.55]
HQ Ferreira 2019a; 60deg; IKD; Bmass	182.26	49.92	30	286.25	53.54	30	5.8%	-1.98 [-2.61, -1.36]
HQ Keet 2007; 60deg; IKD; NA	362	92.9	15	458	83.33	20	5.1%	-1.07 [-1.79, -0.35]
HQ Nunes 2020; 60deg; IKD; Bmass	217.2	46	26	246.5	38.8	26	6.4%	-0.68 [-1.24, -0.12]
HQ Stensdotter 2007; 30deg; IKD; NA	258	62	17	273	74	17	5.4%	-0.21 [-0.89, 0.46]
MQ Baellow 2020; 90deg; HHD; Bmass	1.09	0.32	15	1.15	0.44	15	5.1%	-0.15 [-0.87, 0.57]
MQ Bolgla 2011; 60deg; HHD; Bmass	27.3	8.7	18	31.5	8.3	18	5.5%	-0.48 [-1.15, 0.18]
MQ Carvalho 2016; 60deg; HHD; Bmass	0.2	0.06	25	0.25	0.07	25	6.2%	-0.75 [-1.33, -0.18]
MQ De Oliveira Silva 2018;60deg;IKD;Bmass;Crepitus	223.85	72.89	33	265.88	56.6	17	6.0%	-0.61 [-1.21, -0.01]
MQ De Oliveira Silva 2018;60deg;IKD;Bmass;No Crep.	225.23	68.37	32	278.27	60.82	36	7.0%	-0.81 [-1.31, -0.32]
MQ Felicio 2019; 90deg; NA; Bmass	42.6	14.5	24	46.1	11.1	22	6.2%	-0.26 [-0.85, 0.32]
MQ Gallina 2019; 45deg; IKD; Bmass	1.88	0.54	36	2.31	0.41	20	6.3%	-0.85 [-1.42, -0.28]
MQ Rathleff 2013; 60deg; HHD; Bmass	2.27	0.489	57	2.8	0.565	29	7.2%	-1.02 [-1.49, -0.55]
Subtotal (95% CI)			**495**			**400**	**100.0%**	**-0.64 [-0.87, -0.41]**
Heterogeneity: Tau² = 0.13; Chi² = 38.36, df = 15 (P = 0.0008); I² = 61%								
Test for overall effect: Z = 5.56 (P < 0.00001)								
2.Concentric knee extension peak torque								
HQ Briani 2020; 30d/s; IKD; from 90 to 20d	183.6	50	56	220.2	41.8	46	19.0%	-0.78 [-1.19, -0.38]
HQ Keet 2007; 120d/s; IKD; NA	84	23.7	15	112	25.64	20	7.2%	-1.10 [-1.82, -0.38]
HQ Nunes 2020; conc-60d/s; IKD; from 90d to 20d	133	42.6	26	169.2	28.8	26	10.7%	-0.98 [-1.56, -0.40]
MQ De Oliveira Silva 2018;30d/s;IKD;Bmass;Crepitus	183.51	63.62	33	215.34	41.71	17	10.1%	-0.55 [-1.14, 0.05]
MQ De Oliveira Silva 2018;30d/s;IKD;Bmass;NoCrep.	205.85	71.52	32	223.4	41.71	36	14.6%	-0.30 [-0.78, 0.18]
MQ Duffey 2000; 60&240d/s; IKD; Bmass	56.45	16.9	99	62.65	12.54	70	27.8%	-0.40 [-0.71, -0.10]
MQ Hazneci 2005; 60d/s; IKD; NA	126	49	24	154	46	24	10.6%	-0.58 [-1.16, -0.00]
Subtotal (95% CI)			**285**			**239**	**100.0%**	**-0.61 [-0.81, -0.40]**
Heterogeneity: Tau² = 0.01; Chi² = 7.33, df = 6 (P = 0.29); I² = 18%								
Test for overall effect: Z = 5.85 (P < 0.00001)								
3.Eccentric knee extension peak torque								
HQ Briani 2020; 30d/s; IKD; from 90 to 20d	237.3	72.6	56	280.4	70.2	46	33.6%	-0.60 [-1.00, -0.20]
HQ Keet 2007; 120d/s; IKD; NA	132	46	15	156	40.59	20	11.4%	-0.55 [-1.23, 0.14]
HQ Nunes 2020; ecc-60d/s; IKD; from 90d to 20d	172.9	56.7	26	208.4	59.4	26	17.2%	-0.60 [-1.16, -0.05]
MQ De Oliveira Silva 2018;30d/s;IKD;Bmass;Crepitus	230.75	81.01	33	265.33	80.08	17	15.3%	-0.42 [-1.01, 0.17]
MQ De Oliveira Silva 2018;30d/s;IKD;Bmass;NoCrep.	237.66	70.21	32	279.55	70.52	36	22.5%	-0.59 [-1.08, -0.10]
Subtotal (95% CI)			**162**			**145**	**100.0%**	**-0.56 [-0.79, -0.33]**
Heterogeneity: Tau² = 0.00; Chi² = 0.28, df = 4 (P = 0.99); I² = 0%								
Test for overall effect: Z = 4.78 (P < 0.00001)								
4. Concentric knee flexion peak torque								
HQ Briani 2020; 20 to 90d; 30d/s; IKD; Bmass	92.3	24.1	56	109.9	19.4	46	31.2%	-0.79 [-1.20, -0.38]
MQ Duffey 2000; 60&240d/s; IKD; Bmass	32.35	10.94	99	36.6	8.366	70	53.5%	-0.42 [-0.73, -0.12]
MQ Hazneci 2005; 60d/s; IKD; NA	70	27	24	87	29	24	15.3%	-0.60 [-1.18, -0.02]
Subtotal (95% CI)			**179**			**140**	**100.0%**	**-0.57 [-0.79, -0.34]**
Heterogeneity: Tau² = 0.00; Chi² = 1.98, df = 2 (P = 0.37); I² = 0%								
Test for overall effect: Z = 4.89 (P < 0.00001)								
5. Knee extension total work								
MQ Duffey 2000; 240d/s; 30reps; IKD; Bmass; N.m	2,075.2	674.6	99	2,314	769.7	70	66.2%	-0.33 [-0.64, -0.02]
MQ Hazneci 2005; 180d/s;15reps; IKD; Bmass; Joules	94	28	24	121	39	24	33.8%	-0.78 [-1.37, -0.19]
Subtotal (95% CI)			**123**			**94**	**100.0%**	**-0.48 [-0.90, -0.07]**
Heterogeneity: Tau² = 0.04; Chi² = 1.76, df = 1 (P = 0.18); I² = 43%								
Test for overall effect: Z = 2.28 (P = 0.02)								
6. Knee flexion total work								
MQ Duffey 2000; 240d/s; 30reps; IKD; Bmass; N.m	1,468.7	785.04	99	1,752.7	750.484	70	57.8%	-0.37 [-0.68, -0.06]
MQ Hazneci 2005; 180d/s;15reps; IKD; Bmass; Joules	57	20	24	81	25	24	42.2%	-1.04 [-1.65, -0.44]
Subtotal (95% CI)			**123**			**94**	**100.0%**	**-0.65 [-1.31, 0.00]**
Heterogeneity: Tau² = 0.17; Chi² = 3.79, df = 1 (P = 0.05); I² = 74%								
Test for overall effect: Z = 1.95 (P = 0.05)								
7.Extension rate of force developement (RFD) 30% of maximal isometric torque								
HQ Briani 2020; 60d; RFD 30% MaxIsoTorque	1.87	0.44	56	2.09	0.59	46	66.1%	-0.43 [-0.82, -0.03]
HQ Nunes 2020; 60deg; RFD 30% MaxIsoTorque	0.57	0.27	26	0.83	0.37	26	33.9%	-0.79 [-1.36, -0.22]
Subtotal (95% CI)			**82**			**72**	**100.0%**	**-0.55 [-0.89, -0.21]**
Heterogeneity: Tau² = 0.00; Chi² = 1.07, df = 1 (P = 0.30); I² = 7%								
Test for overall effect: Z = 3.18 (P = 0.001)								
8.Extension rate of force developement (RFD) 60% of maximal isometric torque								
HQ Briani 2020; 60d; RFD 60% MaxIsoTorque	1.37	0.49	56	1.62	0.46	46	66.6%	-0.52 [-0.92, -0.12]
HQ Nunes 2020; 60deg; RFD 60% MaxIsoTorque	0.47	0.24	26	0.67	0.33	26	33.4%	-0.68 [-1.24, -0.12]
Subtotal (95% CI)			**82**			**72**	**100.0%**	**-0.57 [-0.90, -0.25]**
Heterogeneity: Tau² = 0.00; Chi² = 0.21, df = 1 (P = 0.64); I² = 0%								
Test for overall effect: Z = 3.48 (P = 0.0005)								
9.Extension rate of force developement (RFD) 90% of maximal isometric torque								
HQ Ferreira 2019b; 60deg; RFD 90% MaxIsoTorque	1.05	0.27	38	1.37	0.31	38	51.9%	-1.09 [-1.57, -0.61]
HQ Nunes 2020; 60deg; RFD 90% MaxIsoTorque	0.15	0.08	26	0.2	0.15	26	48.1%	-0.41 [-0.96, 0.14]
Subtotal (95% CI)			**64**			**64**	**100.0%**	**-0.76 [-1.43, -0.10]**
Heterogeneity: Tau² = 0.16; Chi² = 3.31, df = 1 (P = 0.07); I² = 70%								
Test for overall effect: Z = 2.25 (P = 0.02)								
Test for subgroup differences: Chi² = 0.91, df = 8 (P = 1.00), I² = 0%								

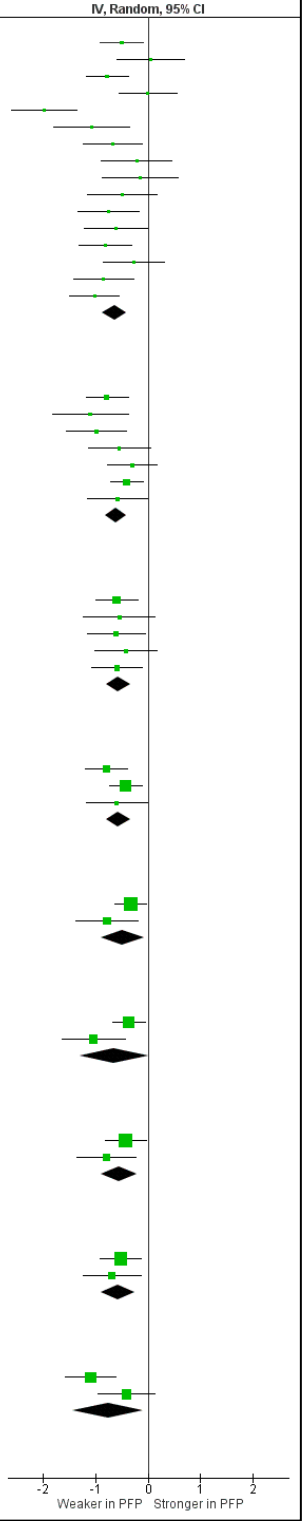


Figure 3.7: Muscles performance investigations.

Figure 3.7 shows muscle performance investigations. For extension peak torque tests, moderate evidence with medium effect was found for the isometric test (eight HQ and seven MQ), strong evidence with medium effect for the concentric test (three HQ and three MQ), and strong evidence with small effect for the eccentric test (three HQ and one MQ). Moderate evidence of small effect indicates lower concentric flexion peak

torque (one HQ and two MQ) and lower total extension work (two MQ). Included studies showed conflicting evidence regarding knee flexion total work in PFP. Moderate evidence of small effect shows lower rate of force development (RFD) at 30% and 60% (two HQ), and medium effect shows lower RFD at 90% of maximum voluntary contraction (MVC) in PFP (two HQ).

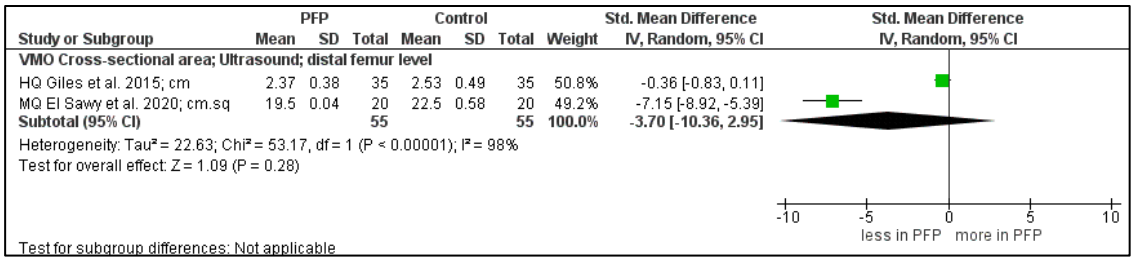


Figure 3.8: Muscle cross-sectional area investigation of Vastus Medialis Obliquus.

Figure 3.8 shows muscle CSA investigations. Pooled data showed conflicting evidence regarding VMO CSA in PFP.

3.4 Discussion

In this systematic review, we comprehensively synthesised the evidence for specific deficits local to the knee joint found in individuals with PFP under 40 years of age. Such deficits should be targeted by interventions within management strategies, and changes in symptoms should be investigated alongside modifications in these deficits. Therefore, our results should be considered in future interventional studies. Data from 67 case-control studies were extracted (including a total of n=1552 PFP and n=1508 controls) and 27 outcome variables were meta-analysed. Ten neuromuscular characteristics were found to be associated with PFP; two muscle EMG characteristics identified during functional tasks, and eight during isolated tasks within muscle EMG, flexibility, and performance characteristics.

3.4.1 Evidence gap-map

The limitations of the research in this field are highlighted by the evidence gap map, which shows an absence of investigations for muscle groups that pass over the knee and could consequently impact the patellofemoral joint. The quadriceps muscle group was the most targeted muscle group within the available research, which is understandable due to the direct anatomical relation between the quadriceps and the patella. Since this review focused on the muscles that cross the knee, it revealed the lack of investigations of commonly overlooked muscles that are importantly involved in knee control. For instance, the popliteus is a well-known knee stabiliser during gait,

and it reduces excessive tibial rotation (231). In addition, the sartorius and gracilis are direct tibial internal rotators (232), and the work of all these muscles in relation to PFP has not been investigated yet. Nevertheless, higher BF mean amplitudes, hamstring tightness and weaker concentric flexion were found to be present in patients with PFP. This lack of reporting, compared to the quadriceps, could be attributed to practical research limitations (e.g. difficulties in collecting EMG activity of the mentioned muscles, especially during movement). Therefore, future research should consider different methods and approaches to identify local characteristics related to PFP within different muscle groups around the knee.

The reported variables drove the process of clustering the neuromuscular characteristics into specific categories. As such, any absent variable in the gap map means that no included study reported that variable. For instance, no muscle morphological data was found (i.e. pennation angles, fascicle length) other than CSA, so further investigations of other morphological characteristics is recommended.

3.4.2 Electromyographic Activity Domain

Our results demonstrate a difference in motor control of the major muscle groups working directly on the knee in individuals with PFP. Motor control imbalances of quadriceps, including VM onset delays are factors commonly reported and referred to as a possible cause of patellofemoral joint loading imbalances (12). Stepping tasks are recommended as a part of the diagnosis procedure (15). Our findings show that VM:VL delays are consistently reported during similar loading tasks, indicating that they could be used as a neuromuscular mechanistic marker following treatment interventions. Although the statistical difference is small, a pooled effect was evident between VM-VL excitation onset but not when investigating individual VM excitation onsets. Therefore, our results indicate that deficits may arise if within-muscle variability in excitation onset is investigated rather than individual muscles' onset between different participants, and that the way signals were analysed might affect deficit detection. This raises an important question about the reproducibility of these results, and studies are encouraged to clarify the details of the signal processing procedures.

For the findings regarding the BF muscle, two studies (194,215) investigated the muscle's excitation, during SLTHT, and presented significant pooled effect suggesting higher BF mean excitation amplitudes to be associated with PFP. Single leg hops

require higher demands on the knee joint (233), and a higher muscle activity might indicate that higher demands were needed to stabilise the knee, especially when manifesting in an antagonist knee muscle (234). Interestingly, VL mean excitation amplitude in the same task was investigated by both studies, but did not present a significant pooled effect, further confirming the importance of choosing the best method of detection for these neuromuscular deficits. Moreover, future research is recommended to investigate the co-contraction requirements within Individuals with PFP. Overall, higher BF mean excitation amplitudes during SLTHT is associated with PFP.

To test spinal reflexes, knee jerk test is conducted by mechanically stretching the muscle spindle to test spinal stretch reflex. Similarly, H-reflex tests stimulate muscle spindle sensory neurons (Ia afferents), but by using electrical stimuli, bypassing the need for a mechanical stimulus. Therefore, deficits found within both tests would be possibly related to alterations in the neurophysiological mechanisms governing spinal motor-neurons excitability (235,236). In our meta-analysis, the data of two studies that investigated H-reflex amplitudes were pooled, showing significantly lower maximum VM H-reflex amplitude to be a possible neuromuscular characteristic associated with PFP. For H-reflex testing, a lower amplitude is possibly related to pain as the two included case-controls had similar finding with a study by Park and Hopkins (237) that tested H-reflex amplitude following induced anterior knee pain using hypertonic saline injections. In these studies, the H-reflex was hypothesised to be a potential discriminating tool for detecting PFP. Within spinal reflexes, quadriceps response time after knee jerk reflex have been investigated in three included studies (two MQ and one LQ), reporting conflicting results between no delay (192), onset sequence alteration of VL with a stable VM onset time across both groups (103) and a delay in VM onset (75). Unfortunately, data pooling was not possible for knee jerk reflex due to data presentation and study quality. Results found in this review support a further exploration to confirm the hypothesis of altered spinal stretch reflexes in PFP, which might help detect, or understand PFP effects on spinal controlling mechanisms (236).

Results of our systematic review further confirm that alterations of local motor control are found in individuals with PFP when compared to uninjured controls and can be found during voluntary and involuntary contractions. The meta-analysis suggests these

alterations present as a delay in VM excitation onset relative to VL during stepping and stair negotiations, higher mean excitation amplitude of BF during SLTHT, and a lower maximum H-reflex amplitude of VM.

3.4.3 Muscle Flexibility Domain

Four case-control studies investigating hamstring flexibility were included, with pooled data showing significantly tighter hamstrings in individuals with PFP. Higher patellofemoral joint loading is linked to PFP (12) and structures' flexibility, including hamstring tightness, around the knee might influence these loads (238). The relationship between patellofemoral joint forces and the hamstrings has been investigated in cadavers and healthy adults, finding forces to increase with hamstring loading and tightness (239). Moreover, two other variables within this domain were reported by Earl et al. (77) (ITB flexibility), and Christou (201) (gastrocnemius flexibility), with only the former reporting ITB tightness to be a significant identifier of PFP.

Our results indicate that hamstring tightness is a local characteristic of PFP. The results also suggest that other muscles around the knee require further investigations, especially given that flexibility tests are easily applied in a clinical setting and could guide intervention prescription.

3.4.4 Muscle performance Domain

Data sets from 18 studies were pooled and significantly weaker knee extensors in PFP versus uninjured groups were found. Additionally, two studies involved in the meta-analysis showed significantly weaker concentric flexion in PFP.

General muscle weakness of lower limbs is frequently reported in PFP (12,29,31,81,82,180) and rehabilitation incorporating strengthening of lower limb musculature is a commonly recommended treatment protocol (97). Most included studies did not assess pain during extension strength tests, and as such we do not know whether the reduced torque was due to pain avoidance or not. Interestingly, meta-analyses by Neal et al. (31) and Lankhorst et al. (29) investigated the risk factors of PFP and also found significantly weaker quadriceps in prospective cohorts. However, weakness in the knee flexors, which was found in our study to be associated with PFP, was not found as a risk factor in these meta-analyses (29,31) as both included two prospective cohort studies that did not show significant pooled effect.

When combining previous reviews with our findings, we can conclude that quadriceps weakness seems to be a risk and an associated factor of PFP, forming a clear target for interventional protocols, whilst more research is needed to investigate potential weaknesses in other muscles surrounding the knee.

Rate of force development deficits in the quadriceps of people with PFP were found when compared to uninjured controls. The ability to produce force quickly could be imperative to improve the ability in normal daily activities and sport demands (240). It is important to mention that two included studies that investigated RFD also found it to be lower in hip muscles (79,119), indicating that this deficit might not be directly related to pain inhibition. A recent feasibility study suggests that programmes that target different aspects of muscle performance, like power, are applicable and can have beneficial results (241). This indicates that the specifics of exercise interventions in clinical practice should aim to improve different aspects of muscle performance and not just strength.

3.4.5 Cross-sectional Area Domain

Only two eligible case-control studies (two HQ) were found investigating quadriceps muscle atrophy (207,213). Investigations of VMO muscle thickness using ultrasound were pooled and the results showed conflicting evidence regarding CSA. However, CSA was found to be significantly lower in within-subject comparisons by Giles et al. (213), but not when compared to the uninjured group. Interestingly, a systematic review with meta-analysis by Giles et al. (182) produced a pooled effect from three case-control studies that were not included here due to eligibility criteria (patients aged >40 years (242,243), and with previous surgeries (244)). One plot from Giles et al. (182) showed lower CSA when comparisons were made within individuals with PFP (between both knees). Another plot showed the same result when patients were compared against uninjured participants. In the included case-control, Giles et al. (213) performed both types of comparisons, but findings were not similar. Causes of the results differences between the review and the case-control by Giles et al. (182,213) cannot be identified, but the mentioned differences in eligibility criteria might be the reason.

Reduced force production is commonly associated with reduced muscle CSA, which could be caused by mechanisms like pain inhibition or disuse (245–248). Although difficult to draw a conclusion, less CSA from within-subject comparisons might be

caused by these mechanisms, especially given that asymptomatic limbs of the PFP group had a higher mean CSA compared to matched limbs of the uninjured group in the included study (Giles et al. (213)). This was not the case with El Sawy et al. (207), as reported differences were significant. This warrants further investigations in this field. Moreover, it should be noted that only VMO data could be pooled, as one study only investigated the VMO (207). The other considered the quadriceps, but none of the other muscles that work directly on the knee (213).

Overall, conflicting evidence was found within the CSA regarding the VMO. This suggests an essential consideration of further research within CSA domain to specify analysis methods to identify deficits associated with PFP, especially with muscle weakness comprehensively researched and established in PFP populations.

3.4.6 Limitations

Poor reporting of participant characteristics within the included studies could confound the outcomes from this review. Specifically, although all studies reported mean and SD of participants' ages, several studies did not clearly state the upper limit of the age range of recruited groups. Further, poor reporting of other possible confounders includes pain levels, PFP chronicity and activity levels, impacting on the differences seen in the outcomes of included studies. The lack of clear data reporting and uniqueness of some investigation methods had large impact on the outcomes of this review. A recently published consensus statement that aims to enhance the reporting of PFP studies have highlighted these aspects, with some elements being strongly recommended (98). The methodological diversity and quality within the targeted domains led to difficulties in pooling the data. This is clear as we were unable to include data from 20 MQ and HQ studies, as well as nine LQ studies in the meta-analysis.

Some investigations reported their data from vastus medialis as; VM, VMO and VML. In a similar manner, vastus lateralis data were presented as VL, VLL and VLO. For the vastus medialis, we named the data sets in some plots as VM even if the study used the guidelines to target vastus medialis oblique (VMO). This was undertaken to offer greater clarity when presenting the results. However, placement methodology of EMG electrodes is seen to be a factor of inconsistency in the results of EMG studies (83,170), and electrode placement was not clearly reported in most included studies.

This required a further look into referenced literature for a better identification of electrode placement. For instance, two studies reported data of VM (195,214) although the referenced method reported it as VMO (249). In the VM excitation onset meta-analysis, all studies reported their data for VMO. However, VM-VL excitation onset meta-analysis was formed by studies with mixed reporting of VM and VMO. This could explain the differences in I^2 test results between both, where the former had statistically homogenous results. For VML, the obtained data was not eligible for pooling. The issue was similar for VL, as only the electrode site of VLL was similar to that in SENIAM guidelines (192,227). This partitioning within the VM is based on anatomical, neural supply and functionality differences (250). In contrast, the studies that investigated the partitions of VL relate them to the fascicular orientation (251). More investigations are needed to find a difference in EMG behaviour of these parts and associate it to knee joint disorders (250). Some studies reported multiple data sets of exactly the same task (104), investigating multiple step heights during a step-up task. Such data were combined, and subsequently pooled. Other studies (76,191) performed multiple types of the same task (e.g., different directions of stepping). Such data sets were pooled but not combined, as they represent different physical demands, yet are within the same task category.

Our decision of pooling data of different tasks from the same task category might affect the internal validity of our study, but it serves the aim to identify any deficit in groups affected with PFP. In fact, this approach seemed to show some neuromuscular characteristics associated with PFP, that were not contradicting the findings of previous work (12,81,83). This approach can be accepted for two reasons; the modified Van Tulder et al. (190) guidelines (Table 3.2) control for statistical heterogeneity, as it takes statistical heterogeneity into account and mitigates the effects of high I^2 score by lowering evidence level. The second reason is that this study aimed to detect deficits as PFP individuals performed tasks within specific categories, assuming a deficit would be present if PFP is truly the cause. These methodological differences are assumed to cause the statistical heterogeneity seen in our pooled findings.

Data shown in forest plots were not derived from all eligible studies. This was due to either reporting differing data sets that cannot be pooled together, or not reporting

means and SDs and inability to derive data from graphs. Most of the authors were contacted, as contact details of some authors were not found. Some authors responded with missing data which allowed this review to present unique findings (i.e. meta-analysed H-reflex data).

During different functional and isolated tasks of other included case-control studies, other variables showed significant differences between PFP and control groups within the EMG domain and are summarised in tables in Appendix 3. Although these findings cannot be ignored and support abnormal neuromuscular representations in PFP, these unique methodologies are yet to be supported by further research and allow collective pooling for a comprehensive answer.

Lastly, these results are mostly found in females With PFP, as most of the population recruited in the included studies in this systematic review are females. While PFP is more prevalent in females, Peng et al. (225) aimed to address this question, and indeed found differences between uninjured female and male groups within quadriceps EMG investigations. Therefore, a question is raised regarding finding similar deficits in affected male populations.

3.4.7 Recommendations

Future research is recommended to identify the changes of these neuromuscular characteristics in PFP after treatment, presenting a better understanding of the interventional mechanisms of effects, and helping identify PFP sub-groups with best response to prescribed interventions. This will also aid in simplifying interventions, potentially improving patients' adherence levels to rehabilitation programmes. Another recommendation for studies investigating risk factors is to aim to approve whether the identified characteristics can be predisposing uninjured people to develop PFP, aiding to understand local neuromuscular preventative treatment targets.

3.5 Conclusion

We investigated local neuromuscular characteristics associated with PFP compared with uninjured controls. Within functional tasks, delays of EMG excitation onset of VM relative to VL during stepping and stair negotiation tasks were found. Furthermore, a higher mean amplitude of BF was present in PFP during SLTHT. Within isolated tasks, results suggest that lower maximum amplitude of VM H-reflex, hamstrings weakness and tightness, and quadriceps weakness and slower torque development are

associated with PFP. After sufficient feasibility testing of interventional programmes, identifying the effectiveness of these interventions in modifying PFP deficits that are found in this review is recommended. Also, implementing a battery of tests that can accurately detect these deficits in interventional studies is imperative. This could lead to a better mechanistic understanding of observed symptomatic and functional improvement, or its absence.

4 The effects of interventions on local neuromuscular characteristics associated with patellofemoral pain: a systematic review and meta-analysis

In this chapter, the aim was to identify possible interventional approaches that can change the deficits associated with PFP. With that, the thesis can provide treatment approaches that can change the previously identified deficits. This systematic review was presented at the BASEM conference in May 2022, and the International Patellofemoral Pain Retreat in Bologna, Italy (June 2023).

4.1 Introduction

Patellofemoral pain (PFP) is described as insidious pain around the retropatellar area of the knee commonly affecting people of all age ranges (15) and affecting quality of life, especially among athletes (32,33). The mechanisms through which associated neuromuscular factors of PFP change with interventions should be identified to improve prescription of tailored and targeted treatment programmes.

Witvrouw et al.(8) proposed a need for tailored interventions based on subgroups of pathology or etiology that may be unique to specific PFP populations. At a local neuromuscular level, multiple characteristics that show significant differences in people with PFP compared to uninjured individuals have been identified and may plausibly be associated with symptom persistence (176). Identifying interventions that affect change in these characteristics is of clear importance to further improve treatment outcomes.

Limitations in the available literature hinder a clear identification of interventions that can be chosen according to patient-specific local neuromuscular characteristics. Unclear reporting of intervention programmes represents a barrier to implementation of the treatment approaches delivered within the study by treating clinicians (8,87,97,252). Within a Cochrane systematic review on exercise interventions, consistent yet very low-quality evidence was found showing resultant improvements from exercise therapy (252). Van der Heijden et al. (252) also found insufficient evidence identifying the effects of exercise therapy against other unimodal or multimodal conservative interventions. Therefore, recommendations were for future research to compare between interventions and improve reporting of intervention specifics. Recently, Willy et al. (15) provided important guidelines for clinicians on preferred interventions to be prescribed for PFP, reporting strong evidence for combined physical therapy interventions compared with single interventions, and the combination of hip and knee targeted exercise. However, a systematic review by Holden et al. (89) investigating the reporting of the details of intervention of PFP showed general poor reporting of exercise prescription.

The overarching aim is to identify specific interventions that result in local neuromuscular change, representing a treatment approach with an identified neuromuscular mechanism of effect. The secondary aim is to identify if the changes of

neuromuscular characteristics were associated with an improvement in PFP condition. Therefore, a systematic review with meta-analysis was conducted to provide an updated, thorough synthesis to reach the aim. The objective is to synthesise all interventions in published work, that were investigated for their effects on local neuromuscular characteristics. The impact is guiding the selection of interventions according to the influence of the different treatments on people with PFP who have specific neuromuscular deficits. This improves the choice of interventions according to subgroups of PFP based on their local neuromuscular characteristics. Thus, simplifying intervention protocols and improve patients' adherence (87).

4.2 Methods

4.2.1 Protocol registration

This review was completed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement and was registered with PROSPERO (CRD42020148709).

4.2.2 Data source and strategy

PubMed, Embase, Cochrane Library, Scopus and Web of Science were systematically searched from inception to March 2022 by two reviewers (S.A. and C.B.). The search strategy used four groups of keyword combinations relating to PFP, neuromuscular characteristics and rehabilitation. No limits were set on publication years or status. The electronic search was complemented by hand searching reference lists of similar systematic reviews and citation tracking, completed using Google Scholar (Table 4.1).

Table 4.1: Keywords used to perform the literature search

Keywords	**In all text**		(pfp OR retropatellar OR "retro patellar" OR peripatellar OR "peri patellar" OR parapatellar OR "para patellar" OR patellofemoral OR "patello femoral" OR femoropatellar OR "femoro patellar" OR "knee anterior" OR "anterior knee" OR chondromalacia OR runner*) AND (pain* OR discomfort OR syndrom* OR dysfunction* OR patella OR knee OR track*)
	In all text	**AND**	(Neural OR Neuromuscular OR "Motor unit*" OR neuromotor OR musc* OR muscle OR muscular) AND (activ* OR activity OR activation OR respons* OR adapt* OR adaptation OR adaptive OR onset OR "firing rate*" OR "firing frequency" OR timing OR coactivation OR co-activation OR "Descending drive" OR "Adaptive respons*" OR recruitment OR electromyograph* OR emg OR proprioception OR proprioceptive OR "joint position sense")
	In all text	**AND**	(Rehabilitation OR therapy OR treatment OR intervention OR therap* OR treatment* OR intervention* OR exercis* OR sham OR placebo)
	In titles	**NOT**	("systematic review" OR "anterior cruciate" OR "posterior cruciate" OR acl OR pcl)

4.2.3 Eligibility criteria

Males and females were included from interventional studies. The included studies should have at least one local neuromuscular characteristic investigated in individuals with PFP, and data from muscles that do not cross the knee were excluded. Populations with a history of surgeries or other knee pathologies, as well as subjects over 40 years of age were excluded.

4.2.4 Review process

Studies identified through the search strategy were downloaded into Mendeley (version 1.19.4, Elsevier, Amsterdam, Netherlands) in which duplicates were deleted and titles searched. Next, a study screening web application (Rayyan) (184) was used to screen abstracts for eligibility. Full texts were obtained for eligible studies. Search and screening were undertaken by two independent reviewers (SA and CB), and a third reviewer (SL) was available for any discrepancies.

4.2.5 Methodological assessment

Four methodological assessment tools were used to examine the methodological and reporting quality of the included studies (two risk of bias, one exercise reporting and one PFP criteria assessments). All studies were assessed by two independent reviewers (SA and CB) and any discrepancies resolved at a consensus meeting with a third reviewer (SL).

4.2.5.1 Risk of bias

Research bias was assessed using two tools; the Cochrane risk of bias tool Version one (ROB) (253) for randomised control trials (RCT), and Risk of bias for non-randomised interventional studies (ROBINS-I) (254). Cochrane ROB assesses RCTs on five possible bias types; selection bias (randomization and allocation procedures), performance and detection bias (blinding of participants, personnel, and outcomes), attrition bias (completeness of outcomes data collection), reporting bias (selective reporting), and other sources of bias (253). For the non-randomised studies, ROBINs-I assesses possible bias through multiple confounding sources, selection of participants, classification of interventions, deviations from intended interventions, missing data, outcomes' measurement and results reporting (254). For this review, any differences in groups' characteristics and outcome measures at baseline were noted as "other sources of bias" as this review aimed to identify changes in neuromuscular characteristics caused by an intervention.

4.2.5.2 Assessment of studies' eligibility criteria

A PFP inclusion/exclusion criteria checklist (255) was used. The PFP diagnostic checklist is a seven-item scale that identifies key inclusion and exclusion criteria for the diagnosis of insidious non-traumatic PFP. A higher score indicates a greater number of key criteria having been reported representative of a more comprehensive diagnosis of PFP.

4.2.5.3 Assessment of exercise interventions' reporting quality

The completeness of exercise reporting was assessed using the Consensus on Exercise Reporting Template (CERT) (256,257). Similar intervention-specific methodology assessment tools could not be found for other intervention types (e.g. taping). Holden et al.(89) recommends assessing reporting quality of exercise interventions, as they performed similar investigation, and highlighted the inconsistency in exercise reporting in PFP.

4.2.5.4 Data extraction

Recruited groups, intervention type and length, and the means and standard deviations of neuromuscular data from muscles crossing the knee pre- and post-intervention were extracted. Studies' characteristics are presented in Table 4.2.

4.2.5.5 Data analysis

Data analysis was completed using "Comprehensive Meta-analysis" software (Version 3; Biostat, Englewood, NJ, USA) to calculate Hedge's g standardized mean differences (SMD) and 95% confidence intervals (95% CI) (258). Data were calculated using pre-post means, SD and sample sizes and variance were chosen as a 'common variance' as the data were from the same group at different time points. A random effects model was used for meta-analysis. For comparability with previous meta-analyses in the field (31,169,180), calculated SMDs were categorised as small (≤ 0.59), medium (0.60–1.19) or large (≥ 1.20) effect sizes. Presence of statistical heterogeneity for pooled data was identified using I^2 statistics with the level of significance set at $p<0.05$. Levels of evidence were determined by recommendations proposed by Van Tulder et al. (190), modified according to the risk of bias tools used:

i. Strong: based on results derived from multiple studies, including a minimum of two studies with Low ROB by the Cochrane's ROB and Robins-I, which are statistically homogenous ($I^2 < 50\%$).

ii. Moderate: based on results derived from multiple studies, including at least one study with low ROB, which are statistically heterogeneous (I^2 >50%), or from multiple studies which are statistically homogenous (I^2 < 50%) regardless of ROB level.

iii. Limited: based on results derived from multiple studies which are statistically heterogeneous (I^2 >50%), or from one study with low ROB.

iv. Very limited: based on results derived from one study (other than studies with low ROB).

v. Conflicting: based on insignificant pooled results derived from multiple studies regardless of quality, which are statistically heterogeneous (I^2 >50%).

4.2.5.6 Deviations from protocol

To optimally establish methodological homogeneity, multiple categories were used in the process of populating forest plots. Initially, all data from the same outcome measure were exported into Microsoft Excel (Microsoft Corporation, USA). For EMG, outcome measures and tasks had to be the same to be exported (e.g., VM mean excitation amplitude in squatting). For muscle performance tests, the tasks are already the same (seated extensions) as strength data of multi-joint tasks were considered not solely representing the performance of the muscles that cross the knee. For flexibility, tasks were gathered whenever it is an isolated flexibility test of a specific muscle group or structures that cross the knee (iliotibial band included).

Some studies that presented multiple data sets of the same test (e.g., if same group were tested for concentric peak torque at 60° and 180°/second), such data sets were combined. “Comprehensive Meta-analysis” allowed for the setting of moderators to do further subgroup analyses. Data sets from each arm of a study with multiple arms (groups receiving different interventions) were extracted separately. All single study data were gathered and presented in the supplementary file.

Data synthesis and pooling was presented using a step-wise approach;

a. The data were categorised according to intervention type (e.g. exercise, taping etc) and pooled effects were calculated to achieve the primary aim of the review. Studies data can be viewed in the supplementary file (Appendix 4), and the results summarised in gap-maps (tables 4.4-4.6).

b. Specific intervention types (e.g., exercise) demonstrating a significant pooled effect of a neuromuscular characteristic outcome (e.g., peak isometric extension torque) were further analysed if the intervention achieved a minimally clinically important difference (MCID) in pain (through visual or numeric pain scales) or function (Anterior Knee Pain Scale (AKPS)). Crossley et al. (259) identified two or 20 points change in pain (in 10 and 100 points scales, respectively) and 10 points in AKPS to reach a MCID.
c. Studies demonstrating an improvement in pain or function AND significant pooled effects on the neuromuscular characteristic, were further analysed according to specific treatment approach (e.g. hip and knee targeted exercise), to maximise the clinical applicability of the findings.

4.3 Results

The search yielded 8723 studies, from which duplicates were removed and the resultant 4181 studies screened (Figure 4.1). Forty-six studies were included (23 RCTs and 23 non-randomised interventional studies) (Table 4.2). Due to methodological differences or data unavailability, 25 studies were included in the meta-analyses. Exercise protocols reporting from n=28 included studies was assessed using CERT (Figure 4.2). All local neuromuscular investigations conducted by interventional studies are presented in table 4.3, with the overlaps with the previous systematic review of Chapter three highlighted. All findings of included studies are presented in the Appendix 4.

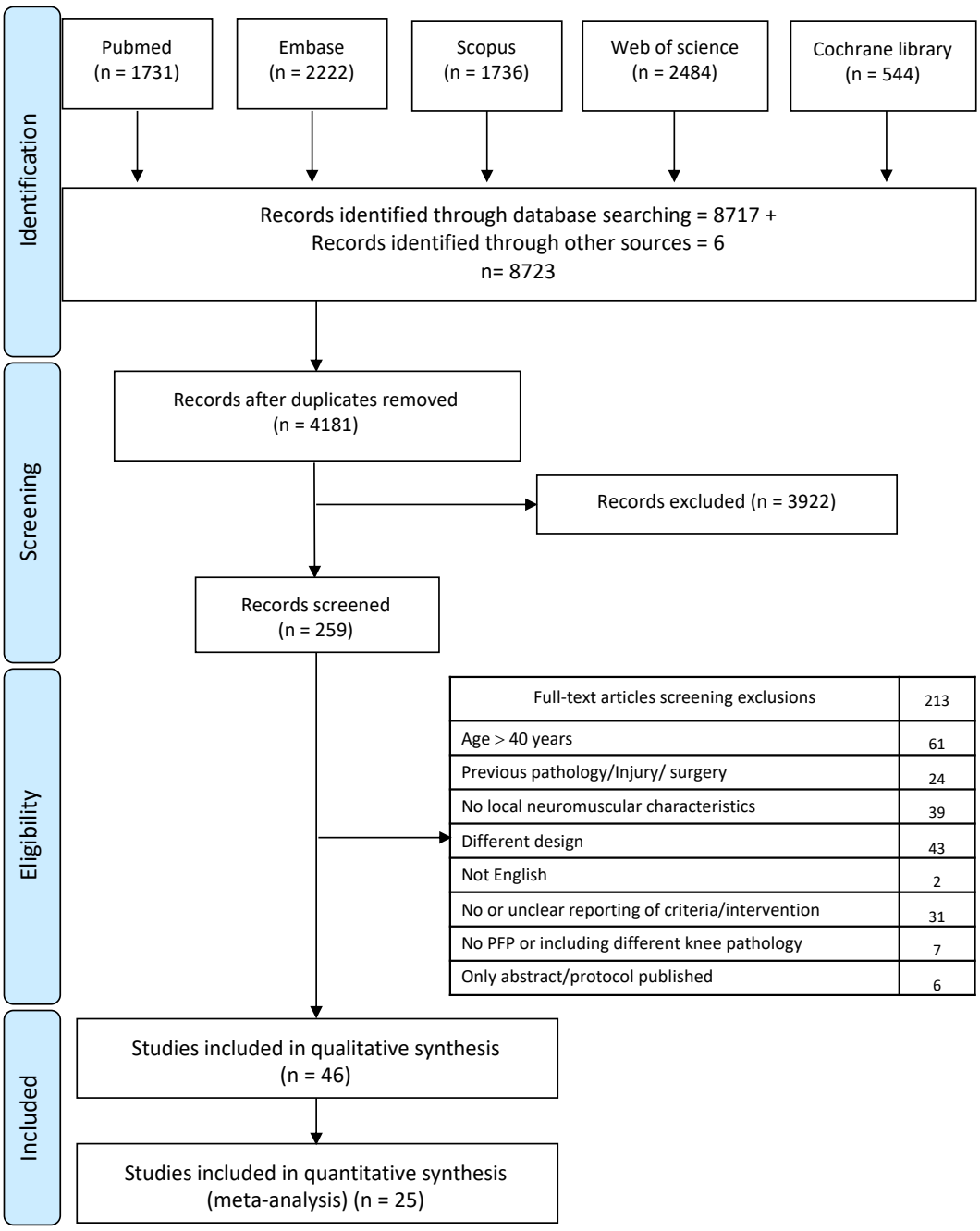


Figure 4.1: PRISMA chart representing the search and screening process.

Table 4.2: included studies' characteristics and methodology assessments results. Studies in **Bold** *are randomised clinical trials, underlined bias scores are from ROBINS, and empty cells are due to data unavailability.*

	Authors	groups	intervention duration	total sessions	intervention type	demographics													methodology scoring			reported neuromuscular outcomes		
						age	SD	males	females	total n	height	SD	mass	SD	bmi	SD	pain duration	SD	risk of bias	CERT	PFP criteria	strength	EMG	flexibility
1	**Araujo et al. 2016** (141)	G1	1 session	1	McConnel taping	23.0	3.3	0	20	20	1.6	0.1	61.0	11.0			47.0	45.0	**M**		3		✓	
		G2			placebo taping	23.0	3.4	0	20	20	1.6	0.1	61.0	14.0			57.0	41.0						
2	**Aytar et al. 2011** (156)	G1	1 session	1	Kinesio tape (KT)	22.4	1.6	0	12	12					20.6	2.3	16.2	9.7	**H**		3	✓		
		G2			placebo KT taping	26.2	3.5	0	10	10					21.9	2.2	13.7	8.0						
3	**Baldon et al. 2014** (260)	G1	8 weeks	24	functional stabilisation exc.	22.7	3.2	0	15	15	1.7	0.1	57.1	8.2	20.6	2.0	60.0		**M**	12	6	✓		
		G2			standard exc.	21.3	2.6	0	16	16	1.6	0.1	58.3	7.3	22.3	2.5	27.0							
4	**Bily et al. 2008** (151)	G1	12 weeks	≅40	Supervised physiotherapy (PT)	23.7	5.5	5	14	19	1.7	4.9	59.4	5.7			16.0		**H**	10	5	✓		
		G2			PT+Electrical Muscle Stimulation	27.0	7.7	9	10	19	1.7	9.3	68.8	13.7			12.0							
5	Cabral et al. 2008 (139)	G1	8 weeks	16	knee targeted open kinetic chain (OKC) exc.	21.0	1.0	0	10	10	1.6	0.0	55.6	5.0	21.6	2.4			*C*	8	4		✓	✓
		G2			knee targeted closed kinetic chain (CKC) exc.	20.0	1.0	0	10	10	1.6	0.1	57.7	10.1	22.2	4.9								
6	Christou et al. 2004 (201)	G1	1 session	1	placebo taping	26.3	1.5	0	15	15	1.7	0.0	60.8	1.4					*C*		2		✓	
		G1			medial glide taping																			
		G1			lateral glide taping																			
7	**Clark et al. 2000** (261)	G1	12 weeks	6	exc. + tape + education	26.0	7.4	10	10	20					24.8	5.7			**H**	4	2	✓		
		G2			exc. + education	29.5	6.2	12	8	20					24.9	4.2								
		G3			tape	29.3	6.8	10	9	19					25.0	3.9								
		G4			education	27.1	7.2	13	9	22					25.2	4.2								
8		G1	4 weeks	12	hip and knee exc.	30.5	16.0	16	14	30	1.7	0.1	72.4	16.9	24.7	4.3	11.0	17.0	**H**	13	6	✓		

	Constantinou et al. 2022 (262)	G2			hip and knee exc. + Blood Flow Restriction	25.5	14.0	17	13	30	1.7	0.1	72.5	11.1	24.6	3.0	14.0	16.0						
9	**Corum et al. 2018** (157)	G1	8 weeks	24	whole body vibratio+exc.	32.7	7.3	0	18	18	161.0	5.7	63.1	11.0	24.2	4.2			**H**	5	3	✓		
		G2			strengthening and stretching	33.7	7.7	0	16	16	163.0	6.3	63.0	9.8	23.5	3.1								
10	dos Santos et al. 2019 (149)	G1	2 weeks	8	running retraining; forefoot landing	28.5	2.7	2	4	6	1.7	0.0	66.3	13.6			8.4	8.8	S	6	4		✓	
		G2			running retraining; 10% step-rate inc	26.5	5.4	4	2	6	1.8	0.1	74.8	10.1			48.7	43.8						
		G3			running retraining; forward Trunk lean	26.8	2.7	3	3	6	1.7	0.1	64.3	11.0			26.3	46.0						
11	Drover et al. 2004 (263)	G1	1 session	1	active release technique (quadriceps and patellar tendon)	25.7	3.5	4	5	9									S		3	✓		
12	**Ferber et al. 2015** (153)	G1	6 weeks	18	Hip: balance, core and hip strengthening exc.	29.4	8.7	34	77	111	170.4	17.5	67.7	12.9			25.4	61.0	**M**	15	5	✓		
		G2			Knee targeted strengthening exc.	28.8	8.5	32	56	88	171.8	10.2	72.1	16.4			30.6	49.6						
13	**Glaviano et al. 2019** (162)	G1	4 weeks	12	Patterened electrical neuromuscular stimulation (PENS) +exc.	23.8	5.6	3	8	11	169.1	7.3	68.2	11.4			26.3	26.3	**L**	14	6	✓		✓
		G2			Sham PENS+exc.	23.0	3.7	2	8	10	166.7	7.8	69.8	19.0			23.0	27.8						
14	**Glaviano et al. 2020** (264)	G1	4 weeks	12	Patterened electrical neuromuscular stimulation (PENS) +exc.	23.0	6.0	0	8	8	166.8	5.7	65.7	9.6			28.0	30.6	**L**	14	6		✓	
		G2			Sham PENS+exc.	23.5	4.0	0	8	8	165.3	6.4	66.8	17.3			24.5	31.3						
15	**Grindstaff et al. 2012** (154)	G1	1 session	1	lumbopelvic joint manipulation (grade 5)	25.4	7.7	16	0	16	173.5	9.1	73.0	10.2					**H**		5	✓		
		G2			passive lumbar flexion/extension in side-lying; 1 min	25.1	9.6	16	0	16	175.5	11.2	78.1	21.4										
		G3			prone extension on elbows; 3 min	24.6	7.4	16	0	16	173.0	13.4	84.1	16.0										
16	Gulling et al. 1996 (142)	G1	1 session	1	patellar brace (before after brace)	24.5		16		16									S		4		✓	
17	Hamstra-Wright et al. 2017 (265)	G1	6 weeks	18	HIP: balance, core and hip strengthening exc.	28.5	8.7	26	63	89	1.7	0.1	67.0	17.9			23.4	56.3	S	15	5	✓		
		G2			knee targeted strengthening exc.	28.2	7.9	26	42	68	1.7	0.1	71.2	15.5			27.6	50.4						
18	Hazneci et al. 2005 (45)	G1	6 weeks	18	knee targeted open kinetic chain (OKC) exc.	25.0	2.0	24	0	24	175.0	6.0	72.0	5.0			5.0	3.0	S	2	5	✓		
19	Hickey et al. 2016 (143)	G1	1 session	1	Mulligan taping	22.7	2.7	0	20	20	169.2	6.2	65.5	12.1					C		6		✓	
20	**Hott et al. 2019** (152)	G1	6 weeks	18	knee targeted strengthening exc.	28.5	6.2	13	24	37									**M**	13	4	✓		
		G2			hip targeted strengthening exc.	27.8	8.6	14	25	39														
		G3			free physical activity	26.3	7.0	12	24	36														

21	Keet et al. 2007 (140)	G1 G1	1 session	1	medial glide taping placebo tape	29.1	5.1	4	11	15			65.2	9.6			28.9	45.7	S		5	✓	✓		
22	**Kurt et al. 2016** (158)	G1 G2	1 session	1	Kinesio tape placebo kinesio tape	31.6 30.9	6.9 7.2	19 16	25 24	44 40	168.3 167.9	14.7 9.8	69.6 68.7	14.7 15.3	23.7 23.2	2.4 3.0	19.3 21.1	5.5 4.5	**H**		2	✓			
23	Lack et al. 2014 (146)	G1	1 session	1	prefabricated foot orthosis	28.5	4.2	9	11	20	171.9	7.0	64.8	9.7					S		6		✓		
24	Lee et al. 2012 (147)	G1 G2	1 session	1	foot taping retraining; short foot contraction	20.1 20.1	1.6 1.6	6 6	12 12	18 18	165.3 165.3	5.9 5.9	57.5 57.5	11.1 11.1	20.9 20.9	3.3 3.3			M		6		✓		
25	Lima et al. 2020 (135)	G1	12 weeks	36	hip abduction exc.	21.5	2.9	0	11	11			55.1	5.2					S	13	6		✓		
26	**Ma et al. 2021** (148)	G1 G2	6 weeks	6	Dry needling sham dry needling	22.5 25.1	2.4 6.0	13 10	12 13	25 23	1.7 1.7	8.1 9.3	66.4 64.1	11.7 12.9	22.7 21.8	2.7 3.3			**H**		5				✓
27	Malarvizhi et al. 2017 (266)	G1	1 week	7	hip exc. + ITB stretching			20	0	20									C	1	1				✓
28	McCrory et al. 2004 (144)	G1	1 session	1	brace without resistance brace with resistance	23.4	3.1	0	21	21	1.7	0.1	65.3	20.4					S		2		✓		
29	Mills et al. 2012 (267)	G1 G2	1 session	1	Mobile foot: Hard orthosis; medium orthosis; soft orthosis; soft-flat orthosis Less mobile foot: Hard orthosis; medium orthosis; soft orthosis; soft-flat orthosis	28.7 31.2	6.1 4.4	8 3	19 10	27 13	1.7 171.2	14.9 8.4	71.0 71.2	12.0 11.2					M		6		✓		
30	Mostamand et al. 2011 (136)	G1	1 session max 6 weeks	1 Varies	taping daily taping	27.9	6.3	11	7	18	1.7	0.1	71.5	9.5					S		5		✓		
31	**Motealleh et al. 2016** (137)	G1 G2	1 session	1	lumbopelvic manip sham lumb.p manip	26.9 26.1	5.5 3.9	6 6	8 8	14 14	166.0 169.0	6.7 9.5	61.6 70.4	12.1 12.2					**M**		6	✓	✓		

32	**Orscelik et al. 2015** (159)	G1	6 weeks	NA	single Platelet-Rich Plasma+exc.	27.2	5.7	13	7	20	174.5	7.9	73.4	12.8	24.0	3.0			**H**	0	2	✓		
		G2			triple Platelet-Rich Plasma+exc.	28.7	6.0	6	4	10	170.8	6.6	71.1	12.5	24.2	3.4								
		G3			exc. only	27.7	5.7	19	11	30	173.2	7.6	72.6	12.5	24.0	3.1								
33	Osorio et al. 2013 (160)	G1	1 session	1	McConnel taping Spider taping	21.2	2.9	7	13	20	169.2	16.8	68.1	11.6	24.5	7.0			*L*		1	✓		
34	Paoloni et al. 2012 (161)	G1 G2	12 weeks	NA	Exc+tape+stretching (injured side) Exc+tape+stretching (uninjured side)	28.5	9.2	15	29	44	171.8	12.8	71.6	8.2			13.7	9.2	*S*	11	6	✓		
35	**Rabelo et al. 2017** (268)	G1	4 weeks	12	strengthening exc	25.3	8.1	0	17	17	1.6	0.1	57.6	5.7	22.8	1.8	49.3	40.5	**L**	15	3	✓		
		G2			motor control + strengthening exc	25.9	5.5	0	17	17	1.6	0.1	57.0	8.9	21.8	2.8	46.2	33.0						
36	**Rathleff et al. 2016** (145)	G1	12 weeks	36	education	17.0	16-18	0	29	29	168.1	4.8	59.4	5.7	21.0	2.0	36.0	iqr	**H**	13	6	✓	✓	
		G2			education and exc	17.0	16-18	0	28	28	169.3	5.8	58.0	6.4	20.2	1.7	24.0	iqr						
37	Rathleff et al. 2018 (163)	G1	12 weeks	36	strength,stretch,taping and education	14.6	1.1	4	16	20	167.0	10.0	55.2	9.0					*M*	18	5	✓		
38	**Riel et al. 2018** (269)	G1	6 weeks	18	hip and knee exc with force feedback only	16.5	1.5	4	16	20	167.8	8.1	61.8	7.0	22.0	2.3			**L**	16	5	✓		
		G2			hip and knee exc with auditory and force feedback	16.9	1.5	1	19	20	167.5	5.9	62.6	11.9	22.3	3.6								
39	**Saad et al. 2018** (164)	G1	8 weeks	16	quadriceps exc	23.2	2.5	0	10	10	1.6	0.1	56.3	5.9	21.8	1.7			**M**	10	6	✓		
		G2			hip exc	22.5	1.1	0	10	10	1.6	0.0	55.3	4.0	22.0	2.0								
		G3			stretching exc	21.3	1.2	0	10	10	1.6	0.0	54.7	2.2	21.9	1.3								
		G4		none	control (wait-and-see)	23.2	1.0	0	10	10	1.6	0.1	55.4	2.0	21.3	1.3								
40	*Singer et al. 2006 (155)	G1	12 weeks	NA	Exc+butox	29.0		0	8	8							60.0		*S*	6	3	✓		
41	Song et al. 2015 (150)	G1	1 session	1	femoral rotational taping sham tape	25.7	6.1	0	16	16	164.1	5.4	55.5	5.8	20.6	1.4	9.5	11.1	*S*		5		✓	
42	Thomee et al. 1997 (270)	G1	12 weeks	36	eccentric ecercise programme	20.2	3.2	0	40	20	169.0	6.4	64.1	8.8			43.0	31.2	*S*	15	5	✓		
		G2			isometric excercie programme					20														
43	**Witvrouw et al. 2000** (85)	G1	5 weeks	15	knee targeted open kinetic chain			10	20	30	169.5	6.8	63.2	7.6					**M**	10	4	✓		✓
		G2			knee targeted closed kinetic chain			10	20	30	171.4	7.7	66.1	8.3										

44	**Witvrouw et al. 2003** (138)	G1	5 weeks	15	knee targeted open kinetic chain			10	20	30	169.5	6.8	63.2	7.6					**M**	12	4		✓	
		G2			knee targeted closed kinetic chain			10	20	30	171.4	7.7	66.1	8.3										
45	**Witvrouw et al. 2004** (86)	G1	5 weeks	15	knee targeted open kinetic chain			10	20	30	169.5	6.8	63.2	7.6					**H**	13	4	✓		
		G2			knee targeted closed kinetic chain			10	20	30	171.4	7.7	66.1	8.3										
46	Yosmaoglu et al. 2020 (271)	G1	6 weeks	18	multimodal programme	27.0	9.0			61	170.0	8.0	65.0	13.0	22.5	3.0	24.0	28.0	S	8	4		✓	✓
		G1a	plus 6 weeks	+ 18	proprioception/balance exc. + patellar bracing + Activity modification					18														
		G1b	plus 6 weeks	+ 18	CKC exc. + Weight management strategies					12														
		G1c	plus 6 weeks	+ 18	CKC exc. + Foot orthoses + Activity modification					10														
	Total (range)							621	1260	1982							Studies administered exercises interventions:			28		28	19	6

Risk of bias					
	ROB (V1)	Low	Moderate	High	
	ROBINS-I	Low	Moderate	Serious	Critical

; Singer et al. (155) investigated quadriceps cross-sectional area but data is unretrievable.

Table 4.3: Types of variables investigated in all included studies. Highlighted in blue are variables that were included in our previous meta-analysis (176) *(to show the overlapping within local neuromuscular characteristics investigated).VM; Vastus medialis, VL; Vastus lateralis, RF; Rectus femoris, BF; Biceps femoris, Gast.M; Gastrocnemius medialis*

#		Muscle performance variables	Number of studies (citations)		Electromyographic variables	Number of studies (citations)		Muscle flexibility and cross-sections	Number of studies (citations)
1	Isometric tests	Extensors isometric peak torque 90d	7 (153,154,162,163, 261,265,271)	Excitation Amplitude	VM mean excitation amplitude	16 (135–137,139–147,201,264,267,270)	Muscle flexibility	Quadriceps flexibility	3 (85,162,271)
2		Flexors isometric peak torque 90d	1 (162)		VL mean excitation amplitude	14 (135–137,139,141–147,149,264,267)		Hamstrings flexibility	3 (85,139,162)
3		Extensors isometric peak torque 60d	9 (140,145,151,152, 163,164,262,268, 269)		RF mean excitation amplitude	5 (144,149,150,267,270)		Gast. flexibility	3 (85,162,271)
4		Extensors isometric peak torque 30d	2 (151,155)		BF mean excitation amplitude	4 (144,149,264,267)		Iliotibial-band flexibility	2 (162,266)
5		Flexors isometric peak torque 30d	1 (164)		Gast. M. mean excitation amplitude	1 (149)	CSA	Quadriceps	1 (155)
6		Extensors isometric average torque	2 (263,270)		Gast. M. peak excitation amplitude	1(267)			
7	Concentric tests	Extensors concentric peak torque 60d/s	9 (45,85,86,156–161)		VM/VL mean excitation amplitude ratio	5 (135,136,140,141,148)			
8		Extensors concentric peak torque 180d/s	4 (85,86,156,158)	Excitation Onset	VM excitation onset	1 (138)			
9		Flexors concentric peak torque 60d/s	6 (45,85,86,157–159)		VL excitation onset	5 (137,138,143,146,267)			
10		Flexors concentric peak torque 180d/s	2 (86,158)		RF excitation onset	1 (267)			
11		Extensors concentric peak torque 240d/s	2 (157,159)		BF excitation onset	1 (267)			
12		Flexors concentric peak torque 240d/s	2 (157,159)		Gast. M. excitation onset	1 (267)			
13		Extensors Concentric peak torque 300d/s	1 (86)		VM/VL excitation onset ratio	4 (135–138)			
14		Flexors concentric peak torque 300d/s	1 (86)	Excitation Duration	VM excitation duration	2 (135,144)			
15		Extensors concentric ratio 60/180 d/s	1 (158)		VL excitation duration	2 (135,144)			
16		Flexors concentric ratio 60/180 d/s	1 (158)		BF excitation duration	1 (144)			
17		Concentric extensors/flexors ratio 60d/s	1 (43)		RF excitation duration	1 (144)			
18		Concentric extensors/flexors ratio 180d/s	1 (158)	Excitation time to peak	VM excitation time to peak	1 (267)			
19		Concentric flexors/extensors peak torque ratio 240d/s	1 (157)		VL excitation time to peak	1 (267)			
20		Extensors concentric average torque	1 (270)		RF excitation time to peak	1 (267)			
21	Eccentric tests	Extensors eccentric peak torque 60d/s	1 (260)		BF excitation time to peak	1 (267)			
22		Flexors eccentric peak torque 60d/s	1 (260)		Gast. M. excitation time to peak	1 (267)			
23		Extensors eccentric average torque	1 (270)	Excitation offset	VM excitation offset	1 (267)			
24	Endurance tests	Extensors total work 60d/s	1 (159)		VL excitation offset	1 (267)			
25		Flexors total work 60d/s	1 (159)		RF excitation offset	1 (267)			
26		Extensors total work 180d/s	1 (45)		BF excitation offset	1 (267)			
27		Flexors total work 180d/s	1 (45)		Gast. M. offset	1 (267)			
28		Extensors total work 240d/s	3 (157,159,160)						
29		Flexors total work 240d/s	2 (157,159)						
30		Quadriceps mean muscle inhibition	2 (154,263)						

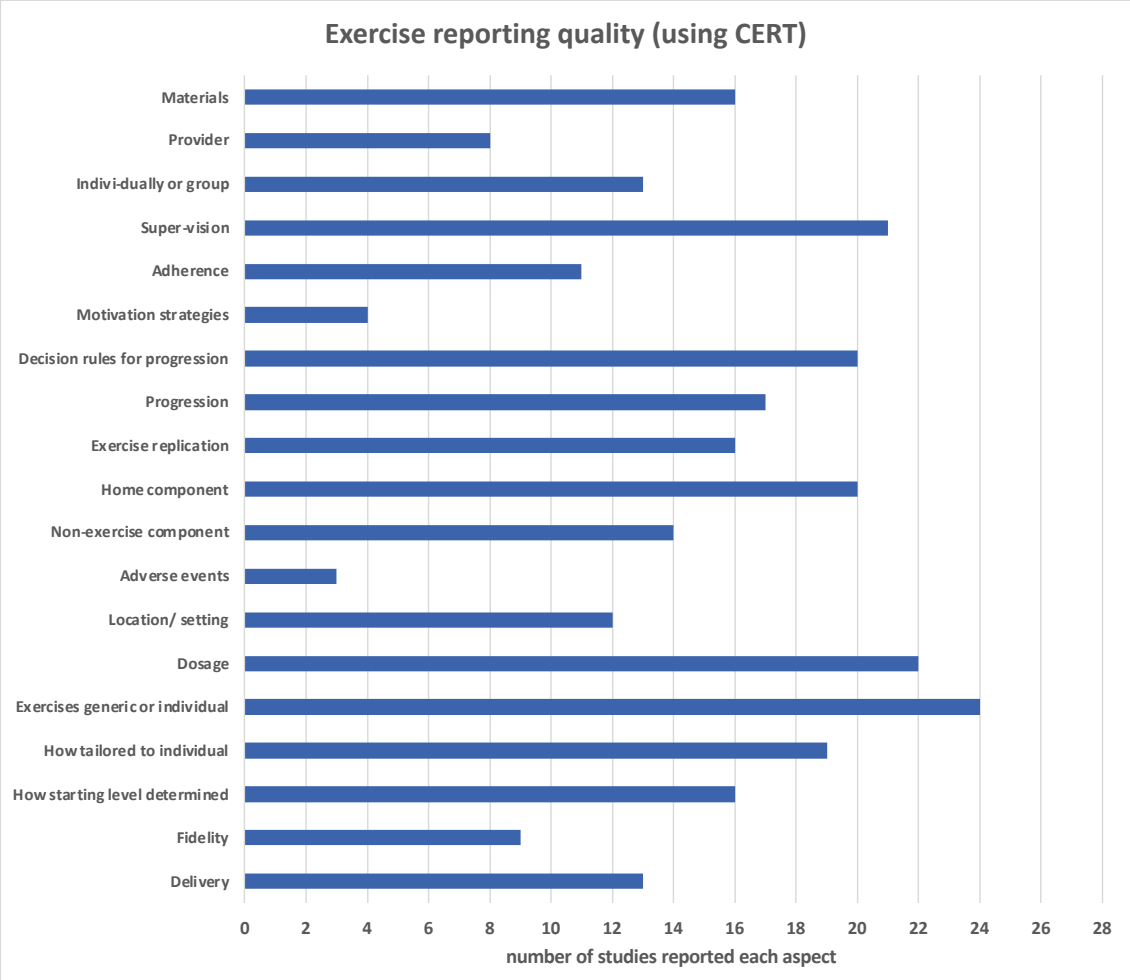


Figure 4.2: Summary of scores for exercise reporting in included studies. 28 out of 46 used exercise interventions. The Consensus on Exercise Reporting Template was used to score exercise reporting.

4.3.1 Results of the meta-analyses of interventional effects on local neuromuscular deficits

All pooled effects are categorised according to intervention type. Significant changes were further analysed according to changes in pain scores and AKPS. All other findings that were not included in the meta-analysis are presented in Appendix four and summarised in the evidence gap-map (tables 4.4-4.6).

4.3.1.1 Electromyography investigations

Nineteen studies conducted EMG investigations to monitor changes of local muscles' activation after interventions. Meta-analyses of mean excitation amplitudes of VM, VL, RF and BF in seated extensions, stepping and stair negotiations, squatting and running/walking were produced. Other EMG outcomes were found (e.g. VM mean excitation amplitude in rock-task (137)) but were not pooled due to differences in tasks during which the data were collected (Appendix four shows the studies that were not pooled with reasons). All results presented very limited evidence indicating no changes in investigated characteristics after interventions. Figure 4.3 summarises the whole meta-analyses of EMG investigations.

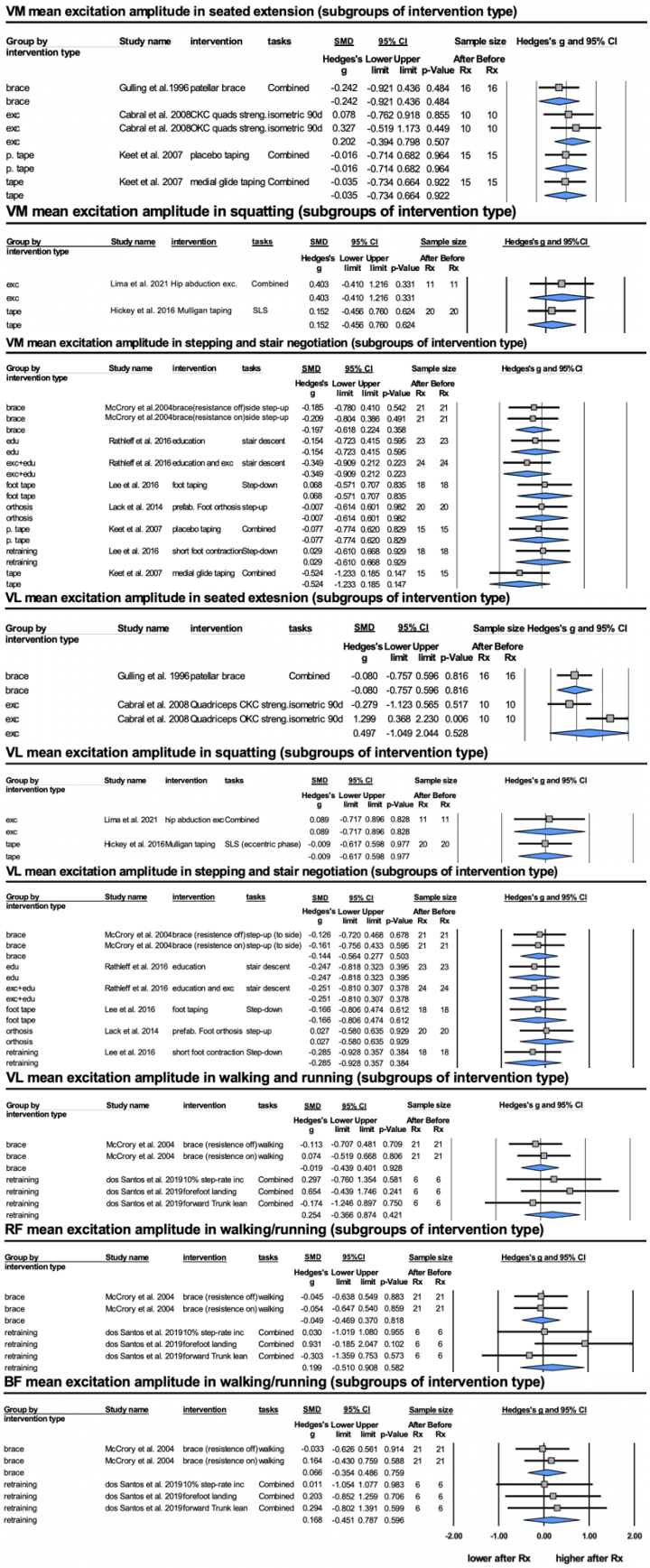


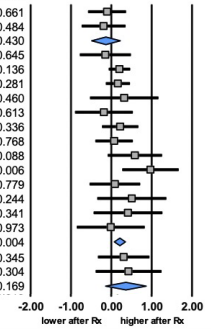
Figure 4.3: All pooled results within EMG investigations. Data were categorised according to intervention type. No significant effects of any intervention were caused to VM, VL, RF and BF mean excitation amplitudes when they were pooled within similar tasks. All results are summarised in the gap-map (tables 4.4-4.6). exc; exercise, p.; placebo, edu; education, Combined; multiple angles of same test., SLS; single leg squat.

4.3.1.2 Muscle performance

4.3.1.2.1 Isometric knee extension peak torque

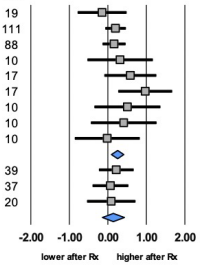
Knee extension isometric peak torque (subgroups of intervention types)

Group by intervention type	Study name	Intervention	tasks	Hedges's g	Lower limit	Upper limit	p-Value
edu	Hott et al. 2019	free physical activity	isometric 60d of flexion (N; after Rx)	-0.105	-0.572	0.363	0.661
edu	Rathleff et al. 2016	education	isometric 60d of flexion (Nm/kg)	-0.193	-0.733	0.347	0.484
edu				-0.142	-0.496	0.211	0.430
exc	Bily et al. 2008	PT training	Combined	-0.148	-0.780	0.483	0.645
exc	Ferber et al. 2015	HIP: balance, core and hip strengthening exc.	isometric 90d (nm/kg)	0.200	-0.063	0.463	0.136
exc	Ferber et al. 2015	knee targeted strengthening exercises	isometric 90d (nm/kg)	0.162	-0.133	0.457	0.281
exc	Glaviano et al. 2019	Sham pens+Exc	isometric 90d (n/kg)	0.319	-0.527	1.164	0.460
exc	Grindstaff et al. 2012	prone ext on elbows 3 min	isometric 90d (N)	-0.184	-0.897	0.529	0.613
exc	Hott et al. 2019	hip targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	0.219	-0.227	0.666	0.336
exc	Hott et al. 2019	knee targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	0.069	-0.391	0.530	0.768
exc	Rabelo et al. 2017	motor control + strengthening exc	isometric 60d of flexion (Nm/kg)	0.585	-0.086	1.256	0.088
exc	Rabelo et al. 2017	strengthening exc	isometric 60d of flexion (Nm/kg)	0.971	0.275	1.667	0.006
exc	Rathleff et al. 2018	strength., stretch., taping and education	isometric 60d of flexion (Nm/kg)	0.089	-0.535	0.713	0.779
exc	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	0.508	-0.346	1.362	0.244
exc	Saad et al. 2018	quadriceps exc	isometric (N/kg) angle: NA	0.413	-0.437	1.262	0.341
exc	Saad et al. 2018	stretching exc	isometric (N/kg) angle: NA	-0.015	-0.854	0.825	0.973
exc				0.203	0.065	0.341	0.004
exc+stim	Bily et al. 2008	EMS + PT training	Combined	0.306	-0.330	0.942	0.345
exc+stim	Glaviano et al. 2019	PENS+Exc	isometric 90d (n/kg)	0.427	-0.387	1.240	0.304
exc+stim				0.352	-0.149	0.853	0.169



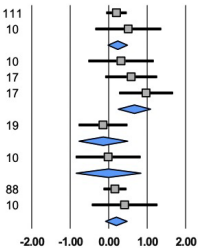
Exercise intervention effects on knee extension isometric peak torque (subgroups of pain MCID)

Group by pain; Rx type	Study name	Intervention	tasks	SMD Hedges's g	95% CI Lower limit	95% CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
imp; exc	Bily et al. 2008	PT training	Combined	-0.148	-0.780	0.483	0.645	18	19
imp; exc	Ferber et al. 2015	HIP: balance, core and hip strengthening exi	isometric 90d (nm/kg)	0.200	-0.063	0.463	0.136	111	111
imp; exc	Ferber et al. 2015	knee targeted strengthening exercises	isometric 90d (nm/kg)	0.162	-0.133	0.457	0.281	88	88
imp; exc	Glaviano et al.2019	Sham pens+exc	isometric 90d (n/kg)	0.319	-0.527	1.164	0.460	10	10
imp; exc	Rabelo et al. 2017	motor control + strengthening exc	isometric 60d of flexion (Nm/kg)	0.585	-0.086	1.256	0.088	17	17
imp; exc	Rabelo et al. 2017	strengthening exc	isometric 60d of flexion (Nm/kg)	0.971	0.275	1.667	0.006	17	17
imp; exc	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	0.508	-0.346	1.362	0.244	10	10
imp; exc	Saad et al. 2018	quadriceps exc	isometric (N/kg) angle: NA	0.413	-0.437	1.262	0.341	10	10
imp; exc	Saad et al. 2018	stretching exc	isometric (N/kg) angle: NA	-0.015	-0.854	0.825	0.973	10	10
imp; exc				0.245	0.083	0.406	0.003		
no imp; exc	Hott et al. 2019	hip targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	0.219	-0.227	0.666	0.336	37	39
no imp; exc	Hott et al. 2019	knee targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	0.069	-0.391	0.530	0.768	34	37
no imp; exc	Rathleff et al. 2018	strength., stretch., taping and education	isometric 60d of flexion (Nm/kg)	0.089	-0.535	0.713	0.779	18	20
no imp; exc				0.135	-0.151	0.420	0.355		



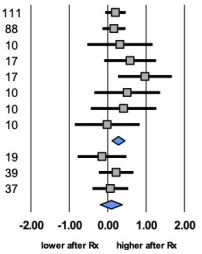
Exercise intervention effects in groups with improvement in pain score (sub-grouped according to exercise target)

imp; hip (streng.)	Ferber et al. 2015	HIP: balance, core and hip strengthening exi	isometric 90d (nm/kg)	0.200	-0.063	0.463	0.136	111	111
imp; hip (streng.)	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	0.508	-0.346	1.362	0.244	10	10
imp; hip (streng.)				0.227	-0.025	0.478	0.077		
imp; hip+knee (streng.)	Glaviano et al.2019	Sham pens+exc	isometric 90d (n/kg)	0.319	-0.527	1.164	0.460	10	10
imp; hip+knee (streng.)	Rabelo et al. 2017	motor control + strengthening exc	isometric 60d of flexion (Nm/kg)	0.585	-0.086	1.256	0.088	17	17
imp; hip+knee (streng.)	Rabelo et al. 2017	strengthening exc	isometric 60d of flexion (Nm/kg)	0.971	0.275	1.667	0.006	17	17
imp; hip+knee (streng.)				0.660	0.240	1.079	0.002		
imp; hip+knee (streng.+stretch)	Bily et al.2008	PT training	Combined	-0.148	-0.780	0.483	0.645	18	19
imp; hip+knee (streng.+stretch)				-0.148	-0.780	0.483	0.645		
imp; hip+knee (stretching only)	Saad et al.2018	stretching exc	isometric (N/kg) angle: NA	-0.015	-0.854	0.825	0.973	10	10
imp; hip+knee (stretching only)				-0.015	-0.854	0.825	0.973		
imp; knee (streng.)	Ferber et al. 2015	knee targeted strengthening exercises	isometric 90d (nm/kg)	0.162	-0.133	0.457	0.281	88	88
imp; knee (streng.)	Saad et al. 2018	quadriceps exc	isometric (N/kg) angle: NA	0.413	-0.437	1.262	0.341	10	10
imp; knee (streng.)				0.189	-0.089	0.467	0.183		



Exercise intervention effects on knee extension isometric peak torque (subgroups of AKPS MCID)

Group by akps; Rx type	Study name	Intervention	tasks	SMD Hedges's g	95% CI Lower limit	95% CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
imp; exc	Ferber et al. 2015	HIP: balance, core and hip strengthening exi	isometric 90d (nm/kg)	0.200	-0.063	0.463	0.136	111	111
imp; exc	Ferber et al. 2015	knee targeted strengthening exercises	isometric 90d (nm/kg)	0.162	-0.133	0.457	0.281	88	88
imp; exc	Glaviano et al. 2019	Sham pens+Exc	isometric 90d (n/kg)	0.319	-0.527	1.164	0.460	10	10
imp; exc	Rabelo et al. 2017	motor control + strengthening exc	isometric 60d of flexion (Nm/kg)	0.585	-0.086	1.256	0.088	17	17
imp; exc	Rabelo et al. 2017	strengthening exc	isometric 60d of flexion (Nm/kg)	0.971	0.275	1.667	0.006	17	17
imp; exc	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	0.508	-0.346	1.362	0.244	10	10
imp; exc	Saad et al. 2018	quadriceps exc	isometric (N/kg) angle: NA	0.413	-0.437	1.262	0.341	10	10
imp; exc	Saad et al. 2018	stretching exc	isometric (N/kg) angle: NA	-0.015	-0.854	0.825	0.973	10	10
imp; exc				0.272	0.105	0.439	0.001		
no imp; exc	Bily et al. 2008	PT training	Combined	-0.148	-0.780	0.483	0.645	18	19
no imp; exc	Hott et al. 2019	hip targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	0.219	-0.227	0.666	0.336	37	39
no imp; exc	Hott et al. 2019	knee targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	0.069	-0.391	0.530	0.768	34	37
no imp; exc				0.086	-0.200	0.372	0.555		



Exercise intervention effects in groups with improvement in AKPS score (sub-grouped according to exercise target)

imp; hip (streng.)	Ferber et al. 2015	HIP: balance, core and hip strengthening exi	isometric 90d (nm/kg)	0.200	-0.063	0.463	0.136	111	111
imp; hip (streng.)	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	0.508	-0.346	1.362	0.244	10	10
imp; hip (streng.)				0.227	-0.025	0.478	0.077		
imp; hip+knee (streng.)	Glaviano et al.2019	Sham pens+exc	isometric 90d (n/kg)	0.319	-0.527	1.164	0.460	10	10
imp; hip+knee (streng.)	Rabelo et al. 2017	motor control + strengthening exc	isometric 60d of flexion (Nm/kg)	0.585	-0.086	1.256	0.088	17	17
imp; hip+knee (streng.)	Rabelo et al. 2017	strengthening exc	isometric 60d of flexion (Nm/kg)	0.971	0.275	1.667	0.006	17	17
imp; hip+knee (streng.)				0.660	0.240	1.079	0.002		
imp; hip+knee (stretching ory)	Saad et al.2018	stretching exc	isometric (N/kg) angle: NA	-0.015	-0.854	0.825	0.973	10	10
imp; hip+knee (stretching only)				-0.015	-0.854	0.825	0.973		
imp; knee (streng.)	Ferber et al. 2015	knee targeted strengthening exercises	isometric 90d (nm/kg)	0.162	-0.133	0.457	0.281	88	88
imp; knee (streng.)	Saad et al. 2018	quadriceps exc	isometric (N/kg) angle: NA	0.413	-0.437	1.262	0.341	10	10
imp; knee (streng.)				0.189	-0.089	0.467	0.183		

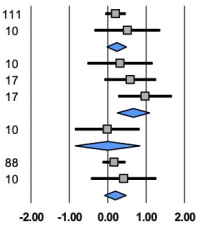


Figure 4.4: Effects of interventions on isometric knee extensors peak torque. Further subgroup analyses for the exercises plot are also presented. edu; education, exc; exercise, inj; injection, stim; stimulation, manip/mobil; manipulation/mobilisation, p.; placebo, PT; physiotherapy, Combined; different angles for same outcome done, pens; patterned electrical neuromuscular stimulation, ext; extension, min; minutes, EMS; electrical muscle stimulation, flex; flexion.

a. Analysed according to intervention type

There are moderate evidence indicating that education alone (-0.142 [-0.469,0.211], I^2=0%, *p*=0.809) and exercise combined with muscle stimulation (0.352 [-0.149,0.586], I^2=0%, *p*=0.819) cause no changes in people with PFP. There is strong evidence with small effect (0.203 [0.065,0.341]) indicating that exercise interventions increase knee extensors isometric peak torque in people with PFP (Figure 4.4).

b. Subgroups of exercise intervention based on MCID of pain and AKPS scores

Strong evidence with small effect (0.245 [0.083,0.406]; I^2=0%, *p*=0.439) indicates an increase in isometric knee extension peak torque following exercise interventions in groups demonstrating an improvement in pain. There is a significant increase in isometric knee extension peak torque, presenting strong evidence with small effect (0.272 [0.105,0.439]; I^2=0%, *p*=0.495) in groups with improvement in function (Figure 4.4).

c. Groups with MCID in pain and AKPS scores analysed according to specific exercise target

For groups with MCID in pain scores, strong evidence with medium effect was shown in groups receiving hip and knee targeted strengthening (0.66 [0.24,1.079]; I^2=0%, *p*=0.486). Moderate evidence indicates no change in isometric extension peak torque after undergoing strengthening of hip (0.227 [-0.025,0.478]; I^2=0%, *p*=0.499) or knee (0.189 [-0.089,0.467]; I^2=0%, *p*=0.585) in isolation. When groups with MCID in AKPS scores were analysed according to exercise target, results were the same as all groups showing MCID in pain scores showed MCID in AKPS scores (Figure 4.4).

4.3.1.2.2 Isometric knee flexion peak torque

Effects of interventions on isometric knee flexors peak torque

Group by Intervention type	Study name	Groups	tasks	SMD Hedges's g	95%CI Lower limit	95%CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
exc	Glaviano et al. 2019	Sham pens+Exc	isometric 90d (n/kg)	1.315	0.382	2.248	0.006	10	10
exc	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	0.349	-0.497	1.195	0.419	10	10
exc	Saad et al. 2018	quadriceps exc	isometric (N/kg) angle: NA	0.521	-0.334	1.376	0.232	10	10
exc	Saad et al. 2018	stretching exc	isometric (N/kg) angle: NA	-0.068	-0.908	0.771	0.873	10	10
exc				0.504	-0.045	1.053	0.072		

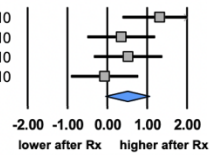


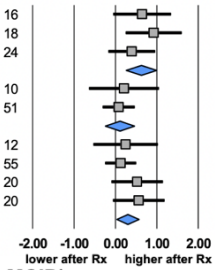
Figure 4.5: Effects of exercise intervention on isometric knee flexors peak torque. No further subgroup analyses conducted as no significant pooled effects were found. edu; education, exc; exercise, stim; stimulation, PENS; patterned electrical neuromuscular stimulation.

Pooled results indicate that there are no changes in isometric flexion peak torque after exercise programmes (0.504 [-0.045,1.053]; I^2=37.65%, *p*=0.186) (Figure 4.5)

4.3.1.2.3 *Concentric knee extension peak torque*

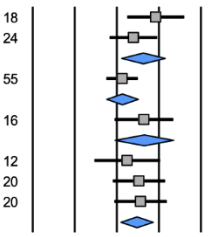
Concentric knee extensors peak torque (grouped by intervention type)

Group by intervention type	Study name	intervention	tasks	SMD Hedges's g	95%CI Lower limit	95%CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
exc	Corum et al. 2018	stren. & stretch.	Combined	0.644	-0.051	1.339	0.069	16	16
exc	Corum et al. 2018	whole body vibratio + exc	Combined	0.923	0.249	1.597	0.007	18	18
exc	Hazneci et al. 2005	OKC quads strengthening	concentric peak torque 60d/s (Nm)	0.393	-0.169	0.955	0.170	24	24
exc				0.620	0.253	0.987	0.001		
p. tape	Aytar et al. 2011	placebo KT tape	Combined	0.207	-0.635	1.049	0.630	10	10
p. tape	Kurt et al. 2016	placebo kinesio tape	Combined	0.080	-0.305	0.466	0.684	51	51
p. tape				0.102	-0.248	0.453	0.568		
tape	Aytar et al. 2011	Kinesio tape	Combined	0.246	-0.530	1.021	0.535	12	12
tape	Kurt et al. 2016	Kinesio tape	Combined	0.126	-0.246	0.497	0.507	55	55
tape	Osorio et al. 2013	McConnel tape	Combined	0.524	-0.095	1.142	0.097	20	20
tape	Osorio et al. 2013	Spider tape	Combined	0.563	-0.057	1.183	0.075	20	20
tape				0.294	0.028	0.560	0.030		



Exercise and taping effects on concentirc knee extensors peak torque (subgroups of pain MCID)

Group by pain; Rx type	Study name	intervention	tasks	SMD Hedges's g	95%CI Lower limit	95%CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
imp; exc	Corum et al. 2018	whole body vibratio + exc	Combined	0.923	0.249	1.597	0.007	18	18
imp; exc	Hazneci et al. 2005	OKC quads strengthening	concentric peak torque 60d/s (Nm)	0.393	-0.169	0.955	0.170	24	24
imp; exc				0.624	0.110	1.139	0.017		
imp; tape	Kurt et al. 2016	Kinesio tape	Combined	0.126	-0.246	0.497	0.507	55	55
imp; tape				0.126	-0.246	0.497	0.507		
no imp; exc	Corum et al. 2018	stren. & stretch.	Combined	0.644	-0.051	1.339	0.069	16	16
no imp; exc				0.644	-0.051	1.339	0.069		
no imp; tape	Aytar et al. 2011	Kinesio tape	Combined	0.246	-0.530	1.021	0.535	12	12
no imp; tape	Osorio et al. 2013	McConnel tape	Combined	0.524	-0.095	1.142	0.097	20	20
no imp; tape	Osorio et al. 2013	Spider tape	Combined	0.563	-0.057	1.183	0.075	20	20
no imp; tape				0.471	0.090	0.852	0.015		



Exercise intervention effects on knee extension concentric peak torque in groups with improvement in pain score (subgroups of exercise target)

imp; knee (stren.)	Hazneci et al. 2005	OKC quads strengthening	concentric peak torque 60d/s (Nm)	0.393	-0.169	0.955	0.170	24	24
imp; knee (stren.)				0.393	-0.169	0.955	0.170		
imp; knee+hip (stren.+stretch)	Corum et al. 2018	whole body vibratio + exc	Combined	0.923	0.249	1.597	0.007	18	18
imp; knee+hip (stren.+stretch)				0.923	0.249	1.597	0.007		

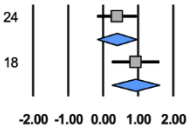


Figure 4.6: Effects of interventions on concentric knee extensors peak torque. exc; exercise, stren.; strengthening, stret.; stretching, OKC; open kinetic chain, PRP; platelet-rich plasma.

a. Analysed according to intervention type

Results show significant increase in extensors concentric peak torque with moderate evidence and medium effect from exercise (0.62 [0.253,0.987]; I^2=0%, *p*=0.495) and with moderate evidence and small effect from taping (0.294 [0.028,0.560]; I^2=0%, *p*=0.561). Moderate evidence indicates that placebo taping cause no significant changes (0.102 [-0.248,0.453]; I^2=0%, *p*=0.789) (Figure 4.6).

b. Subgroups of exercise and taping interventions based on MCID of pain and AKPS scores

In PFP groups with MCID in pain, moderate evidence with medium effect indicates that exercise interventions showed significant increases (0.624 [0.11,1.139]); I^2=28.5%, *p*=0.237). For taping, very limited evidence shows no changes after Kinesio taping. No further analyses were performed as Hazneci et al. (45) did not report AKPS scores, and Corum et al. (157) showed no improvement. For taping, included studies either showed no improvement (158) or did not report AKPS scores (156,160) (Figure 4.6).

c. Groups with MCID in pain scores analysed according to specific exercise target

Further analysis of the exercise groups sub-plot showed very limited evidence with medium effect of significant increase after exercises with whole body vibration targeting knee and hip (0.923 [0.249,1.597]), and very limited evidence indicates knee targeted exercise caused no changes (Figure 4.6).

4.3.1.2.4 Concentric knee flexion peak torque

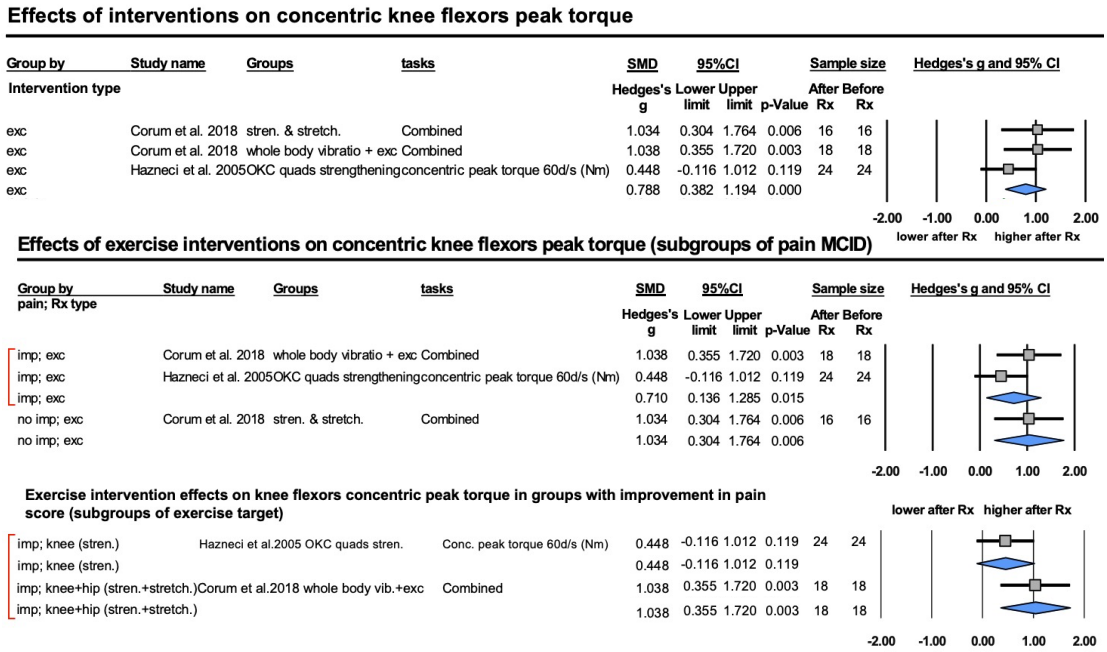


Figure 4.7: Effects of exercise on concentric knee flexors peak torque. exc; exercise, stren.; strengthening, stret.; stretching, OKC; open kinetic chain.

a. Analysed according to intervention type

Concentric flexors peak torques show significant increase with moderate evidence and medium effect after exercise (0.788 [0.382,1.194]; I^2=14.69%, *p*=0.31) (Figure 4.7).

b. Subgroups of exercise intervention based on MCID of pain and AKPS scores

Moderate evidence with medium effect indicates that exercise interventions cause significant increase (0.71 [0.136,0.128]; I^2= 41.35%, *p*=0.192). Regarding AKPS, no further analyses were performed as Hazneci et al. (45) did not report AKPS scores, and Corum et al. (157) showed no improvement (Figure 4.7).

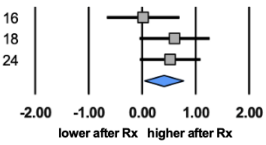
c. Groups with MCID in pain scores analysed according to specific exercise targe

Very limited evidence with medium effect indicates an increase in concentric flexors peak torque after exercises targeting both hip and knee combined with whole body vibration (1.038 [0.355,1.72]). Very limited evidence indicates no changes after knee targeted exercises (Figure 4.7).

4.3.1.2.5 *Knee extension total work*

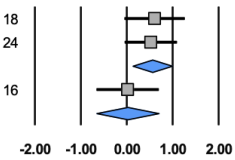
Effects of interventions on knee extensors total work

Group by Intervention type	Study name	Groups	tasks	SMD Hedges's g	95%CI Lower limit	95%CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
exc	Corum et al. 2018	stren. & stretch.	total work (J/kg) 240d/s	0.019	-0.657	0.694	0.957	16	16
exc	Corum et al. 2018	whole body vibratio + exc	total work (J/kg) 240d/s	0.606	-0.048	1.260	0.069	18	18
exc	Hazneci et al. 2005	OKC quads strengthening	total work 180d/s (Nm)	0.524	-0.043	1.090	0.070	24	24
exc				0.404	0.043	0.766	0.028		



Effects of exercise interventions on knee extensors total work (subgroups of pain MCID)

Group by pain; Rx type	Study name	Groups	tasks	SMD Hedges's g	95%CI Lower limit	95%CI Upper limit	p-Value	Sample size After Rx	Sample size Before Rx
imp; exc	Corum et al. 2018	whole body vibratio + exc	total work (J/kg) 240d/s	0.606	-0.048	1.260	0.069	18	18
imp; exc	Hazneci et al. 2005	OKC quads strengthening	total work 180d/s (Nm)	0.524	-0.043	1.090	0.070	24	24
imp; exc				0.559	0.131	0.987	0.010		
no imp; exc	Corum et al. 2018	stren. & stretch.	total work (J/kg) 240d/s	0.019	-0.657	0.694	0.957	16	16
no imp; exc				0.019	-0.657	0.694	0.957		



Exercise intervention effects on knee extensors total work in groups with improvement in pain score (subgroups of exercise target)

imp; knee (stren.)	Hazneci et al. 2005	OKC quads strengthening	total work 180d/s (Nm)	0.524	-0.043	1.090	0.070	24	24
imp; knee (stren.)				0.524	-0.043	1.090	0.070		
imp; knee+hip (stren.+stretch.)	Corum et al. 2018	whole body vibratio + exc	total work (J/kg) 240d/s	0.606	-0.048	1.260	0.069	18	18
imp; knee+hip (stren.+stretch.)				0.606	-0.048	1.260	0.069		

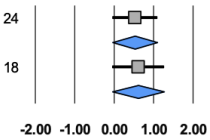


Figure 4.8: Effects of interventions on knee extensors total work. exc; exercise, stren.; strengthening, stret.; stretching, OKC; open kinetic chain.

a. Analysed according to intervention type

Results show significant increases in knee extensors total work after exercise interventions with moderate evidence and small effect (0.404 [0.043,0.766]; I^2=0%, *p*=0.409) (Figure 4.8).

b. Subgroups of exercise intervention based on MCID of pain and AKPS scores

Moderate evidence with small effect indicates that exercise caused significant increase (0.599 [0.131,0.987]; I^2=0%, *p*=0.851). Results show no changes in a group that showed no improvement in pain scores (very limited evidence). For AKPS, no analyses were undertaken as Hazneci et al. (45) did not report AKPS scores, and Corum et al. (157) showed no improvement (Figure 4.8).

c. Groups with MCID in pain scores analysed according to specific exercise target

Very limited evidence indicates that neither exercises targeting the knee alone nor targeting knee and hip caused changes in extensors total work in groups with MCID in pain scores (Figure 4.8).

4.3.1.2.6 *Knee flexion total work*

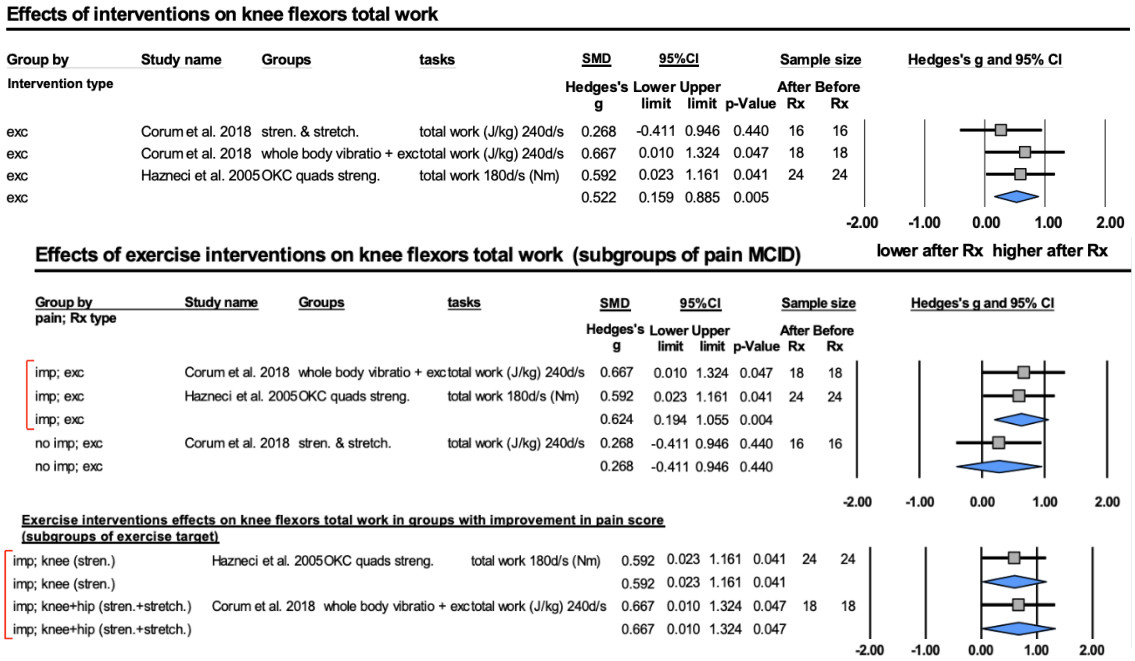


Figure 4.9: Effects of interventions on knee flexors total work. exc; exercise, stren.; strengthening, stret.; stretching, OKC; open kinetic chain.

a. Analysed according to intervention type

Results show a significant increase in knee flexors total work after exercise interventions with moderate evidence and small effect (0.522 [0.159,0.885]; I^2=0%, *p*=0.675) (Figure 4.9).

b. Sub-groups of exercise intervention based on MCID of pain and AKPS scores

In PFP groups with improvement in pain, exercises show significant increase with moderate evidence of medium effect (0.624 [0.194,1.05]; I^2=0%, *p*=0.866). AKPS scores were not reported by Hazneci et al. (45), and Corum et al. (157) showed no improvement (Figure 4.9).

c. Groups with MCID in pain scores analysed according to specific exercise target

Data from PFP groups showing MCID in pain scores indicate significant increase with very limited evidence and medium effect in knee flexors total work after exercises targeting knee (0.592 [0.023,1.161]) and both knee and hip with whole body vibration (0.667 [0.01,1.324]) (Figure 4.9).

4.3.1.3 Muscle flexibility

4.3.1.3.1 Hamstrings

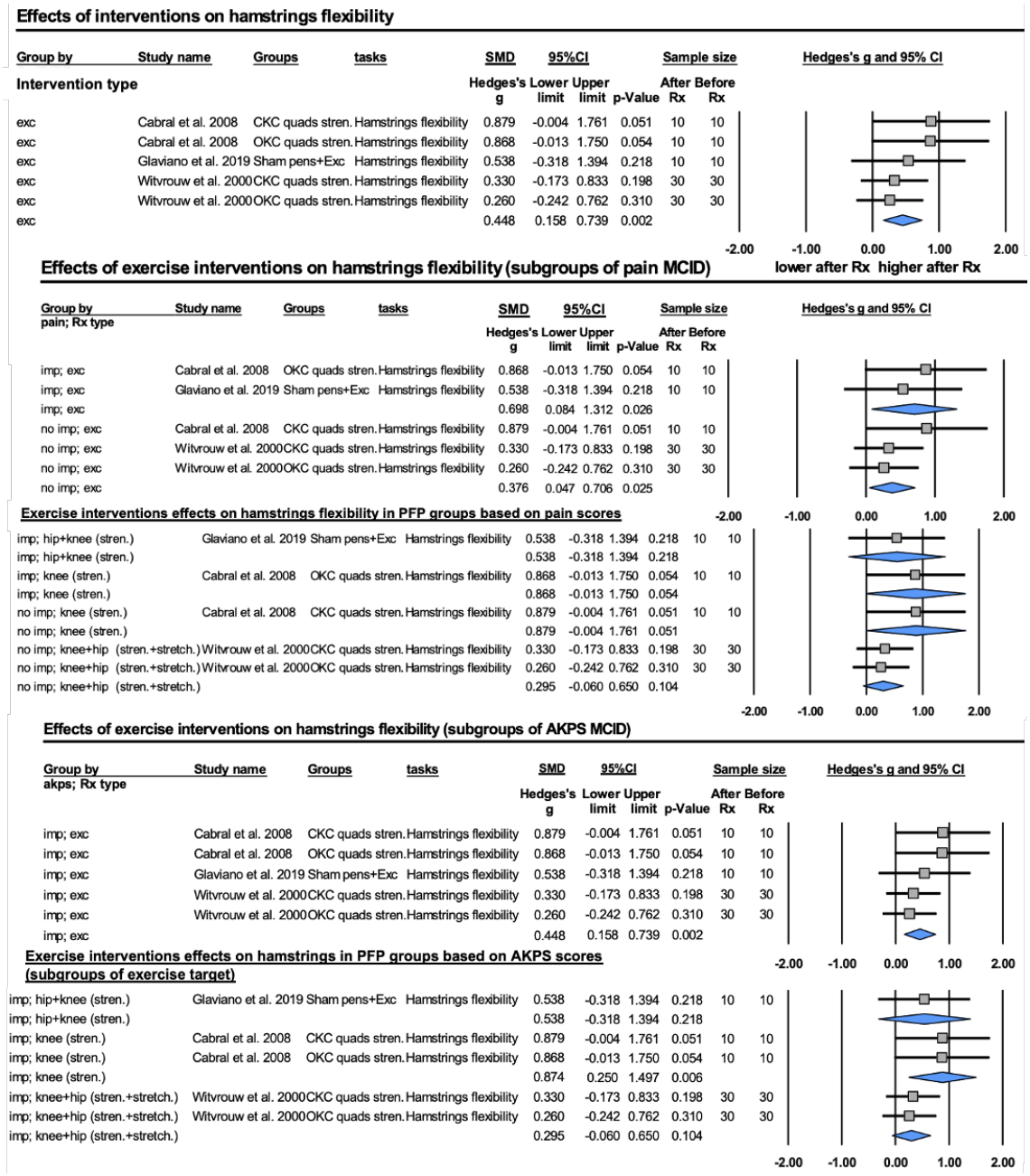


Figure 4.10: Effects of interventions on Hamstrings flexibility. exc; exercise, stim; stimulation, OKC; open kinetic chain, CKC; closed kinetic chain, pens; patterned electrical neuromuscular stimulation.

a. Analysed according to intervention type

Hamstrings flexibility show significant increase with moderate evidence and small effect after exercises (0.448 [0.158,0.739]; I^2=0%, *p*=0.63) (Figure 4.10).

b. Sub-groups of exercise intervention based on MCID of pain and AKPS scores

Moderate evidence with medium effect indicates that exercises cause significant increases in groups showing MCID in pain scores (0.698 [0.084,1.312]; I^2=0%, *p*=0.598). All groups showed MCID in AKPS scores yielding similar results to main plot (significant

increase with moderate evidence and small effect (0.448 [0.158,0.739]; I^2=0%, *p*=0.63)) (Figure 4.10).

c. Groups with MCID in pain and AKPS scores analysed according to specific exercise target

In PFP groups with MCID in pain scores, results indicate no changes in hamstrings flexibility after sham PENS and hip and knee exercise with limited evidence (162) and after knee strengthening with very limited evidence (139). For AKPS, limited (162) and very limited evidence (85) indicate no changes in hamstrings flexibility, and a very limited evidence indicating significant increases with medium effect (0.874 [0.25,1.497]) after closed and open kinetic chain strengthening targeting the knee (139) (Figure 4.10).

4.3.1.3.2 Quadriceps

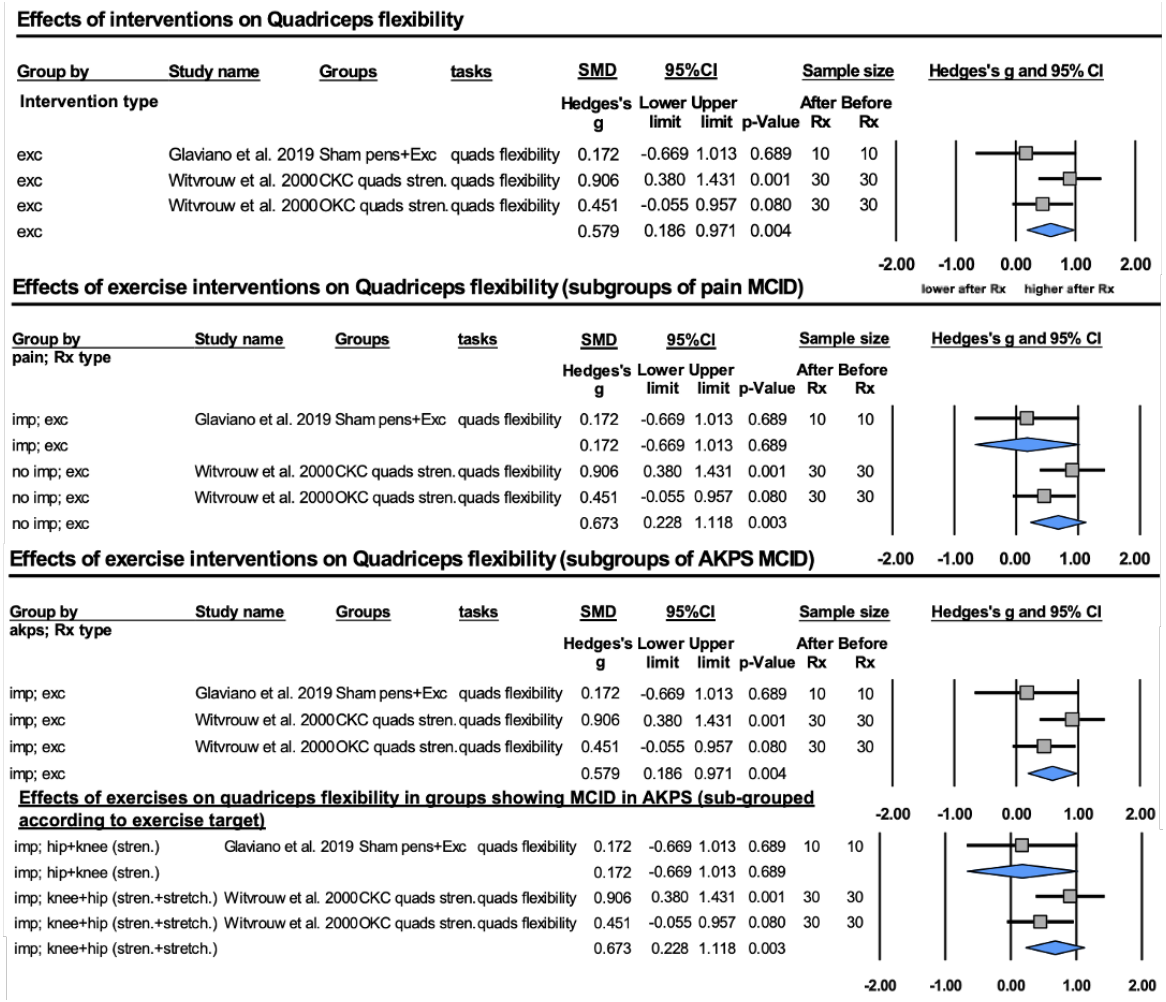


Figure 4.11: Effects of interventions on quadriceps flexibility. exc; exercise, stim; stimulation, OKC; open kinetic chain, CKC; closed kinetic chain, pens; patterned electrical neuromuscular stimulation.

a. Analysed according to intervention type

The effects of interventions on quadriceps flexibility show significant increases after exercises with moderate evidence and small effect (0.579 [0.186,0.971]; I^2=23.84%, *p*=0.269) (Figure 4.11).

b. Sub-groups of exercise intervention based on MCID of pain and AKPS scores

Results show limited evidence indicating no changes in a group showing MCID in pain scores (162). No further sub-analyses performed as results yielded single study data. All groups had improvement in AKPS scores, yielding similar results to the main plot (moderate evidence and small effect (0.579 [0.186,0.971]; I^2=23.84%, *p*=0.269)) (Figure 4.11).

c. Groups with MCID in AKPS scores analysed according to specific exercise target

Both included studies used hip and knee targeted exercises, with one showing no changes with limited evidence (162) and the other showing very limited evidence of significant increases with medium effect (0.673 [0.228,1.11]) (85) (Figure 4.11).

4.3.1.3.3 Iliotibial band

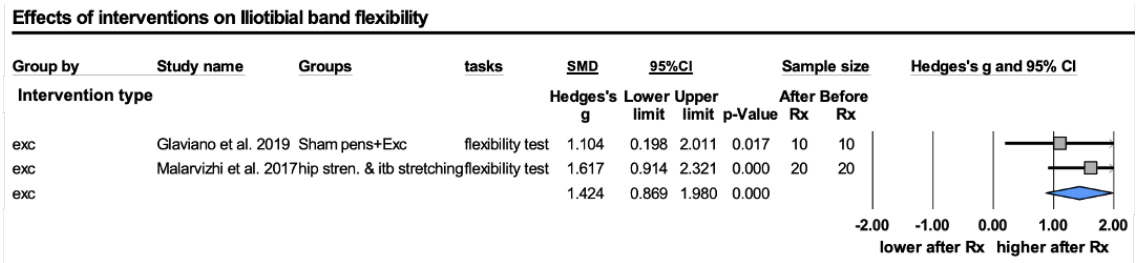


Figure 4.12: Effects of interventions on Iliotibial band flexibility. exc; exercise, pens; patterned electrical neuromuscular stimulation, stren.; strengthening.

Iliotibial band (ITB) flexibility shows significant increase after exercise interventions, with moderate evidence and large effect (1.42 [0.869,1.98]; I^2=0%, *p*=0.381). Same effect is found as both groups showed MCID in pain scores, and only Glaviano et al. (162) reported AKPS scores, showing improvement as well (Figure 4.12).

4.3.1.3.4 Gastrocnemius

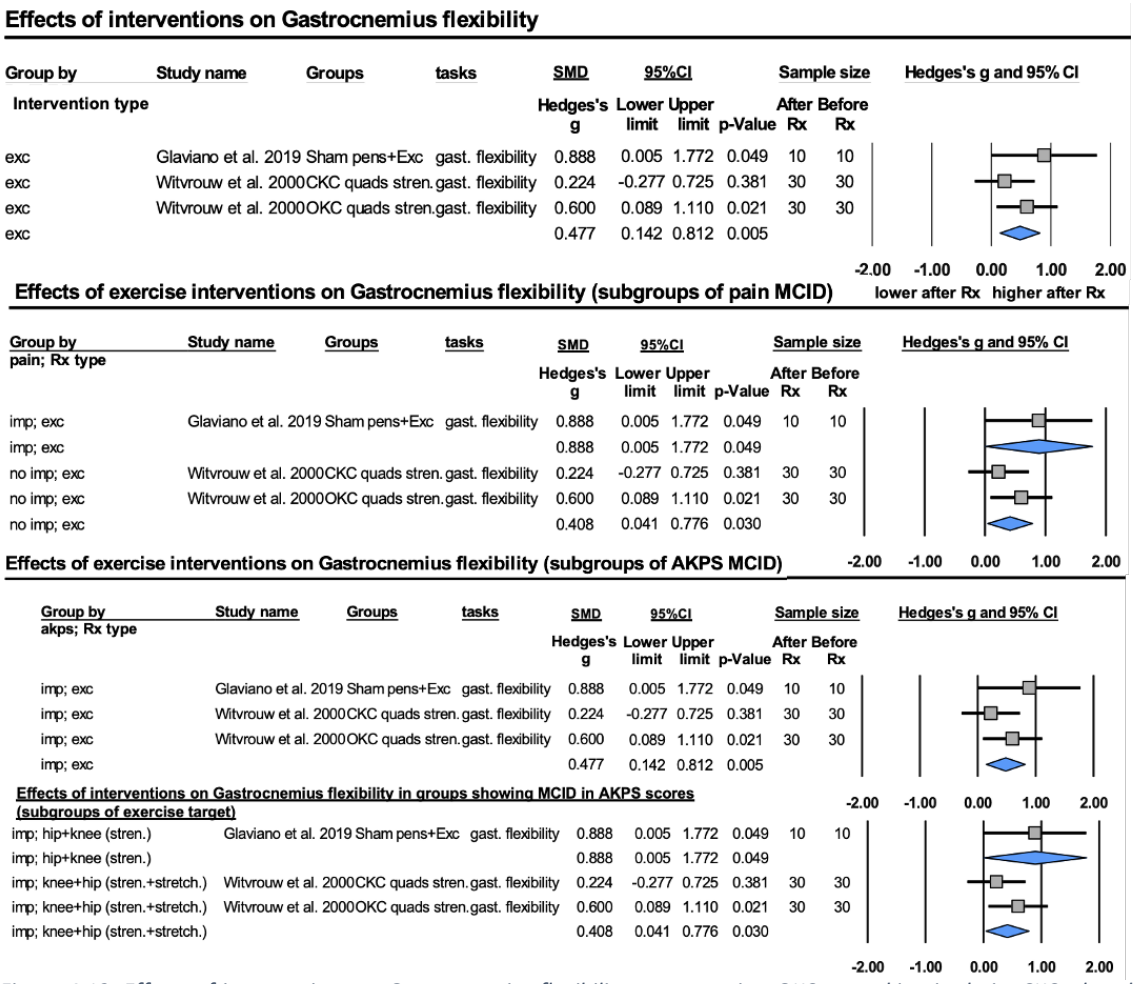


Figure 4.13: Effects of interventions on Gastrocnemius flexibility. exc; exercise, OKC; open kinetic chain, CKC; closed kinetic chain, pens; patterned electrical neuromuscular stimulation

a. Analysed according to intervention type

Gastrocnemius flexibility show significant increase with moderate evidence and small effect (0.477 [0.142,0.812]; I^2=1.6%, *p*=0.362) (Figure 4.13).

b. Sub-groups of exercise intervention based on MCID of pain and AKPS scores

Significant increases are seen with limited evidence and medium effect (0.88 [0.005,1.722]). All arms showed MCID in AKPS scores, yielding the same results of the main plot (significant increase with moderate evidence and small effect (0.477 [0.142,0.812]; I^2=1.6%, *p*=0.362)) (Figure 4.13).

c. Groups with MCID in AKPS scores analysed according to specific exercise target

Sub-group analyses show significant increases after hip and knee targeted exercises, with limited evidence and medium effect (0.88 [0.005,1.722]), and very limited evidence with small effect (0.408 [0.041,0.766]) (Figure 4.13).

4.3.1.4 Summary of meta-analyses results

All results of the meta-analyses were summarised (in tables 4.4 to 4.6). These results incorporate the findings shown previously, as well as the findings of single studies seen in the supplementary file (Appendix 4).

Table 4.4: Results summary of the meta-analyses of interventions' effects on electromyographic outcomes.

Electromyography			
outcomes	task	Results (studies cited)	
VM mean excitation amplitude	seated knee extensions	=	Knee brace (142)
		=	Exercise (139)
		=	Taping (140)
	squatting	=	Exercise (135)
		=	Taping (143)
	stepping and stair negotiations	=	Knee brace (144)
		=	Education (145)
		=	Exercise + education (145)
		=	Foot taping (147)
		=	Orthosis (146)
		=	Retraining (147)
		=	Taping (140)
VL mean excitation amplitude	seated knee extensions	=	Knee brace (142)
		=	Exercise (139)
	in squatting	=	Exercise (135)
		=	Taping (143)
	stepping and stair negotiations	=	Knee brace (144)
		=	Education (145)
		=	Education & exercise (145)
		=	Foot taping (147)
		=	Orthosis (146)
		=	Retraining (147)
	walking and running	=	Knee brace (144)
		=	Retraining (149)
RF mean excitation amplitude	walking and running	=	Knee brace (144)
		=	Retraining (149)
BF mean excitation amplitude	walking and running	=	Knee brace (144)
		=	Retraining (149)

Evidence level	strong	moderate	limited	very limited	conflicting
Effect size	Small ↑	Medium ↑↑	Large ↑↑↑	No change =	

Table 4.5: Results summary of the meta-analyses of interventions' effects on muscle performance and flexibility outcomes. This table shows results of overall pooled effects. Individual studies could have different effects on deficits and the reader is recommended to include the data shown in the forest plots in the interpretations of the results. All results cited with single studies were not included in the forest plots.

Muscle Performance and Flexibility			
Outcomes	muscle group	Results (studies included in the meta-analyses)	
Isometric peak torque	knee extensors	=	Education (145,152)
		↑	Exercise (151–154,162–164,268)
		=	Exercise + education (145)
		=	Exercise + injection (155)
		=	Exercise + stimulation (151,162)
		=	Manipulation/mobilisation (154)
		=	Taping (140)
		=	Wait-and-see (164)
	knee flexors	=	Exercise (162,164)
		=	Exercise + education + taping (163)
		=	Exercise + stimulation (162)
		=	Wait-and-see (164)
Concentric peak torque	knee extensors	↑↑	Exercise (45,157)
		↑↑	Exercise + injection (159)
		↑↑	Exercise + taping (161)
		↑	Taping (156,158,160)
	knee flexors	↑↑	Exercise (45,157)
		↑↑	Exercise + injection (159)
		=	Taping (158)
Total work	knee extensors	↑	Exercise (45,157)
		↑↑	Exercise + injection (159)
		↑	Taping (160)
	knee flexors	↑	Exercise (45,157)
		↑↑	Exercise + injection (159)
Muscle flexibility	Hamstrings	↑	Exercise (85,139,162)
		=	Exercise + stimulation (162)
	Quadriceps	↑	Exercise (85,162)
		↑↑	Exercise + stimulation (162)
	Iliotibial band	↑↑↑	Exercise (162,266)
		=	Exercise + stimulation (162)
	Gastrocnemius	↑	Exercise (85,162)
		=	Exercise + stimulation (162)

Evidence level	strong	moderate	limited	very limited	conflicting
Effect size	Small ↑	Medium ↑↑	Large ↑↑↑	No change =	

Table 4.6: Results within groups that showed interventions with and without possible mechanisms of benefit, by having a minimal clinically important change in pain or Anterior knee pain scale scores, with presence or absence of significant changes in corresponding deficits. AKPS; Anterior Knee Pain Scale.

Patellofemoral pain groups showing minimal clinically important difference in PAIN scores after a specific treatment				
Outcomes	**Strong**	**Moderate**	**Limited**	**Very limited**
Isometric extension peak torque	↑↑ hip+knee streng. (162,268)	= hip streng. (153,164) = knee streng. (153,164)		= hip+knee streng.+stretch. (151) = hip+knee stretch. only (164)
concentric extension peak torque				↑↑ hip+knee streng.+stretch. (157) = knee streng. (45)
Concentric flexion peak torque				↑↑ hip+knee streng.+stretch. (157) = knee streng. (45)
Extension total work				= hip+knee streng.+stretch. (157) = knee streng. (45)
Flexion total work				↑↑ hip+knee streng.+stretch. (157) ↑↑ knee streng. (45)
Hamstrings flexibility			= hip+knee streng. (162)	= knee streng. (139)
Quadriceps flexibility			= hip+knee streng. (162)	
Gastrocnemius flexibility			↑↑ hip+knee streng. (162)	
Iliotibial band flexibility			↑↑↑ hip+knee streng. (162)	↑↑↑ hip streng.+stretch. (266)
Patellofemoral pain groups showing minimal clinically important difference AKPS scores after a specific treatment				
Outcomes	**Strong**	**Moderate**	**Limited**	**Very limited**
Isometric extension peak torque	↑↑ hip+knee streng. (162,268)	= hip streng. (153,164) = knee streng. (153,164)		= hip+knee stretch. only (164)
hamstrings flexibility			= hip+knee streng. (162)	↑↑ knee streng. (139) = hip+knee streng.+stretch. (85)
Quadriceps flexibility			= hip+knee streng. (162)	↑↑ hip+knee streng.+stretch. (85)
Gastrocnemius flexibility			↑↑ hip+knee streng. (162)	↑↑ hip+knee streng.+stretch. (85)
Iliotibial band flexibility			↑↑↑ hip+knee streng. (162)	

4.4 Discussion

This systematic review with meta-analysis aimed to investigate the effects of interventions on local neuromuscular characteristics in people with PFP. Multiple types of interventions have been investigated and have reported change of these local neuromuscular characteristics, representing plausible mechanisms of effects. Differences in reported outcomes, data collection methods and intervention types (Appendix 4) had direct impact on the results of the meta-analysis.

4.4.1 Interventional effects on EMG deficits

A total of 27 different EMG investigations were reported in 19 included studies. The most investigated variables were VM and VL mean excitation amplitudes, which were performed by 16 (135–137,139–147,201,264,267,270) and 14 studies (135–

137,139,141–147,149,264,267), respectively. This is in line with the consensus statement of the PFP retreat by Powers et al. (12) highlighting vasti imbalances as a possible pathway leading to elevated patellofemoral joint stress, therefore, warranting investigation. Contrarily, 18 EMG variables of timing and excitation amplitudes of VM, VL, RF, BF and GM were individually investigated by three studies (138,144,267).

Studies show extensive exploring of EMG characteristics using multiple methods and interventions which causes the results of meta-analyses to be of very limited evidence. As no pooled effects were produced from any EMG investigation, possible reasons are discussed below.

4.4.1.1 The attenuation of EMG findings in PFP literature

Meta-analyses require clinical and methodological homogeneity within included studies to be performed (167), hence the adapted categorisation of tasks and intervention types. This has obvious impact on the results, as unique studies would not be included. Patellofemoral pain is a condition that gained ample EMG exploration in the literature (5,29,31,83,170,176,181). However, the various tasks (and interventions) reported within the EMG domain led to an attenuation of a clear consensus regarding which deficit needs to be changed to improve a patient's condition. Chester et al. (83) published the results of their systematic review in 2008 without presenting pooled effects. This was due to an unexplained heterogeneity, and we suspect that to be due to the variety in studies' methodologies. Lankhorst et al. (81) conducted a systematic review in 2013 on factors associated with PFP. They were able to pool eight variables out of 523, and indicated that EMG findings were provided by single studies. In our review in 2021 (176), we found 53 studies investigating EMG within local muscles, but only two significant pooled effects were obtained out of a total of seven studies (176,178), so this trend remains.

Two EMG deficits were found to be associated with PFP in our previous review (176), one of which was found to be investigated in the current review. Onset timing of VM-VL was investigated in four studies, that showed a MCID in pain scores after knee taping (136), lumbopelvic manipulation (137), open kinetic chain (OKC) exercises (138) and hip abduction exercises (135). The intervention arms receiving taping (136) and hip abduction exercises (135) showed significant changes. However, VM-VL onsets were not significantly different after manipulation (collected in rock task) (137) and

OKC exercises (in knee-jerk reflex) (138) despite the improvement in pain, and both studies had moderate ROB. Mostamand et al. (136) collected VM-VL timing during single-leg squatting. Lima et al. (135) performed two tests to collect VM-VL timing; significant changes were found in squatting with isometric hip abduction, but not in free squatting, and both studies had serious ROB.

These results indicate several points. Firstly, there are weak overlapping between the studies that explored the EMG deficits associated with PFP (176) and the interventional studies that targeted local EMG deficits found in the current systematic review. Secondly, we cannot produce a meta-analysis that can ascertain whether these changes were associated with an improvement, as all used different methods to detect the deficit and reported different results. Thirdly, the significant findings were associated with higher ROB (135,136). Lastly, only one study reported reliability measures and their VM-VL findings were not significant (137). Two explanations are reasonable. It could be that specific subgroups of PFP show specific deficits. This theory was considerably explored by the work of Selfe et al. (272), as some deficits can be used to categorise PFP subgroups to identify treatment targets. However, as the method of detection is different between all four studies, it could mean that the deficit requires a very specific method to be detected, which questions its existence. With all the work of VM-VL timing in PFP, it still requires further research, especially to find a mechanism of effects after interventions.

4.4.1.2 The reproducibility of EMG results

A larger impact preventing a clear consensus to be found is lack of reliability testing and poor methodological details reporting. In a recent systematic review by Bazett-Jones et al. (273), a synthesis of kinematic and kinetic gait characteristics associated with PFP was conducted. Authors indicate that reliability was reported by small proportion of included studies (17%; nine out of 55). Moreover, Bazett-Jones et al. (273) evaluated the reporting of specific biomechanical methods details and their results showed sup-optimal reporting. So, studies of biomechanics in PFP can include poorly reported methods. Objectively addressing these limitations by attempting to produce a reliable deficit-detection protocol based on the reporting quality of investigations' methodologies is needed (presented in Chapters five and six).

Consequently, introducing more testing protocols that might be, partially or collectively poorly reliable, would be avoided (80,274).

To summarise, we were unable to withdraw a well-defined interventional effect on any local EMG deficit, as we could not pool multiple studies together. This was due to methodological differences. In addition, we suspect that a paucity in reporting reliability measures and clarifying EMG-specific methodological elements had major impact in the disagreement between individual studies' findings. This assumption is reasonable especially when studies adapt previous EMG investigations without sufficient reliability establishment.

4.4.2 Interventional effects on local muscles' performance deficits

Most investigations were within muscle performance as 28 of the included studies (n=46) investigated this domain. Multiple pooled results were found, and further analysed to identify associated improvement in pain and function. This review found interventions that can change local strength deficits in PFP.

Muscle performance data were pooled from a total of four types of interventions; exercise, exercise with platelet-rich plasma (PRP) injections, exercise with taping, and taping alone (Table 4.6).

4.4.2.1 Exercise

Our results indicate that exercise intervention can change multiple local strength deficits. Exercises are the most recommended intervention type in PFP research. In a recent well-conducted meta-analysis, Neal et al. (4) investigated interventions' efficacy in all available literature. Six types of interventions were recommended, of which four fully or partially included exercise treatment. Muscle weakness is frequently targeted by exercise prescription guidelines (4,15,275) as it could lead to or exist with PFP (29,31,81,176). For knee extensors, our results indicate that exercise can increase isometric and concentric peak torques, and total work (strong and moderate evidence). For the knee flexors, exercise increases concentric peak torque and total work (moderate evidence). The results of our previous review recommends deficits of maximal extensors and flexors strength in PFP to be detected using isometric peak torque and total work (for extensors) and concentric peak torque tests (for both) (176). It also recommends testing eccentric peak torque and rate of torque development (RTD). Due to lack of agreement between case-control (176) and

interventional studies (this chapter), eccentrics and RTD were not within current findings.

When analysed according to pain and function improvement, a clearer guidance on interventions can be presented. Pooled effect from two high quality studies showed that a four-weeks hip and knee targeted exercise programme can significantly increase isometric peak torque in PFP groups that showed MCID in pain and function (162,268). In their guidelines paper, Willy et al. (15) found strong evidence that supports exercise therapy, specifically, hip and knee targeted exercise programmes to improve patients' symptoms and functional levels. Hip and knee targeted exercises have been previously found to be of optimal superiority in treating PFP (4). It is important to note that both studies (162,268) used different angles to measure isometric peak torque (60° and 90°). However, this supports the use of isometric peak torque to detect strength increases as patients show improvement in pain and function.

4.4.2.2 Taping

Moderate evidence indicates that taping increases concentric extensors peak torque (156,158,160). Taping did not increase flexors concentric peak torque in one study with serious ROB (158). Regardless of ROB, this could be due to targeting the anterior structures of the knee with the taping techniques (156,158,160). However, as concentric flexors peak torque is a deficit associated with PFP (176), we have very limited evidence suggesting that knee taping alone cannot change this deficit.

When data were sub-grouped according to PFP symptoms improvement, pooled effects showed the increases in concentric strength to be in groups with no MCIDs. The studies producing the significant pooled effect of extensors concentric peak torque were all studies investigating the immediate effects of taping in one session (156,158,160). Similarly, Osorio et al. (160) showed that taping increases extensors total work (low ROB; limited evidence). The reported changes were not associated with a MCID in pain. Willy et al. (15) recommended taping to be used to acutely improve patients' symptoms and enhance exercise outcomes. This indicates a possible immediate mechanism of effect of taping (in changing a specific strength deficit), further supporting its use in combination with exercise and not alone. This was investigated in one study (161). Paoloni et al. (161) Exercise with taping increases

concentric peak torque and was associated with significant pain and function improvement (serious ROB; very limited evidence).

4.4.2.3 Exercise with PRP injections

One study showed increases in extensors and flexors concentric peak torque and total work after exercise combined with PRP injections (159). As the study showed high ROB, scored 0% in CERT, and did not investigate PRP injections against exercise alone, these results should be treated with caution. Evidence supporting the use of PRP injections in musculoskeletal injuries is variable (276), and is not sufficiently investigated in PFP.

4.4.3 Effects of interventions on muscle flexibility

Exercise increases flexibility of hamstrings (85,139,162), quadriceps (85,162), iliotibial-band (162,266) and gastrocnemius muscles (85,162), all with moderate evidence. All these structures can be targeted in PFP, and are used to identify hypomobile patients subcategories (15). However, there are variations when data were analysed according to MCIDs in pain or function.

In groups showing MCID in pain, the gastrocnemius and iliotibial-band (ITB) showed significant increases after hip and knee exercise (162), but only ITB after hip targeted exercises (266) (limited and very limited evidence, respectively). With MCID in functional levels, limited evidence indicates significant increases in ITB after hip and knee targeted exercise (162). Very limited evidence indicate that a group received knee exercises had increased hamstrings flexibility (139). A similar evidence level shows increased quadriceps and gastrocnemius flexibility after PFP groups had hip and knee targeted exercises (85). Tightness in all investigated structures can have implications to the function of the patellofemoral joint. In hamstrings and quadriceps, tightness might lead to heightened patellofemoral joint forces by the higher quadriceps forces counteracting the resistance of tighter hamstrings (12,123,239). Tightness in ITB can have direct anatomical effects increasing lateral patellar movement through the lateral retinaculum (82), and gastrocnemius has indirect implications on patellar misalignment and maltracking through increased femoral internal rotation (12).

Our review presents possible interventions that can improve pain and/or function in patients with hypomobility impairments. Interventions are mainly exercises that target

hip and/or the knee. Clinicians are encouraged to assess these impairments and individualise interventions accordingly.

4.4.4 Reporting quality of exercise interventions

It was expected from the results to be revolving around exercise interventions. Therefore, the reporting quality of these interventions was assessed. Using CERT, 28 exercise programmes were assessed, and scores average was 10.2/19 (54%). Scores varied from 0% (159) to 95% (163). There are no guidelines to a score-threshold for reproducibility, but 18 studies scored more than 50% (85,86,135,138,145,151–153,161–164,260,262,265,268–270), from those, seven studies scored above 75% (153,162,163,265,268–270). Similar poor reporting findings were identified previously in PFP (89). Studies that showed effects associated with improvement in pain or function (table 4.6) had variable scores. Based on their CERT scores, the programmes that can increase isometric peak torque and gastrocnemius and ITB flexibility, and improve pain and function are the most reproducible (162,268), with scores of 75% and 79%. Both studies used a four-weeks (12 sessions) hip and knee targeted exercise programme and formed strong evidence. Another hip and knee exercise programme increased quadriceps and gastrocnemius flexibility in a group that showed improvement in function formed very limited evidence and scored 53%. Based on the results of our meta-analysis, these programmes are most supported as interventions that can show mechanisms of benefit through local strength deficits.

4.4.5 Limitations and recommendations

This review was specific to local neuromuscular characteristics, and the results should be interpreted accordingly. We used pain and AKPS to identify possible mechanisms of benefits. Inclusion of other patient-reported outcomes (PROMS) could have enhanced the results, like PFP subscale of Knee injury and Osteoarthritis Outcome Score (KOOS-PF) or Eng and Pierrynowski Questionnaire (EPQ) (15). Moreover, we did not include psychological measures (179) which can further enhance our results about associated improvement in PFP (98).

The improved strength in our results were in studies that mainly used dynamic exercise interventions. So, there are clear differences between knee loading that was required for testing and intervening, especially for isometric testing. Isometric testing is common as tools to perform the test, like strain gauges, cable tensiometers, and

hand-held dynamometers are obtainable (IKD excluded) (277,278). One of the advantages of isometric tests is that clinicians can use it to avoid specific painful ROM (279). The International Patellofemoral Pain Retreat (IPFRN) published guidelines for clinicians about exercise therapy. The guidelines recommend avoiding 0-45° angles in early PFP phases during open kinetic chain exercises as this could induce pain flares and lateral patellar maltracking (275). A disadvantage of isometric strength is its specificity to the same angle people get tested and exercise at (277). The American Society of Exercise Physiologists (ASEP) recommends using isotonic contractions (fixed resistance, not speed) to be used to evaluate the strength of a muscle group (277). None of the included studies used isotonic contractions to evaluate strength. Therefore, isotonic tests require further research in PFP, as it has been used in research of other knee conditions (280–282). This impacts the evaluation of improvement in overall strength, if overall strength was targeted. The ability of exercises to improve strength is well-known (283), so the strength type that an intervention targets should be based on patients preferences, status or activity types/levels.

In a Cochrane review by Van der Heijden et al. (173,252), attaining agreement regarding diagnostic criteria and measured outcomes was recommended. Within muscle performance only, we found 30 different variables investigated (table 4.4) and the majority was performed by single studies. For instance, two studies investigated concentric peak torque ratios between hamstrings and quadriceps using IKD (157,158). One study reported it as Hamstrings/Quadriceps and the other reported it as agonist/antagonist. They were not pooled due to differing interventions, but the way data was reported prevents pooling even if interventions were similar. Within knee extensors alone, torque investigations were differing in angles (isometric at 30°, 60° and 90°) and speeds (at 60°, 180°, 240° and 300°/second (concentric)), and these parameters are rarely justified. Being most recent, our previous review found that both concentric and isometric peak torques are lower in PFP (176). In table 4.3, we highlighted the variables that were included in our review of deficits associated with PFP, and the overlap is weak. Studies that aim to identify a mechanism of benefit through local deficits should do so by investigating deficits that demonstrate association with PFP across multiple studies. Therefore, presenting justifications for

the choices of investigation types, probably based on biomechanical reasons, is recommended in future studies.

4.5 Conclusion

Our synthesis of available PFP research showed narrower coverage of interventional studies that investigated the changes of local neuromuscular deficits compared to case-controls that identified these deficits. The results indicate that changes can occur by exercises that target the hip and knee, and taping to be used in combination with exercise. The changes were limited to muscle performance and flexibility deficits. Highest obtained evidence indicates that improvement in PFP can be seen with increases in extensors isometric peak and gastrocnemius and hamstrings flexibility after four-weeks of hip and knee exercises.

5 Building and developing a neuromuscular deficits' detection laboratory protocol

In this Chapter, we aimed to derive a testing protocol based on the results of the meta-analysis presented in Chapter three, that could detect the neuromuscular deficits associated with PFP. A robust approach to achieve the aim was needed to ensure that our testing protocol has the best possibility to detect these deficits. We developed an assessment tool to identify the highest quality, reproducible method for deficit detection from within studies included in the systematic review (Chapter three). The outcomes of this Chapter were the production of a battery of tests that formed the basis for Chapter six. Also, tools to assess the reporting quality of EMG, muscle performance and muscle flexibility testing procedures were created.

5.1 Introduction

There is a lack of clarity in the evidence around local neuromuscular characteristics in PFP (12), which could be due to methodological inconsistency. To address such inconsistencies, a reliable testing protocol that can be used to monitor changes in these characteristics, that is objectively informed by current evidence of highest levels, was needed.

Testing protocols can be developed through a subjective approach of reviewing the literature and the physiological or biomechanical targets that are needed to be evaluated (284). This includes participants' tasks and positioning, signal analyses specifications and general laboratory setting. Due to the way data were categorised for the meta-analyses in Chapter three, we can identify tasks during which data collection could be performed (e.g., stepping and stair negotiations if VM-VL onsets to be investigated). However, the other aspects of the required protocol (equipment, signal analyses, repetitions, etc) cannot be determined without extensive assessment of the methods from studies that formed the meta-analyses. Meta-analyses represent the highest levels of evidence (99), and in Chapter three, the local deficits that are associated with PFP were identified through a meta-analysis (176). Therefore, a unique, objective approach to determine test positions, signal analyses specifications and laboratory setting was performed in this Chapter to identify a laboratory protocol using current literature and minimise methodological inconsistencies.

The aim is to produce a lab study exclusively from the meta-analysed local neuromuscular assessment methodologies. The objective is to assess the tests performed by the studies included in the meta-analyses from Chapter three and choose the most reproducible methods. This will provide the thesis with a lab protocol with empirical basis that predominantly relates to available literature in the field. The resultant battery of tests can be used to identify mechanisms of benefit for interventions in PFP in future.

5.2 Methods

5.2.1 Approach v 1.0

The initial attempt was predominately based on extracting protocols out of studies from meta-analyses that showed significant pooled effects between PFP and uninjured

groups. This process was based on the overall effect size and quality of studies according to the Newcastle-Ottawa scale (NOS) (Figure 5.1).

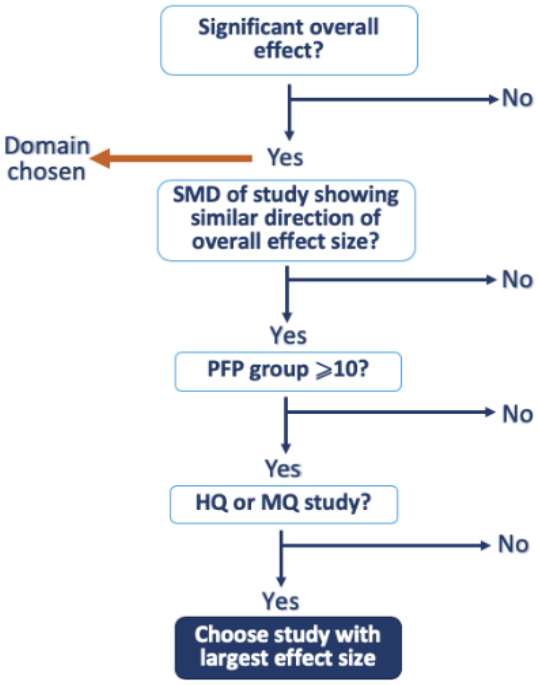


Figure 5.1: The process used the approach v 1.0 to adapt methodologies of detection of neuromuscular deficits associated with PFP. The domain would be the outcome measure. SMD; standardised mean difference, HQ and MQ; high and medium quality.

5.2.1.1 Weaknesses of approach v 1.0

Multiple limitations can be addressed:

1. Some meta-analyses contained LQ studies, increasing the chance of choosing to investigate a deficit based on possibly biased results.
2. Newcastle-Ottawa scale focuses on design, sampling and recruitment of the studies assessed. The decision of extracting methodologies based on quality assessment, effect size and direction might lack the precision in identifying accurate and well-specified experimental protocols.

Therefore, a more rigorous process to translate meta-analyses results into an applicable experimental protocol was needed.

5.2.2 Approach v 2.0

The weaknesses identified in v 1.0 were mainly from methodological aspects of the included studies. Approach v 2.0 aims to target these weaknesses. An experimental protocol with the best chance of detecting local neuromuscular deficits that are associated with PFP was built based on the multiple steps described below.

5.2.2.1 Meta-analyses with significant results from studies with lowest risk of bias (HQ and MQ studies only)

The NOS scale was designed through a Delphi process to assess group selection, comparability, and ascertainment (285). So, any HQ and MQ studies from the review are potentially of good quality within the specific domains that are assessed by the NOS scale. The meta-analyses were further modified by excluding LQ studies for two reasons:

1- After piloting the exclusion of LQ studies, many meta-analyses were maintained in the results, as the review contained 67 studies, larger than other reviews in the same field (81,83,182), and 27 meta-analyses remained.
2- Minimising the effects of LQ studies on the pooled effects, resulting in more robust evidence regarding deficits that are associated with PFP.

Being based on HQ and MQ studies, we can maximise the reproducibility of the resultant protocol. Obviously, this was applied to significant pooled effects that indicated that these deficits are frequently found in people with PFP.

5.2.2.2 Deficits detected with testing protocols of highest quality

The quality assessment (NOS) performed within the review does not assess the specific practical aspects of studies' methodologies (i.e. EMG, muscle performance and flexibility tests). So, deriving a practical laboratory protocol required assessing these aspects. Many guidelines can be found either through text books (284,286–289) or dedicated organisations' websites and publications (290–294). No assessment tools with clear scoring to determine the reporting quality of testing procedures were found. There are assessment tools that can be used to determine the reporting quality of exercise interventions, but not for muscle performance testing (294,295).

Therefore, multiple assessment tools were developed based on published guidelines (286,289,294–296), targeting the testing protocols of studies included in the meta-analyses. Sufficient reporting was considered with scores of $\geq$70% in corresponding assessment tools (EMG, muscle performance or flexibility protocols assessment) (tables 5.1, 5.2 and 5.3).

5.2.2.3 Deficits from a study showing the largest effect size (in same direction of overall effect).

The last part of the process is to choose the methods from studies that showed largest effect. This solves the issue of having multiple studies that have sufficient reporting, and includes a protocol with increased chance of detecting a deficit (due to the larger effect). Figure 5.2 summarises the approach, which was executed in three steps:

1. Low quality studies were removed from the meta-analysis.
2. Rating scales for EMG, muscle performance and muscle flexibility testing protocols were built.
3. These rating scales were used to assess the reporting quality of methods for all studies in each plot, and highest scores with largest effect sizes were extracted.

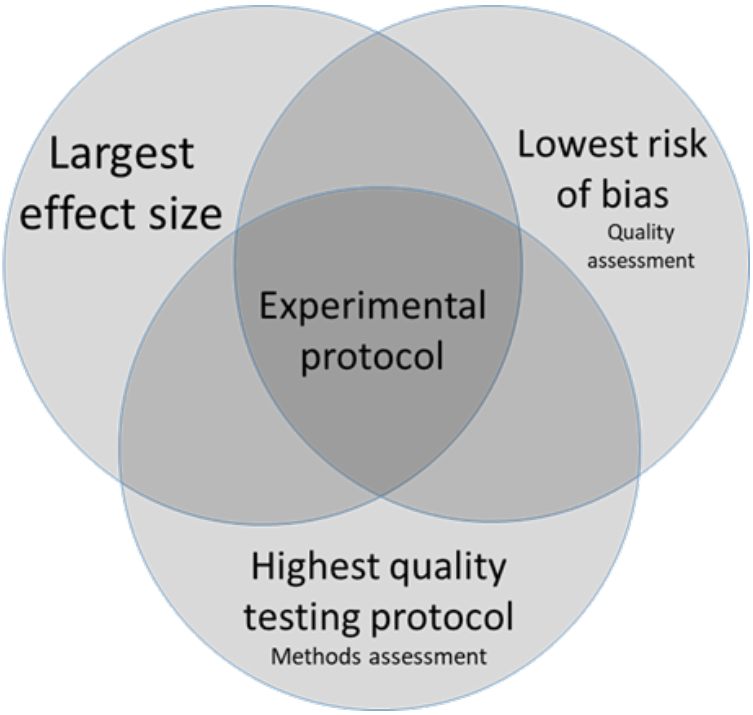


Figure 5.2: A diagram to summarise the methods development procedure.

Table 5.1: Rating scale to assess EMG testing protocols.

item	Criterion	**Decision rule** (derived from Merletti and di Torino 1999 (296) and Winter et al. 2009 (286))
Equipment		**Scoring**
1	EMG equipment description	(1) The number, brand, and model of the equipment is provided (0) No or poor description provided
2	Electrode size, material and shape	(1) size, material and shape described (0) poor description provided
Attachment set-up		
1	Skin preparation and interelectrode distance	(1) skin preparation and interelectrode space clearly mentioned (0) 1 aspect missing or poor description provided
2	position and orientation on each muscle	(2) The position of electrode is clearly defined (with respect to motor points and/or muscle fibers) and referenced. (1) reference mentioned only (or not very clear) (0) none or poor description
Data collection		
1	skin impedance checked	(1) checked and reported (0) not mentioned
2	Detection mode specifications	(2) detection mode type (monopolar, differential, double differential, etc), Common mode rejection ratio, Signal-to-noise ratio (SNR) and Actual gain range reported (1) at least 2 out of 4 reported (0) no or poor reporting
3	Normalisation	(1) sufficiently described (reproducible) (0) poor description
4	Task/exercise description	(1) detailed task description (# of trials, # of conditions, rest/days between trials/conditions, etc.) (0) No or poor description provided
5	Sampling rate	(1) The sampling rate reported for all measurements (0) No or poor description provided
Data processing		
1	Built in filtering	(1) mentioned whether it exists or not. (0) nothing mentioned
2	Filter types and frequencies mentioned	(2) types and freq. mentioned (i.e. Butterworth, Chebyshev, etc) and low and/or high pass cut-off limits used (1) only type or freq. (0) No or poor description provided
3	Rectification	(1) full or half-wave rectification reported (and reason if not rectified) with type of signal used to interpret data (RMS, LE, etc(if applicable)) (0) No or poor description provided
4	Use of kinematics to designate correct EMG detection (if not applicable, skip and decrease total by 2 from all categories)	(2) 3D motion or force plates used to define point of data collection (1) other means used with sufficient justification (2D, synced time points, etc) (0) poor description
Data Reporting		
1	Variables	(1) Variable adequately described, including time point and units (i.e. peak amplitude mv during stance phase=reproducible) (0) Only variable or time point described, or poor description provided
2	Reliability & error	(2) Lab specific measurement reliability and/or standard error reported (performed by same authors) (1) Reliability mentioned using citation (0) No or poor description provided
3	Outcome	(1) Outcomes are described in a way that can be replicated (i.e. negative onset means VM earlier (or later) than VL in onset ratios) (0) No or poor description provided
Total		out of 21 (we used percentage cut-off of 70%)

Table 5.2: Rating scale to assess muscle performance testing protocols

item	Criterion	Decision rule (derived from TIDier (295) and Toigo and Boutellier (294) assessments' criteria)
Test setting and preparation		**Scoring**
1	Equipment used	(1) details to identify the tools are provided (brand, model, etc) (0) No or poor description provided
2	Testing position description (exercise form and ROM)	(2) clearly described with illustrations (1) description without illustrations (0) poor description
3	Protocol/test choice	(1) choice sufficiently justified (0) no details
4	Activity levels consideration	(1) were considered (i.e. no differences between groups in baseline) (0) no description
5	Warm-up	(1) described and justifies (0) no or poor description
Data collection		
1	Sets, Reps, time under tension and rest periods description	(1) Sets, Reps, time under tension and rest periods are clearly reported (0) missing aspects or poor description preventing proper reproducibility
2	Data normalisation	(1) proper normalisation made (0) reported as raw data
3	Level of pain during test	(1) collection of pain levels during tests was done (0) no description
4	Order of tests (if more than 1 test)	(1) description provided (did they show that all participants had same level of fatigue before testing? i.e. if different tests of the same muscle were done, was it randomised or not? and why?) (0) no description
5	Recovery time (did they rest sufficiently? Especially if multiple tests were performed during the session)	(1) reported (0) poor description
Data Reporting		
6	Reliability & error	(2) Lab specific measurement reliability and standard error reported (1) Reliability and/or standard error are reported (using citation) (0) No or poor description provided
7	Variables and outcomes	(1) Variables and outcomes are described in a way that can be replicated (i.e. peak torque of isometric knee extension at 60° in Nm) (0) No or poor description provided
Total		Out of 14 (we used percentage cut-off of 70%)

Table 5.3: Rating scale to assess muscle flexibility testing protocols:

item	Criterion	**Decision rule** (No clear guidelines found, but domains were derived from Reese and Bandy 2013 (289))
Equipment		**Scoring**
1	Type of measurement tool	(1) details to identify the tool are provided (0) No or poor description provided
2	Landmarks description	(1) alignment landmarks are provided (tested angle clearly defined) (0) No or poor description provided
Data collection		
1	Participants positioning	(2) Participant positioning clearly mentioned (with reference) and proximal and distal joint contributions considered. (1) Only reference or brief description (0) No or poor description provided
Data reporting		
1	Variables and outcomes	(1) Variables and outcomes are described in a way that can be replicated (i.e. popliteal angle vs knee flexion angle (reader can quickly address the zero angle) (0) No or poor description provided
2	Reliability & error	(2) Lab specific measurement reliability and standard error reported (1) Reliability and/or standard error are reported (using citation) (0) No or poor description provided
Total		out of 7 (we used percentage cut-off of 70%)

5.3 Results

5.3.1 Methods scoring:

Tables 5.4 to 5.12 show the scores of each study after applying the developed assessment tools. Each table contains studies from meta-analyses with significant pooled effects.

Table 5.4: Scoring investigations to extract Vastus Medialis/Vastus lateralis excitation onset detection/analysis methods.

study		Briani et al. 2016 (HQ)	Crossley et al. 2004 (MQ)	Rathleff et al. 2013 (MQ)	McClinton et al. 2007 (MQ)	Bolgla et al. 2011 (MQ)
Task (stepping and stair negotiations)		Stair ascent	Stair up/down	Stair descent	step-up (5 heights)	stair ascent/ descent
EMG equipment description	EMG equipment description (out of 1)	1	0	0	0	1
	Electrode size, material and shape (out of 1)	1	0	0	0	1
Attachment setup	skin prep. and interelectrode distance (out of 1)	0	1	1	0	1
	position and orientation on each muscle (out of 2)	2	2	1	1	1
Data Collection	Skin impedance (out of 1)	0	0	0	0	0
	Detection mode specifications (out of 2)	1	0	0	1	0
	Normalisation (out of 1)	Na	na	na	Na	Na
	Task description (out of 1)	1	1	1	1	1
	sampling rate (out of 1)	1	1	1	1	1
Data processing	Built-in filtering (out of 1)	1	1	1	1	1
	Filter types and frequencies (out of 2)	2	1	2	2	1
	Rectification and noise reduction (out of 1)	1	1	1	1	1
	Use of kinematics to designate EMG detection (out of 2)	2	1	1	2	2
Data reporting	Reliability and error (out of 2)	0	1	1	1	2
	Variables description (out of 1)	1	1	1	1	1
	Outcome description (out of 1)	1	1	1	1	1
Total score (out of 21)		**15**	**12**	**12**	**13**	**15**
NA fields (subtracted from 21)		1	1	1	1	1
Score % (score/(21-NA))		**75**	**60**	**60**	**65**	**75**

Table 5.5: Scoring investigations to extract Biceps Femoris mean excitation amplitude detection/analysis methods.

study		Bley et al. 2014	Kalytczak et al. 2016 (HQ)
task (Single-leg triple-hop test)		Single-leg triple-hop test	
EMG equipment description	EMG equipment description (out of 1)	0	1
	Electrode size, material and shape (out of 1)	1	1
Attachment setup	skin prep. and interelectrode distance (out of 1)	1	0
	position and orientation on each muscle (out of 2)	2	1
Data Collection	Skin impedance (out of 1)	0	0
	Detection mode specifications (out of 2)	2	2
	Normalisation (out of 1)	1	1
	Task description (out of 1)	1	1
	sampling rate (out of 1)	1	1
Data processing	Built-in filtering (out of 1)	0	0
	Filter types and frequencies (out of 2)	2	2
	Rectification and noise reduction (out of 1)	1	1
	Use of kinematics to designate EMG detection (out of 2)	2	2
Data reporting	Reliability and error (out of 2)	0	0
	Variables description (out of 1)	1	1
	Outcome description (out of 1)	1	1
	Total score (out of 21)	**16**	**15**
	NA fields (subtracted from 21)	0	0
	Score % (score/(21-NA))	**76.2**	**71.4**

Table 5.6: Scoring investigations to extract Vastus Medialis Hoffman-reflex detection/analysis methods.

Study		Pazzinato et al. 2018 (HQ)	de Oliveira Silva et al. 2016
task (stimulation in supine lying position)		Hoffman-reflex/maximum M-wave	
EMG equipment description	EMG equipment description (out of 1)	1	1
	Electrode size, material and shape (out of 1)	1	1
Attachment setup	skin prep. and interelectrode distance (out of 1)	0	0
	position and orientation on each muscle (out of 2)	1	1
Data Collection	Skin impedance (out of 1)	0	0
	Detection mode specifications (out of 2)	1	1
	Normalisation (out of 1)	1	1
	Task description (out of 1)	1	1
	sampling rate (out of 1)	1	1
Data processing	Built-in filtering (out of 1)	0	1
	Filter types and frequencies (out of 2)	0	1
	Rectification and noise reduction (out of 1)	1	1
	Use of kinematics to designate EMG detection (out of 2)	na	na
Data reporting	Reliability and error (out of 2)	0	0
	Variables description (out of 1)	1	1
	Outcome description (out of 1)	1	1
	Total score (out of 21)	**10**	**12**
	NA fields (subtracted from 21)	2	2
	Score % (score/(21-NA))	**52.6**	**63.2**

Table 5.7: Scoring investigations to extract isometric knee extension peak torque detection/analysis methods.

Study		keet et al. 2007 (HQ)	Rathleff et al. 2013	Gallina et al. 2018	de Oliveira Silva et al. 2018	Carvalho-e-silva et al. 2016	Bolgla et al. 2015 (HQ)	Bolgla et al. 2011	Stensdotter et al. 2007 (HQ)	Briani et al. 2018 (HQ)	Ferreira 2019a (HQ)
Task (knee extensors torque tests)		Isometric knee extension peak torque									
test setting and preparation	Equipment used (out of 1)	1	1	1	1	1	1	1	1	1	1
	Testing position description (exercise form and ROM) (out of 2)	1	1	1	1	0	2	2	2	2	2
	Protocol/test choice (out of 1)	1	1	1	1	1	1	1	1	1	1
	Activity levels consideration (out of 1)	1	0	1	0	0	1	0	0	0	1
	warm-up (out of 1)	na	na	na	na	na	na	na	na	na	Na
Data collection	Sets, Reps, time under tension and rest periods description (out of 1)	1	1	1	1	1	1	1	1	1	1
	Data normalisation (out of 1)	0	1	1	1	1	1	1	0	1	1
	Level of pain during test (out of 1)	1	0	0	0	0	0	0	0	0	0
	Order of tests (if more than 1 test) (out of 1)	na	na	na	na	na	na	na	na	na	Na
	Recovery time before test (out of 1)	0	1	0	1	1	1	1	1	1	1
Data reporting	reliability & error (out of 2)	0	0	1	0	1	1	1	0	0	2
	Variables and outcomes (out of 1)	1	1	1	1	0	1	1	1	1	1
Total score (out of 14)		**7**	**7**	**8**	**7**	**6**	**10**	**9**	**7**	**8**	**11**
NA fields (subtracted from 14)		2	2	2	2	2	2	2	2	2	2
Score % (score/(14-NA))		**58.3**	**58.3**	**66.7**	**58.3**	**50.0**	**83.3**	**75.0**	**58.3**	**66.7**	**91.7**

Table 5.8: Scoring investigations to extract concentric knee extension peak torque detection/analysis methods.

Study		keet et al. 2007 (HQ)	Hazneci et al. 2005	de Oliveira Silva et al. 2018	Duffey et al. 2000	Ferreira 2019b (HQ)
Task (knee extensors torque tests)		Concentric knee extension peak torque				
test setting and preparation	Equipment used (out of 1)	1	1	1	1	1
	Testing position description (exercise form and ROM) (out of 2)	1	0	1	0	1
	Protocol/test choice (out of 1)	1	1	1	1	1
	Activity levels consideration (out of 1)	1	1	0	1	1
	warm-up (out of 1)	1	1	0	1	1
Data collection	Sets, Reps, time under tension and rest periods description (out of 1)	1	1	1	1	1
	Data normalisation (out of 1)	0	0	1	1	1
	Level of pain during test (out of 1)	1	1	0	0	0
	Order of tests (if more than 1 test) (out of 1)	1	1	1	1	1
	Recovery time before test (out of 1)	1	1	1	0	1
Data reporting	reliability & error (out of 2)	0	0	0	0	1
	Variables and outcomes (out of 1)	1	1	1	1	1
Total score (out of 14)		**10**	**9**	**8**	**8**	**11**
NA fields (subtracted from 14)		0	0	0	0	0
Score % (score/(14-NA))		**71.4**	**64.3**	**57.1**	**57.1**	**78.6**

Table 5.9: Scoring investigations to extract eccentric knee extension peak torque detection/analysis methods.

Study		keet et al. 2007 (HQ)	de Oliveira Silva et al. 2018	Ferreira 2019b (HQ)
Task (knee extensors torque tests)		Eccentric knee extension peak torque		
test setting and preparation	Equipment used (out of 1)	1	1	1
	Testing position description (exercise form and ROM) (out of 2)	1	1	1
	Protocol/test choice (out of 1)	1	1	1
	Activity levels consideration (out of 1)	1	0	1
	warm-up (out of 1)	1	0	1
Data collection	Sets, Reps, time under tension and rest periods description (out of 1)	1	1	1
	Data normalisation (out of 1)	0	1	1
	Level of pain during test (out of 1)	1	0	0
	Order of tests (if more than 1 test) (out of 1)	1	1	1
	Recovery time before test (out of 1)	1	1	1
Data reporting	reliability & error (out of 2)	0	0	1
	Variables and outcomes (out of 1)	1	1	1
Total score (out of 14)		**10**	**8**	**11**
NA fields (subtracted from 14)		0	0	0
Score % (score/(14-NA))		**71.4**	**57.1**	**78.6**

Table 5.10: Scoring investigations to extract concentric knee flexion peak torque, extension, and flexion total work detection/analysis methods.

Study		Hazneci et al. 2005	Duffey et al. 2000
Task (knee flexors and extensors torque tests)		Concentric flexion peak torque, extension total work, flexion total work	
test setting and preparation	Equipment used (out of 1)	1	1
	Testing position description (exercise form and ROM) (out of 2)	0	0
	Protocol/test choice (out of 1)	1	1
	Activity levels consideration (out of 1)	1	1
	warm-up (out of 1)	1	1
Data collection	Sets, Reps, time under tension and rest periods description (out of 1)	1	1
	Data normalisation (out of 1)	0	1
	Level of pain during test (out of 1)	1	0
	Order of tests (if more than 1 test) (out of 1)	1	1
	Recovery time before test (out of 1)	1	0
Data reporting	reliability & error (out of 2)	0	0
	Variables and outcomes (out of 1)	1	1
Total score (out of 14)		**9**	**8**
NA fields (subtracted from 14)		0	0
Score % (score/(14-NA))		**64.3**	**57.1**

Table 5.11: Scoring investigations to extract rate of torque development detection/analysis methods.

Study		Nunes et al. 2020	Ferreira et al. 2019b
Task (knee extensors torque tests)		Rate of torque development (to 30%, 60% and 90% of peak)	
test setting and preparation	Equipment used (out of 1)	1	1
	Testing position description (exercise form and ROM) (out of 2)	2	2
	Protocol/test choice (out of 1)	1	1
	Activity levels consideration (out of 1)	1	1
	warm-up (out of 1)	0	1
Data collection	Sets, Reps, time under tension and rest periods description (out of 1)	1	1
	Data normalisation (out of 1)	1	1
	Level of pain during test (out of 1)	0	0
	Order of tests (if more than 1 test) (out of 1)	0	1
	Recovery time before test (out of 1)	1	1
Data reporting	reliability & error (out of 2)	2	2
	Variables and outcomes (out of 1)	1	1
	Total score (out of 14)	**11**	**13**
	NA fields (subtracted from 14)	0	0
	Score % (score/(14-NA))	**78.6**	**92.9**

Table 5.12: Scoring investigations to extract hamstrings flexibility detection/analysis methods.

Study		Christou 2004	White et al. 2009	Patil et al. 2010	Earl et al. 2005 (HQ)
Task (muscle flexibility tests)		Hamstrings flexibility			
Equipment	type of measurement tool (out of 1)	0	1	0	0
	Landmarks description (out of 1)	0	1	0	0
Data collection	Participants positioning (out of 2)	2	2	0	1
Data reporting	Reliability and error (out of 2)	0	2	0	0
	Variables and outcomes (out of 1)	0	1	0	1
	Total score (out of 7)	**2**	**7**	**0**	**2**
	Score % (score/7)	**28.5**	**100**	**0**	**28.5**

5.3.2 Extracted methods

Table 5.13 shows the results of approach v 2.0; the outcome measure to be investigated, and the testing protocols chosen based on the largest effect sizes from studies with best reporting of their testing protocols.

Table 5.13: Results of combining methods scoring and meta-analyses effect sizes to choose the tests that formed the local neuromuscular deficits' detection protocol.

	Testing domain		Studies with ⩾70% of methods assessment	Effects sizes	Largest ES
1	***VM-VL onset delay in stepping and stair negotiations***		Bolgla et al. 2011	0.29 [-0.36,0.95]	
			Briani et al. 2016 (HQ)	1.36 [0.53, 2.19]	✓
2	***BF mean amplitude in single leg triple hop test***		Bley et al. 2014	0.71 [0.07, 1.35]	✓
			Kalytczak et al. 2016 (HQ)	0.33 [-0.41, 1.08]	
3	***Isometric extension peak torque***		Bolgla et al. 2011	-0.48 [-1.15, 0.18]	
			Bolgla et al. 2015 (HQ)	-0.50 [-0.91, 0.09]	
			Ferreira et al. 2019a (HQ)	-1.98 [-2.61, -1.36]	✓
4	***Concentric extension peak torque***		Ferreira et al. 2019b (HQ)	-1.80 [-2.33, -1.26]	✓
			Keet et al. 2007 (HQ)	-1.10 [-1.82, -0.38]	
5	***Eccentric extension peak torque***		Ferreira et al. 2019b (HQ)	-1.33 [-1.83, -0.83]	✓
			Keet et al. 2007 (HQ)	-0.55 [-1.23, 0.14]	
6	***Rate of torque development (to specific % of peak force).***	***30%***	Ferreira et al. 2019b (HQ)	-0.48 [-0.93, -0.02]	
			Nunes et al. 2020 (HQ)	-0.79 [-1.36, -0.22]	✓
		60%	Ferreira et al. 2019b (HQ)	-0.87 [-1.34, -0.40]	✓
			Nunes et al. 2020 (HQ)	-0.68 [-1.24, -0.12]	
		90%	Ferreira et al. 2019b (HQ)	-1.09 [-1.57, -0.61]	✓
			Nunes et al. 2020 (HQ)	-0.41 [-0.96, 0.14]	
7	***Hamstrings flexibility testing***		White et al. 2009	-0.82 [-1.55, -0.08]	✓

Based on the procedures described above, a protocol that specifically detects local neuromuscular characteristics that are associated with PFP comprises; the difference between VM and VL timing in a step-up task (196), BF mean excitation amplitude in single-leg triple-hop test (194), peak knee extensors isometric (210), concentric and eccentric (79) torque, rate of torque development during peak isometric extensors contraction (79,119), and hamstrings flexibility (121).

5.3.3 The resultant testing protocol

The tests on which the protocol is based are within three neuromuscular domains; EMG, muscle performance and muscle flexibility. In the next section, the details of each testing procedure are exhibited.

5.3.3.1 Electromyography domain

This domain was investigated through two tests; VM-VL excitation onset during step-up, and BF mean excitation amplitude during single-leg triple-hop test.

5.3.3.1.1 *VM-VL excitation onset*

This test detects the instances (in milliseconds) of EMG excitation onsets of VM and VL muscles, and identifies the difference between both onsets, averaged through multiple repetitions. This targets the imbalances in VM and VL activation during a functional task; which is step-up (196) according to our approach. To identify these parameters, the procedure needs surface EMG data from VM and VL, and vertical ground-reaction force (vGRF) data to identify step initiation.

5.3.3.1.1.1 Acquisition hardware and software

Human performance laboratory at QMUL is equipped with Delsys Trigno Lab system (Delsys Inc, Boston, MA, USA), which was used to collect the EMG data. Odin software (Codamotion, Charnwood Dynamics Limited, Leicestershire, UK) was used to record the EMG data during tasks. The Delsys Trigno (Figure 5.3) includes wireless surface EMG sensors that have parallel bars of 99.9% silver to contact the skin (four contacts (5 x 1 mm), overall sensor dimensions 3.7 x 2.7 x 1.5), and uses single differential detection mode, with a common mode rejection ratio >80 dB, and gain range of ±5 Volts (297). Skin impedance and signal-to-noise ratio (SNR) were not assessed. Odin software was linked to floor-embedded force plates that were used for both tasks (9281B, Kistler Corporation, Switzerland). For the step-up task, a wooden box (20 cm in height) which had exact dimensions of the force plate was placed over it to allow for the task to be undertaken (Figure 5.4).

Figure 5.3: Delsys Trigno EMG sensor.

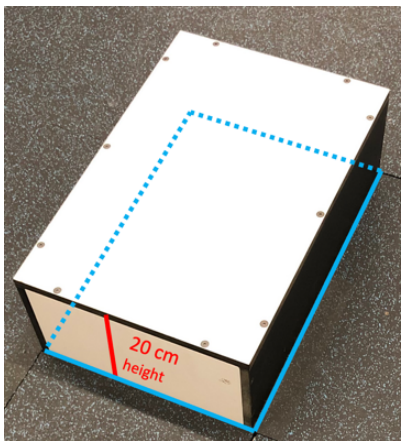


Figure 5.4: wooden box used for the step-up task, with similar dimensions of the force plate (blue).

5.3.3.1.1.2 Attachment set-up of surface EMG sensors

The Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines were followed for the EMG sensors placement (293):

- VM: 80% on the line from anterior superior iliac spine (ASIS) and knee joint space in front of the medial collateral ligament.
- VL: 2/3 of the line from ASIS and lateral border of the patella.

While the participant is lying in supine position, the knee is maintained flexed by a pillow underneath. A tape measure was used to measure the placement distances between bone anatomical references. The skin was shaved, cleaned with alcohol wipes (70% alcohol) and abraded with sandpaper (293). Interelectrode distance is fixed at 10mm due to the configuration of the Delsys sensors. Sensors were secured by a cohesive bandage to avoid falling off during tasks.

5.3.3.1.1.3 Testing procedure

Table 5.14: Procedure of the step-up task (for VM-VL timing).

Step-up	Position of participant and equipment	The wooden box was placed on an embedded force plate to be used to designate timing of the performed steps.
	Encouragement	No auditory encouragement during task.
	Instructions	Please, keep elbows close to body and hands on chest. Next, step on first square (red). Stay standing relaxed (for at least 10 seconds). Now, go; participants step on the box with tested side then contralateral side, and go down starting with tested side then contralateral side. This is done by their own comfortable pace (Figure 5.5).
	Familiarisation	Participants were asked to perform the task at least twice to familiarise themselves with the height of the box and the task overall.
	Repetitions	The stepping up task will be continuous until participants perform at least 9 consecutive steps (5 steps (from 3 to 7) were analysed to get an average onset time of the muscles). Participants were not told how many steps they are going to do so that data is not confounded by their preparation to stop.

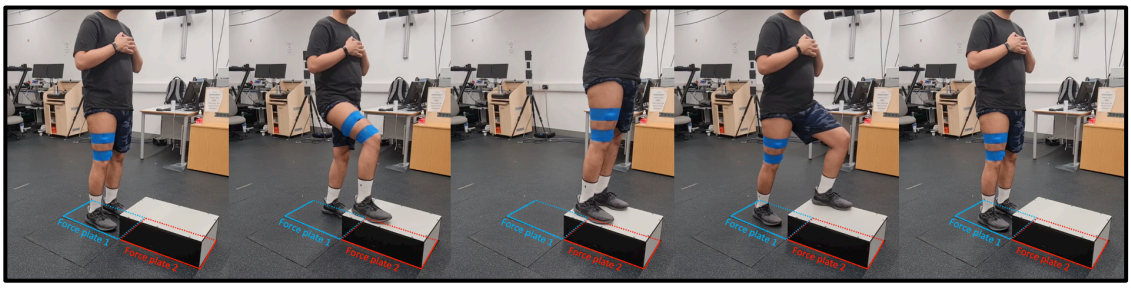


Figure 5.5: Step-up task

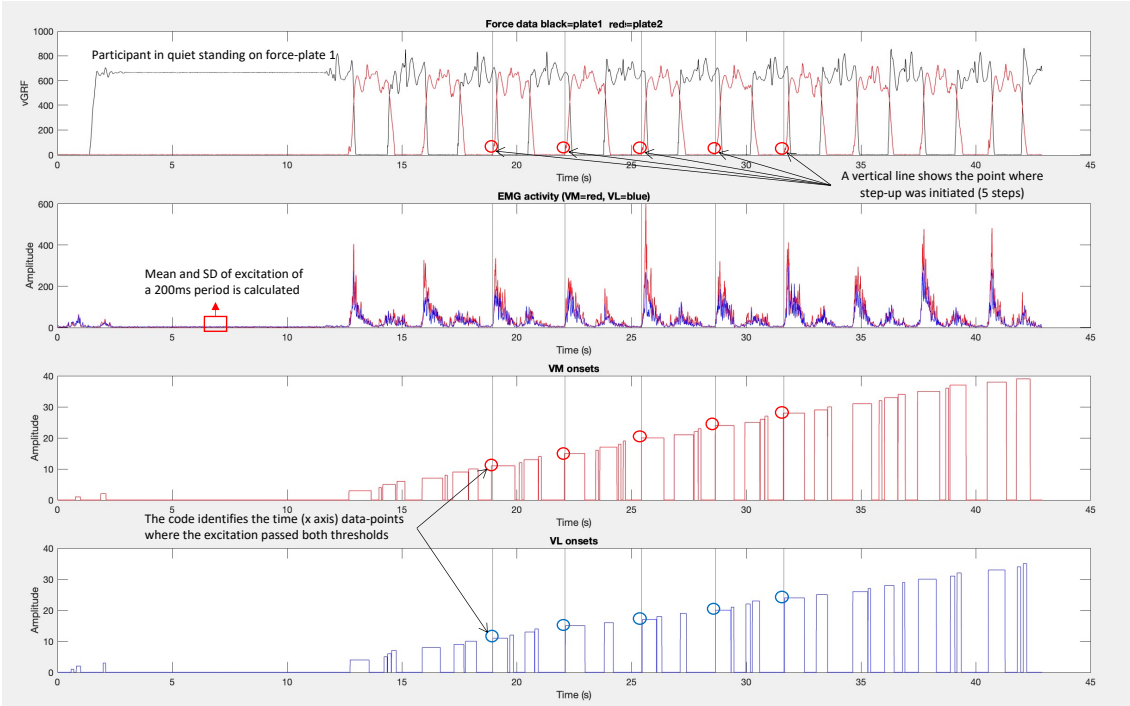


Figure 5.6: a screenshot of the data processing phase performed in MATLAB. The analysis was done on consecutive five steps after two steps at the beginning to allow for consistent pace to be reached (for the script, please see Appendix 5).

5.3.3.1.1.4 Data collection and analysis

Raw data were collected and sampled at 2000 Hz through Odin software (EMG (mV) and force (N)). Data processing and filtering was performed using MATLAB software (R2018, MathWorks, Natick, MA, USA) as follows:

1- VM and VL EMG signals (196):
   a. 4th order Butterworth filter, with a band-pass of 20-500 Hz. Next, signal is rectified (Full-wave), and low-pass filtered at 50 Hz.
2- Force data:
   a. For being used as a time-window, raw signals were used as filtering might shift the true time of contact. Threshold was set to 10 newtons to define initial contact and take-off instances and avoid noise (298).
3- Excitation onset of VM – excitation onset of VL; each onset will be defined using a double-threshold method (287) with parameters used by Briani et al. (196);
   a. First threshold: mean + three standard deviations of the excitation of a 200 ms period of muscle activity during quiet standing before the commencement of the task will be used to set the first threshold.
   b. Second threshold: 25 milliseconds (ms).

Whenever EMG signal passes first threshold (mean+(3xSD)) for at least 25 ms, the passing time of that signal is identified as an excitation onset and subtracted from the time-point of the step-up initial contact. This is applied for both muscles. Negative results mean that VM was activated before VL, and vice versa (Figure 5.6). Appendix five contains the MATLAB scripts.

5.3.3.1.2 BF mean excitation amplitude in single-leg triple-hop test

In this test, the aim is to identify the average EMG excitation of BF muscle during single-leg triple-hop test. Although the choice of this test was based on the meta-analysis, its inclusion was inaccurate as the inclusion of the BF EMG meta-analysis was incorrect. There were methodological differences within the task itself between both studies that formed the forest plot (194,215) and a corrigendum (178) was published to address this issue in detail. The corrigendum was submitted to the journal (in July 2022) after data collection started (in February 2020). The protocol continued to have triple-hop test so that the effects of joint stress and fatigue are not different during the testing session, as recruitment continued after the pandemic (in 2023). A decision was made to continue with the analysis as data was already gathered. However, both studies (194,215) individually found significant differences in BF EMG activity.

5.3.3.1.2.1 Acquisition hardware and software

The same specifications mentioned previously (for the VM-VL procedure) are used for the BF tests. The wooden box was removed during the SLTHT to allow participants to land on the force plates.

5.3.3.1.2.2 Attachment set-up of surface EMG sensors

SENIAM guidelines were followed for the BF as well (293):

- BF: 50% of the distance between ischial tuberosity and lateral tibial epicondyle.

Participant were in prone-lying position, and the knee was maintained flexed by a pillow underneath the shin during this procedure. Sensor's positioning, skin preparation, and fixation to the posterior part of the thigh were performed in a similar manner to VM and VL.

5.3.3.1.2.3 Testing procedures

Table 5.15: Procedures of maximum voluntary contraction (MVC) and single-leg triple hop test (SLTHT) for collecting BF excitation amplitude.

MVC	Position of participant and equipment	Participant in prone lying position, with straps wrapped around hip (for stabilisation) and ankle (for resistance at 60° of knee flexion (0=full extension, Figure 5.7)).
	Encouragement	Auditory encouragement to maintain maximum contraction ("Pull, pull, pull…").
	Instructions	You are going to pull against the strap as much as you can, and keep pulling until I say relax.
	Familiarisation	Participants performed 3 submaximal contractions to familiarise themselves with the strap and knee position during the contraction.
	Repetitions and resting period	5 maximal repetitions were performed with 1 minute rest in between.
SLTHT	Position of participant and equipment	Participant will start by standing on tested side only, with hands on chest, and perform longest triple hops as possible, while landing on an embedded force plate at the end of the 2nd hop (Figures 5.8 and 5.9).
	Encouragement	No auditory encouragement during task.
	Instructions	Please, put your hands on your chest. Ready, go (recording begins and foot position during landing is visually monitored by the assessor to confirm proper contact; within the borders of the force plate).
	Familiarisation	Participants were asked to perform the task multiple times (up to 5 times) to position themselves in a distance that fits the place of the embedded force plate (for 2nd landing-start of 3rd hop). This distance was recorded. Participants were made aware of the importance of landing with whole foot on the force plate.
	Repetitions and resting period	3 repetitions were used in the analysis. Resting period between repetitions is at least 1 minute.

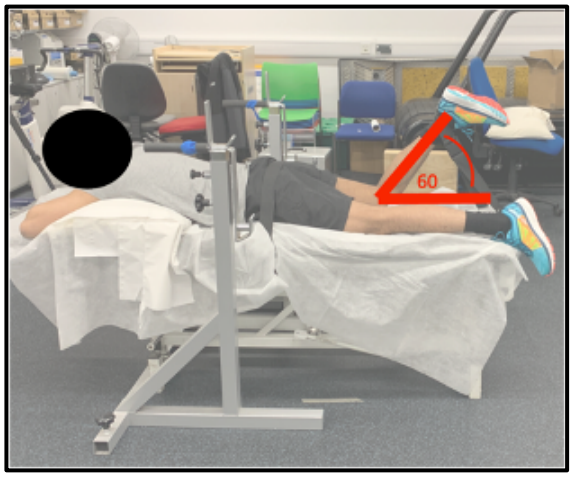


Figure 5.7: maximum voluntary contraction position for BF normalisation.

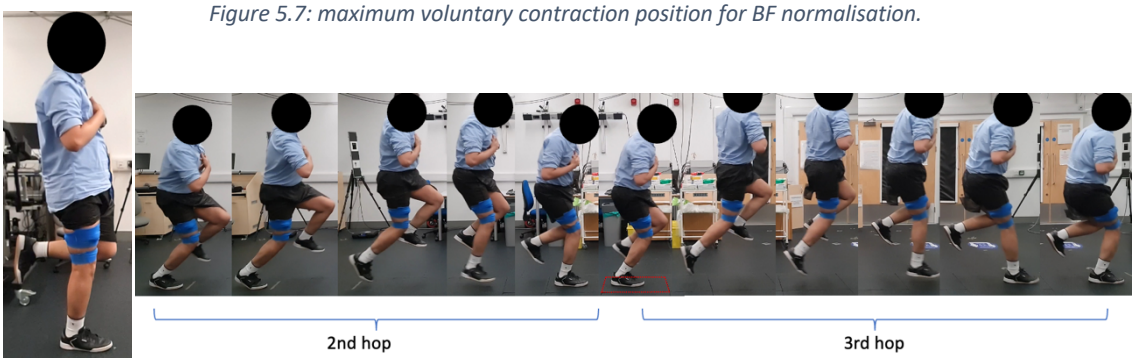


Figure 5.8: starting position and landing between 2nd and 3rd hop in SLTHT on the force plate (red).

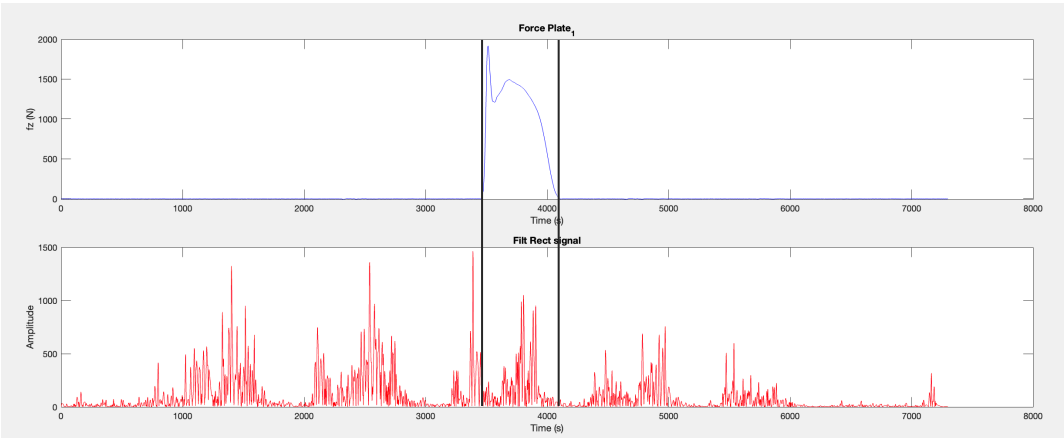


Figure 5.9: Screenshot of MATLAB processing. Black lines show the period in which EMG data is analysed, which is the stance window of the 2nd hop landing-initiation of 3rd hop. vGRF in blue and BF EMG in red (for the MATLAB script, please see Appendix 5).

5.3.3.1.2.4 Data collection and analysis

Sample rate and acquisition software were similar to the VM and VL protocol. Force plate was used to define foot-contact to take-off window (for BF mean excitation amplitude during stance). Further data processing was performed using MATLAB as well. Filtering of EMG signals was performed as follows:

1- BF EMG signal (194):

   a. For MVIC:

i. 4th order Butterworth filter, with band-pass of 20-500 Hz, full-wave rectification then average peak of excitation (of 150 ms moving window) of the period of maximum contraction is used.

- The band-pass filter used by Bley et al. (194) was 20-400 as their sampling rate was 1000 Hz. The low-pass part of the band-pass should not exceed 50% of the sampling rate (296), which could be the reason why Bley et al. (194) used 400 Hz. As we acquired the data in a sample rate of 2000 Hz, we used the same filter used for VM and VL which was 20-500 Hz.

b. For SLTHT:

i. Same signal processing (as MVC) except the window of excitation is set as the whole stance duration (from initial foot contact to complete take-off), and root mean square (RMS) was used to calculate excitation amplitude. Mean excitation amplitude (mV) of BF during the whole stance phase of 2nd landing (end of 2nd hop and start of 3rd hop) in single-leg triple-hop test (SLTHT), normalised by peak excitation of maximum voluntary contraction (MVC) (Figures 5.7 to 5.9).

2- Force data:

a. Same threshold used on raw vGRF (10 newtons) to define initial contact and take-off instances.

5.3.3.2 Muscle performance domain

Data collection procedures of muscle performance outcome measures are derived from Ferreira et al. (79,210), and Nunes et al. (119). As RTD testing was performed as part of the isometric peak torque testing, the next section contains all measures within the muscle performance domain to avoid repetition.

5.3.3.2.1 Knee extensors peak torque and rate of torque development

The outcomes under investigations were:

1- Knee extensors:

a. Isometric peak torque.

b. Concentric peak torque.

c. Eccentric peak torque.

d. Rate of torque development:

i. To 30% of peak isometric torque.

ii. To 60% of peak isometric torque.

iii. To 90% of peak isometric torque.

5.3.3.2.1.1 Acquisition hardware and software

For these outcomes, an isokinetic dynamometer (IKD) was used (Biodex system pro, Biodex Medical Systems, Inc. Shirley, NY, USA). The IKD was connected to a laptop with LabVIEW software (LabVIEW 7.0, National instruments, TX, USA) through a data acquisition device (Multifunction I/O device, Model: USB-6210 (A), National Instruments, TX, USA) (Figure 5.10).

Figure 5.10: The isokinetic dynamometer and the data acquisition device.

5.3.3.2.1.2 Testing position for muscle performance outcomes

1- Knee extensors isometric peak torque:

a. Seated position with hips at 85° (backrest of the BIODEX chair was fully raised) and knee at 60° of flexion (full extension = 0°).

2- Knee extensors concentric peak torque:

a. Same position, but range of motion (ROM) is from 90° to 20° of flexion, and speed was fixed at 30° per second.

3- Knee extensors eccentric peak torque:

a. Same position, but ROM is from 20° to 90° of flexion, and speed was similarly fixed at 30° per second.

4- Rate of torque development (RTD) (to 30%, 60% and 90% of peak torque):

a. Acquired from isometric tests data (analysed in MATLAB).

The cushion of the resistance arm of the IKD was fixed in distal position, above the lateral malleolus. The centre of rotation of the IKD was aligned with the femoral epicondyles.

5.3.3.2.1.3 Tasks' procedures

Table 5.16: Procedure of isokinetic muscle performance investigations (Figure 5.11).

Repetitions, time under tension and rest periods description	Repetitions	For all three types of investigations, participants performed 2 submaximal familiarisation repetitions and 3 maximal recorded repetitions.
	Rest periods	At least 1 minute rest in between repetitions.
	Instructions	1- Isometric: a. Participants were asked to maximally extend (reaching their peak strength as quickly as possible) and stay at their peak for 5 seconds. 2- Concentric and eccentric: a. Participants were asked to maximally extend for the whole range. Whenever a repetition is about to start, participants were asked to maintain a fixed position, by grabbing the belts across the chest or the handles on either side of the IKD chair (the same position used for the retest sessions). The IKD screen was turned to face the participant for visual feedback.
	encouragement	Auditory encouragement to maintain maximum contraction ("push, push, go, go…").

Figure 5.11: Muscle performance testing position, using the isokinetic dynamometer.

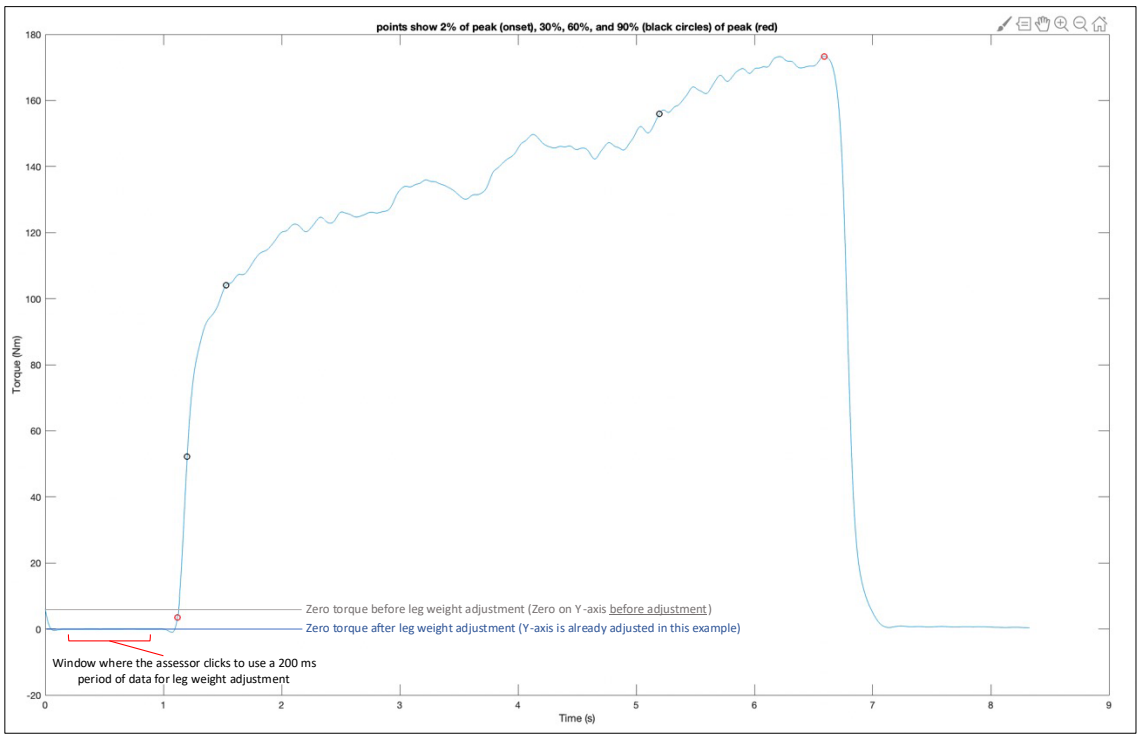


Figure 5.12: Isometric torque data during signal processing. Red and black circles represent 2%, 30%, 60%, 90% and peak (100%) of torque data. For the concentric and eccentric torque data, only the peak data point is extracted (for the script, please see Appendix 5).

5.3.3.2.1.4 Data collection and analysis

Using LabVIEW software, torque data was sampled at 2000 Hz. Acquired signals were then filtered with 4th order Butterworth filter and low-passed at 14 Hz. Signal filtering and identification of all outcome measures were performed by the MATLAB script, and highest peak of all repetitions was used to represent peak torque produced by the participant. Next, data were normalised by body mass (Newton-metre /kilogram x 100). As leg weight changes the starting point of torque data, leg weight correction was added to the MATLAB code. Signal processing requires the assessor to choose a point in time where data is stable (highlighted in figure 5.12) before torque production. This is done by finding the mean of a 200 ms where the mouse was clicked, and sets the “new zero” torque point at the resultant mean.

Rate of torque development outcomes were obtained by finding the points in which torque reached 30%, 60% and 90% of peak torque, dividing torque by time, then normalised by body mass. The onset from which rate is calculated is when torque passes 2% of the peak. So, RTD is measured from the 2% point to 30%, 60% and 90% ((Nm/s)/kg).

5.3.3.3 Muscle flexibility outcome

5.3.3.3.1 Hamstrings flexibility

The final deficit to be investigated is the hamstrings muscle flexibility, which is derived from White et al. (121), where they used an apparatus to fix the hip at 90° degrees while the knee is extended.

5.3.3.3.1.1 Acquisition hardware and software

An electronic inclinometer (built in Iphone six plus) was used to record the angle of the leg as it is passively extended. The phone was aligned with the line between the lateral malleolus and femoral condyle. The built-in inclinometer feature in the Iphone is a reliable and valid tool to assess knee, and other joints' range of motion (299–301). For this test, a barbell and a bench-press rack was used to stop the hip angle at 90° of flexion during passive knee extension. The popliteal angle was reported as; 90° – the measured angle. Lower numbers represent more flexible hamstrings (Figure 5.13).

Table 5.17: Procedure of hamstring flexibility testing

Repetitions, time under tension and rest periods description	Repetitions	Passively, 1 time after checking correct position.
	Instructions	Participants were asked to lye supine and relax, then the bed was pushed under the horizontal bar and moved multiple times until correct position that results in a right-angle of the hip (when thigh is flexed against the bar) is acquired.
	encouragement	Not applicable, but participants were asked to confirm the firm end-feel (at largest achievable range) by asking about pain and feeling of stretch at posterior aspect of the thigh.

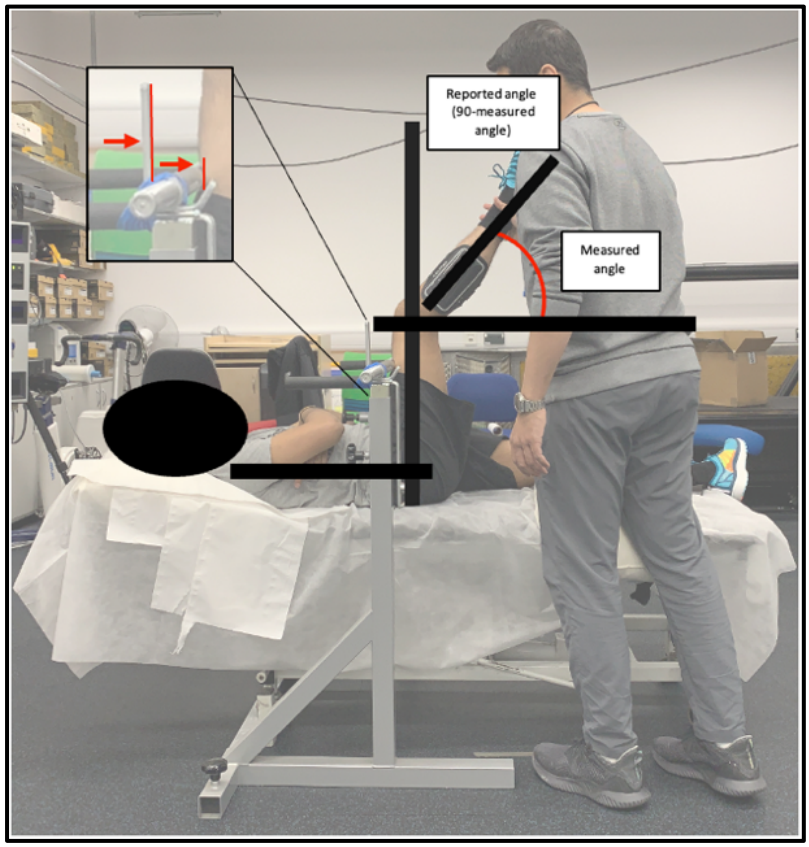


Figure 5.13: Position and procedure of hamstrings flexibility (popliteal angle) measurement. The bench press rack had enough support to prevent the barbell from moving, the barbell was tied firmly to prevent it from moving.

5.4 Discussion

In this Chapter, a lab protocol was successfully produced from adapting the results of a large meta-analysis. The protocol consists of a battery of tests across three domains; EMG, muscle performance and muscle flexibility. As this was a new approach, it is important to discuss the results and explore the limitations and recommendations for the adoption of this protocol in the future.

5.4.1 Extracting the lab protocol from the meta-analysis

Although extracting the lab protocol from a meta-analysis is unique, there were multiple factors that allowed this approach to be conducted. The first project was a large systematic review that specifically investigated local neuromuscular characteristics in PFP. Systematic reviews with meta-analyses are considered the best research type to synthesise the literature (302). Therefore, it is reasonable for a protocol that is developed within this thesis to be based on the results of Chapter three. Also, the meta-analyses were categorised according to tasks (i.e. stepping, jumping, seated extensions, etc), which facilitated this adaptation approach. Developing a new method by subjectively interpreting the results of the meta-analysis was the other option, which only adds to the variable methods seen in the literature,

like the studies included in previous reviews (81,83) and our review (176). For these reasons, the resultant protocol is based on what the data of available literature indicates at (176), which was empirically evaluated by meta-analysis.

As risk of bias and quality assessment tools ultimately give indications about internal validity and results reproducibility (303), practical methods are not assessed by them. This required creating the provided assessment/scoring tools. These tools should have validity and reliability successfully established to be published and used on a larger scale. However, it seemed reasonable to be used within this thesis as their criteria are completely based on published guidelines and textbooks (286,289,294–296).

5.4.2 Including VM-VL delays and BF excitation amplitude deficits in the lab protocol

Abundant EMG studies in PFP can be found in the literature. Yet, a clear link between deficits detected using EMG and PFP persistence or progression was not available (12), and this could be due to multiple reasons. Specifically regarding EMG, there are many inherent methodological limitations (304). For instance, anatomical and physiological aspects, like muscle fibres' length and type, muscle and neuromuscular partitioning, temperature, diameter and fatigue status all play a role in the interpretation of the EMG signal and what it represents (287). The effects of such inherent matters are minimised by multiple efforts that produced consensuses around EMG application, which aim to guide current research (293,305–307). However, there are other aspects that could produce better interpretations if clearly reported, like the listed items in Merletti's ISEK guidelines (296). Therefore, as the systematic review included 53 studies that reported EMG investigations, it seemed reasonable for the testing protocol to be guided by the results of their synthesis.

It is sound to include VM to VL delays testing in the produced protocol. Patellofemoral pain is commonly attributed to imbalances between VM and VL in guiding the movement of the patella (12). Among those imbalances, difference in excitation onsets was extensively researched. This deficit was initially studied by Voight and Wieder in 1991 (103). Followed by multiple research to address links to PFP development in prospective studies (69,72), or persistence in case-control studies (gathered by the review in Chapter three (176)).

The evidence highlighted by the gap-map (Chapter three, table 3.5) indicates that Vasti EMG timing was mostly investigated in stepping/stair negotiations and squatting and leg press tasks. As the studies investigating the deficit in squatting and leg-presses were not meta-analysed (reasons mentioned in Chapter three), stepping/stair negotiations was a clear target. Consequently, the pooled results allowed the inclusion of a test that is based on an extensively researched deficit, in a commonly used task.

Contrary to quadriceps EMG investigations, hamstrings investigations showed lesser focus as only eight studies investigating BF EMG were found, with seven in the amplitude domain. However, pooled results of two studies indicated a deficit in terms of a higher mean excitation amplitude during single-leg triple-hop test. Compared to VM-VL timing, including a BF EMG excitation amplitude investigation in the lab protocol is based on a weaker foundation. However, hamstrings loading can potentially alter knee rotational control and influence lateral patellar shift (239,308), which supports including it in the resultant protocol.

5.4.3 Including quadriceps strength tests in the lab protocol

A largely studied area is muscle strength in people with PFP. Muscle weakness is purported as a factor linked to PFP development (29,31) and persistence (81,82). A published clinical guidelines paper by Willy et al. (15) highlighted the association of quadriceps weakness with PFP and its relevance as a treatment target. Therefore, a testing protocol that investigates multiple aspects of muscle performance is an understandable result.

The review in Chapter three included 20 studies investigating muscle strength; all investigated the quadriceps, but within those, only four studies investigated the hamstrings. This is clearly exhibited by the 3rd gap map (table 3.7) as a total of 34 collective tests of isometric, concentric and eccentric quadriceps strength were acquired, compared to six within the hamstrings. Therefore, targeting the quadriceps to detect muscle strength deficits is well-supported, and not including hamstrings tests is due to the lack of focus of the literature on this muscle group. Treatment plans focusing on the quadriceps are recommended as part of treatment programmes in PFP (24). Multiple strength aspects are altered in PFP, including isometric (113,140), concentric (45,116), eccentric torques (44,117) and RTD and power (116,119,309). As provided by the guidelines recommended by the International Patellofemoral

Research Network (IPFRN) (275), improvement is targeted in strength aspects that the produced lab protocol includes. Therefore, the lab protocol can inform progression and/or monitoring of the changes in these aspects during interventional programmes.

5.4.4 Including hamstrings flexibility in the lab protocol

Hypomobility impairments have been reported in people with PFP (15,122,123) which supports having this domain tested within the lab protocol. Locally, these impairments are found within the quadriceps and hamstrings (12). In our systematic review, six investigations within four studies were found. The hamstrings were investigated in all four studies (46,77,121,201). Hamstrings tightness is usually targeted in PFP for its influence on PF joint forces (238). So, a protocol seeking to identify interventional mechanisms should include hamstrings flexibility testing. Two other structures were found in the included studies to be singularly investigated for tightness; gastrocnemius and iliotibial band. Interestingly, the quadriceps were not investigated within the included studies, although studies reported links of quadriceps tightness to predisposition (69) or existence in PFP (310,311). However, due to lesser support from the results of Chapter three, the testing protocol only included the hamstrings.

5.4.5 Limitations

The project described in this Chapter demonstrated a systematic foundation for a battery of tests that formed a lab protocol. The protocol aims to identify the mechanisms of effects for interventions delivered to people with PFP. However, there are multiple limitations that should be mentioned.

First, the properties of the resultant testing protocol are linked to the research question and eligibility criteria of the systematic review. Fortunately, the aim of the review was to identify the deficits to be measured (i.e. what deficits exist more consistently in PFP). Also, the methodological homogeneity that was required to construct the meta-analyses led to having tasks' categories in the meta-analysis. Hence, it was a reasonable adaptation of the results.

A 70% total cut-off was used within the assessment tool for scoring each methodological element. This cut-off was based on personal knowledge and reading, as well as discussions among supervisors and research students, and may have resulted in an over rigorous exclusion of certain methods.

Deviations from the analysed studies protocols were necessary in the final protocol, due to differences in the equipment used (EMG acquisition sensors/system, force plates, dynamometer type/specifications etc). Specifically, the differing equipment meant signals sampling rate was different from the original studies, as Briani et al. (196) used 4000 Hz, and Bley et al. (194) used 1000Hz. Based on the highest band-pass filters' cut-off frequency being used (which is 500Hz), the sampling rate can meet the requirements of the ISEK EMG methods recommendations if it was 1000Hz. Our equipment were able to record signals with a maximum rate of 2000 Hz. Therefore, this rate was used for the EMG , specially that the same ISEK guidelines recommends higher frequencies for better accuracy and resolution (290). For the IKD data, Ferreira et al. (79) used 100Hz, and Nunes et al. (119) did not specify IKD's data sampling frequency. We used 2000Hz as well, specially that RTD requires a higher frequency for a better detection of muscle performance during testing, as it is torque divided by time. Nevertheless, these are inherent problems, as laboratories will usually differ in available equipment. This aspect of practical research is a limitation only if differences in equipment have significant effects on acquired data. This would raise a question about detecting deficits to guide interventions, especially in methods with many possible confounding sources, like EMG.

Regarding the triple-hop test, the derived protocol was from studies that measured kinematic variables alongside EMG. As this thesis focused exclusively on neuromuscular characteristics, only vGRF through force-plates was used to ascertain the analysis (stance) period, which is satisfactory (284). However, inclusion of 3D kinematics in a functional task like a triple-hop would have offered better future interpretations in a full-scale study (e.g. by providing joint angels) and enhanced alignment to previous methodologies.

The methods adopted in this Chapter have been reliant on an up-to-date systematic review. Inevitably, systematic reviews become outdated, and the 2nd revision of Chapter three for peer-review before publication required a search update to look for new studies, and four studies were found and included (113,116,204,207). This should be considered if a similar approach is conducted in future, as updating can change the results, and eventually, the developed lab protocol.

5.4.6 Recommendations

Although a systematic review represents the highest level of evidence (312) the utilisation of the results of a systematic review must be planned early for any project that adapts a similar approach. This planning must include the initial protocol of the systematic review, from the research question to the methods of data analysis. This Chapter produced assessment tools which can be adapted or modified for future work. If so, a more robust approach to determine the scoring aspects would be favourable, as well as reliability, and if possible, validity to be established (subject to availability of other comparable tools). An example to help solve this limitation would be by contacting dedicated organisations or research groups involved in similar fields to what the assessment tools are evaluating. Finally, it is recommended to develop a lab protocol after the latest version of the systematic review as it can be updated during the writing and publication process.

5.5 Conclusion

This Chapter presented the methodological development project of the thesis. It comprised a unique progression process from the previous systematic review to produce a lab protocol to detect local neuromuscular deficits in PFP. This protocol was built using a battery of tests that are specifically related to local neuromuscular findings in PFP compared to healthy groups from available literature. The protocol targets seven deficits; VM to VL excitation onset delay in step-up, lower BF mean excitation amplitude in SLTHT, lower knee extensors' peak isometric, concentric, eccentric torques, and lower RTD to 30%, 60% ad 90% of peak isometric torque.

6 Reliability of a detection protocol of local neuromuscular deficits in PFP

With a practical testing protocol successfully derived from the meta-analysis, the reliability of it must be established. This chapter comprises reliability research that were conducted to reach that goal. This phase forms an imperative step towards understanding the mechanisms of benefit of interventions in future.

Lab closures caused reliability investigations to be conducted through two separate studies. First, a reliability study on an uninjured group. The second study is a reliability, and preliminary feasibility study on a PFP group.

First Lab closure was due to a ransom-ware attack on QMUL's engineering network (lab is within engineering building) which was from January 30th to February 26th 2020. Second closure was due to COVID-19 pandemic.

In this chapter, the reliability investigations of both studies are presented.

6.1 Background

Patellofemoral pain (PFP) remains one of the most common knee pain complaints, observed in different populations and age groups (2). Recurrence of PFP symptoms and variation in patient reported outcomes, despite completion of evidence informed rehabilitation programmes, is consistently reported (5,8,20). Understanding the effects of rehabilitation on biomechanical characteristics associated with PFP is recommended to improve treatment outcomes (12). Still, the impact of rehabilitation interventions on these characteristics is unclear. This lack of clarity may be attributed to the plethora of methods used to detect and correlate changes in local neuromuscular characteristics to PFP (81,83).

The overarching aim is to provide a laboratory testing protocol that can reliably detect local neuromuscular deficits that are associated with PFP. By implementing this protocol, the future impact is to determine how neuromuscular characteristics, local to the knee, change following the delivery of interventions with proven efficacy. Therefore, we synthesised the results of the meta-analysis in Chapter three and extracted a detailed laboratory protocol in Chapter five. Establishing the reliability of the protocol is required before any further investigations.

Different domains to detect multiple local characteristics related to PFP have been identified. The aim is to assess the reliability of the developed laboratory protocol including; EMG measurements within the quadriceps and hamstrings in different functional tasks, specific strength measurements of the knee extensors, and hamstring flexibility. The objectives were to recruit a group of uninjured people and individuals diagnosed with PFP and investigate test-retest reliability. The impact of this study is to aid planning a protocol that can successfully detect changes attributed to the complaint in patients with PFP following an intervention.

6.2 Methods

Two separate reliability studies (on an uninjured group and a PFP group) were conducted in two separate times (due to the pandemic). As both studies included the same protocol, both are presented in this chapter.

6.2.1 Ethical approval

The ethical application was approved on February 17th 2020 for the study on the uninjured group (QMREC2018/48/038). On December 9th 2021 the ethics application of the study on the PFP group was approved (QMREC2018/48/082). Ethics approval correspondences can be found in Appendix 2.

6.2.2 Research question

What is the reliability of a testing protocol derived from meta-analysis in adults with PFP?

6.2.3 Study design

This study is a test-retest reliability study. It was designed to investigate data collection repeatability by assessing the agreement of several lab-based outcome measurements in symptomatic and asymptomatic individuals over two data collection sessions at least one week apart. The within-session reliability element was added a posteriori, as only the test-retest reliability analyses were originally planned.

6.2.4 Recruitment

6.2.4.1 Recruitment of the targeted groups

The targeted sample consists of two groups. An uninjured group, people with general interests in acquiring more knowledge about knee roles in daily activities, and people with specific interests in PFP. The same pathway was used to recruit a group of people with PFP. Potential participants within QMUL staff and students were recruited. Recruitment presentations, email advertisements and social media platforms were used to recruit participants. Flyers were distributed in venues within QMUL in Whitechapel and Mile-end campuses. Twitter was used to advertise for the study. Reliability investigations of uninjured participants predominantly stress the repeatability of the methods, but in PFP, it incorporates the impact of symptoms on consistency of results. Therefore, uninjured and PFP groups were recruited to enhance the interpretation of the results.

6.2.4.2 Enrolment process

All advertisement's/flyers contained a QR-code that takes interested individuals to a google form containing a brief explanation about the study (study information). If the person agrees to participate, the contact email would be used to send the consent

form and plan both lab visits. After signing the consent, demographic data were gathered and clinical examination were performed to apply the eligibility criteria.

6.2.4.3 Eligibility criteria

Adults ≤ 40 years of age were included to minimise having people with degenerative changes of the knee (42). For the PFP group only; people with pain in anterior part of the knee aggravated by at least two activities that involve loading the knee in a flexion position (stair climbing or descending, squatting, jumping, sitting for long periods and kneeling) (15). Worst pain felt within last month should be ≥3/10 on the visual analogue scale (VAS). Participants were excluded if they were diagnosed with any knee problem (except PFP for the PFP group), such as meniscal and Ligament injuries, knee osteoarthritis, Osgood Schlatter's or patellar tendinopathy (15). To exclude any possible source of anterior knee pain other than PFP (15), Clinical examination were performed by the researcher, who is a physiotherapist with more than eight years of experience (Appendix 7.2). In addition, any history of cardiac or respiratory problems/diseases, musculoskeletal or spinal injuries, previous musculoskeletal surgeries or skin allergies were excluded.

6.2.4.4 Outcomes measure

6.2.4.4.1 Primary outcomes; the local neuromuscular characteristics

Nine primary outcome measures were collected within flexibility, EMG and muscle performance domains;

- Hamstrings flexibility.
- EMG mean excitation amplitude of BF in SLTHT.
- EMG excitation onset difference between VM and VL in a step-up task.
- Isometrics knee extensors peak torque.
- Concentric knee extensors peak torque.
- Eccentric knee extensors peak torque.
- Rate of torque development to 30% of peak isometric torque.
- Rate of torque development to 60% of peak isometric torque.
- Rate of torque development to 90% of peak isometric torque.

The equipment used and the procedures regarding these outcomes are detailed in the previous chapter, and the procedure is summarised in Figure 6.1.

6.2.4.5 Recruitment and testing procedures

6.2.4.5.1 Arrival to the human performance laboratory

For all participants, the sessions began by asking the participants to wear shorts and running shoes provided by the laboratory (all from one brand; Salomon®). Shoe construction could cause changes in biomechanics (313,314), so this step was undertaken for standardisation. Afterwards, participants were asked to walk on a treadmill with a normal pace and comfortable speed for five minutes as a warm-up.

6.2.4.5.2 Randomisation of tests

The study included three stations. The session starts with hamstring flexibility testing, then EMG tests and finally the IKD tests. The step-up task and single-leg triple-hop tests were randomised, as well as the sequence of the strength tests (isometric, concentric and eccentric extension). This sequence of the three stations helps minimise session time, as sensors would require removal and replacement if all tests were randomised together. Secondly, maximum force is required during the IKD tests from the quadriceps. Possibly, randomisation might lead to having patients do triple-hop test after fatiguing the quadriceps in IKD tests. Fatigue could affect the results in triple-jump biomechanical studies (315). Also, the adapted sequence minimises potential injury or severe pain exacerbation as triple-hops is a test of strength and power (316) and power is being tested for multiple repetitions on the IKD. Identifiers of each test were written in opaque folded papers and the participants were asked to pull one paper at a time and each test noted, until all papers were pulled. Figure 6.1 shows the flow of the testing procedures.

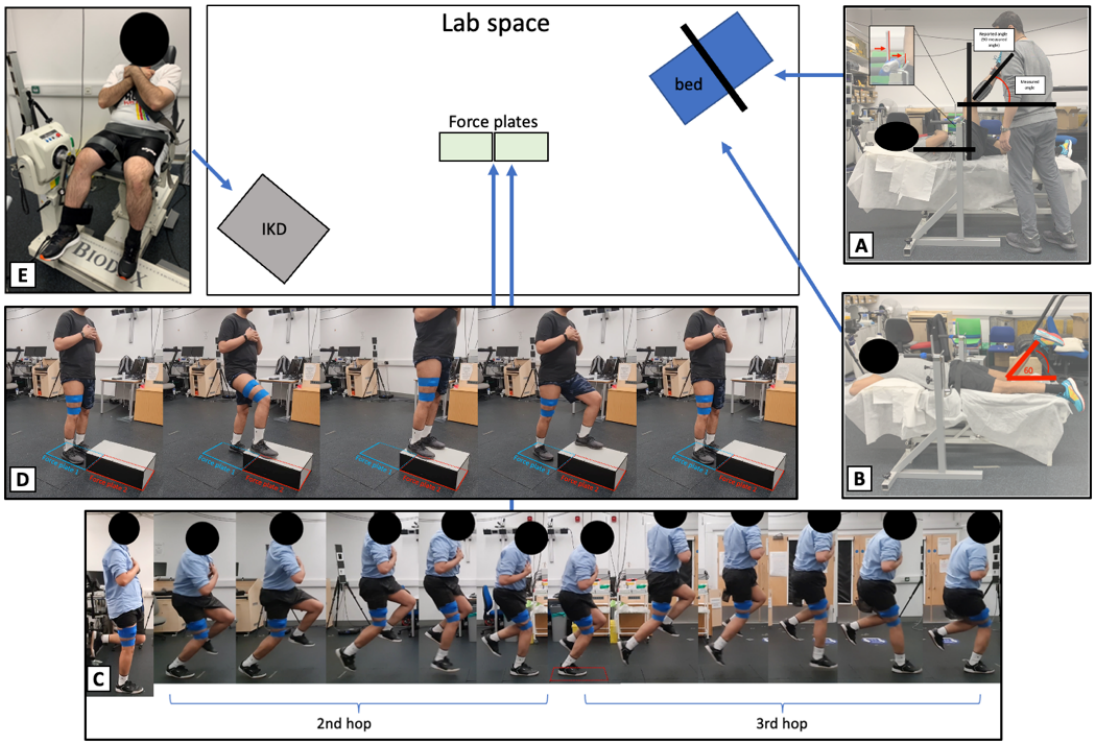


Figure 6.1: The flow of the testing session. Lab space represents the actual configuration of the lab. The sequence is displayed from A to E which is the sequence of testing stations. C and D are randomised, as well as the tests in station E. Tests are; A) hamstring flexibility, B) MVC of BF, C) BF mean amplitude in SLTHT, D) VM-VL onset in step-up task, E) Quadriceps peak torque and RTD tests. IKD; Isokinetic dynamometer.

6.2.4.6 Signal processing and analysis

To avoid repetition, please refer to the previous chapter where this part is mentioned in detail. To summarise;

- VM-VL onset timing is calculated whenever the participants load their foot to step on a 20 cm box.
- BF mean excitation is measured during the stance phase between 2nd and 3rd hop, normalised by MVC, and highlighted by the time-window of foot contact on force plate until take-off.
- Targeted torque data of knee extensors are isometric (at 90°), concentric and eccentric (at 30°/second between 20 and 90 degrees of knee flexion (0=full extension)).
- Rate of torque development is measured in isometric contractions only, from 2% to 30%, 60%, and 90% of peak torque value (normalised by body-mass).

6.2.4.7 Sample size

Based on the results of the meta-analysis (176), effect sizes from plots with significant differences were used for sample calculation. This was undertaken to help establish reliability in a sample size that can be used in future to detect changes in at least one of the primary outcomes (i.e. the outcomes that yielded significant pooled effects in

Chapter three). G*power (Version 3.1.9.4) was used to determine the sample size with a significance level of 0.05 and power of 0.8 for a two-tailed t-test performed on one group with two dependent means (assuming a one group pre-post design). The average sample size from which changes can be detected is n=27. The minimum number to detect changes was n=16, derived from the pooled effect size of the 90% of peak RTD plot. The largest size was from the pooled effect of the VM-VL timing investigations, yielding a minimum sample of n=43 to accurately detect a significant difference.

Therefore, the aim is to recruit 43 participants. Considering potential dropouts, we aimed to recruit 48 so that all outcomes are sufficiently powered, but with challenges associated with recruitment during the pandemic, we aimed to have at least 16 participants.

6.2.4.8 Statistical analysis

Statistical analyses were conducted using SPSS (Version 23.0. Armonk, NY: IBM Corp.). Intra-class correlation coefficient (ICC) with a two-way mixed effects model to assess absolute agreement (317) was used to determine test-retest intra-rater reliability and calculate the agreement between the repeated (single) measures (318). To determine reliability level, the lower bound of the 95% confidence interval (CI) of the ICC was used. Results with lower bounds of 95% CI that are < 0.5 are considered poorly reliable, 0.5 to 0.75 are moderately reliable, 0.75 to 0.9 indicate good reliability, and >0.9 indicate excellent reliability (318). As we aimed to identify absolute reliability, standard error of measurement (SEM), coefficient of variation (CV) and minimal detectable change (MDC) were calculated (319) (Figure 6.2). The SEM and MDC have the same unit as the measurement tool, but the SEM represents scores fluctuations that are due to measurement error, while the MDC identifies differences in scores that can represent true change. The CV is a standardized measure of dispersion within a dataset and can be used to compare variability between different outcome measures (99,319,320). There is no rule-of-thumb for cut-off choices for the CV. However, a 15% cut-off was previously used with similar outcome measures to determine reliable tests (321) based on the work of Stokes (322), in which it was indicated that in biological systems research, 10-15% is the usual limit.

$$\text{Coefficient of variation (CV) \%} = \left(\frac{SD}{mean}\right) \times 100$$

$$\text{Standard error of measurement (SEM)} = SD\sqrt{(1\text{-}ICC)}$$

$$\text{Minimal detectable change (MDC)} = 1.96 \times \sqrt{2} \times SEM$$

Figure 6.2: Formulas used to calculate the Coefficient of variation (CV), the Standard error of measurement (SEM) and the Minimal detectable change (MDC)

Within-session reliability was performed on data that is collected through multiple repetitions (EMG and torque data) from session one.

6.2.4.1 Phases of reliability analyses

As the outcome measures comprise specific parameters, the reliability analyses were performed through two phases. The first phase was the reliability analyses of VM-VL onset (identified using double-threshold method of 3SDs and 25ms), BF mean excitation amplitude normalised by MVC, peak torque of knee extensors isometric (at 60° of flexion), concentric and eccentric contractions (at 30°/s; between 20° to 90°of flexion), and rate of torque development (RTD) at 30%, 60% and 90% of peak isometric torque.

In the second phase, the aim was to further investigate the reliability of the EMG and RTD tests. This was done to identify possible sources within signal analysis for any poor EMG reliability results from phase one, and investigate absolute RTD.

The choice of muscle onset detection method can significantly impact the results (323). The VM-VL onset determination method (the 3SD and 25ms thresholds) was chosen based on the meta-analysis (176) through the process presented in the previous chapter. However, there are other studies that used different thresholds to identify onset (1SD (110), 2SDs (104), 3SD (100)), and 5SD (76)). The second threshold used to detect an onset (time-window) has been used differently in previous studies as well. Crossley et al. (203) used 50ms, McClinton et al. (104) used 20ms, and Hodges and Bui (324) explored 10, 25 and 50ms. The thresholds can fail to detect excitation onset (146,191). A previous study that investigated muscle timing have resorted to changing the method of onset detection when the 3SD and 25ms yielded no results. Aminaka et al. (191) modified their thresholds to 10% of peak excitation amplitude as the participants data exceeded the original thresholds. Lack et al. (146) also faced a rise above the predetermined thresholds and made changes accordingly, although

onset identification was undertaken using a novel method after multiple unsuccessful attempts. Therefore, the double-thresholds were explored from one SD to 15 SDs, and four total timing windows were used to identify the onsets (25, 50, 75 and 100ms).

Previous studies found significant differences in BF excitation amplitude during hops (194,215) but did not publish any reliability results. So, in phase two, a post hoc reliability analysis of BF excitation amplitude normalised (by MVC), unnormalised data and MVC alone (with/without outlier exclusion) were investigated to identify sources of poor reliability.

Rate of torque development (RTD) was investigated by the studies of the adapted methods (79,119) relative to peak torque. In both studies, RTD was measured based in the peak torque at specific percentages (30%, 60% and 90%). For instance, whenever torque curve reaches 30% of peak torque, RTD was calculated. However, this was chosen with no clear reasoning. In phase two, reliability of absolute RTD was analysed and was at 25, 50, 75, 100, 125, 150, 175, 200 ms. Absolute RTD (based on time, regardless of peak torque) can provide a better understanding of RTD deficits, as different physiological properties influence shorter (<75 ms) and longer (>75 ms) force rate production (240), and the spectrum we chose (from 25 to 200ms) covers both ranges. The total number of RTD types investigated for reliability were 11 (three relative and eight absolute).

6.3 Results

Due to its large amount, data is provided in Appendix 6.

6.3.1 Participants

Fourteen participants with PFP and 11 uninjured participants signed the consent form and were eligible, and all completed the first session. For the second session, four participants were lost; one from the uninjured group and three from the PFP group. Reasons and study flow is shown in Figure 6.3.

Tables 6.1 and 6.2 present the demographics.

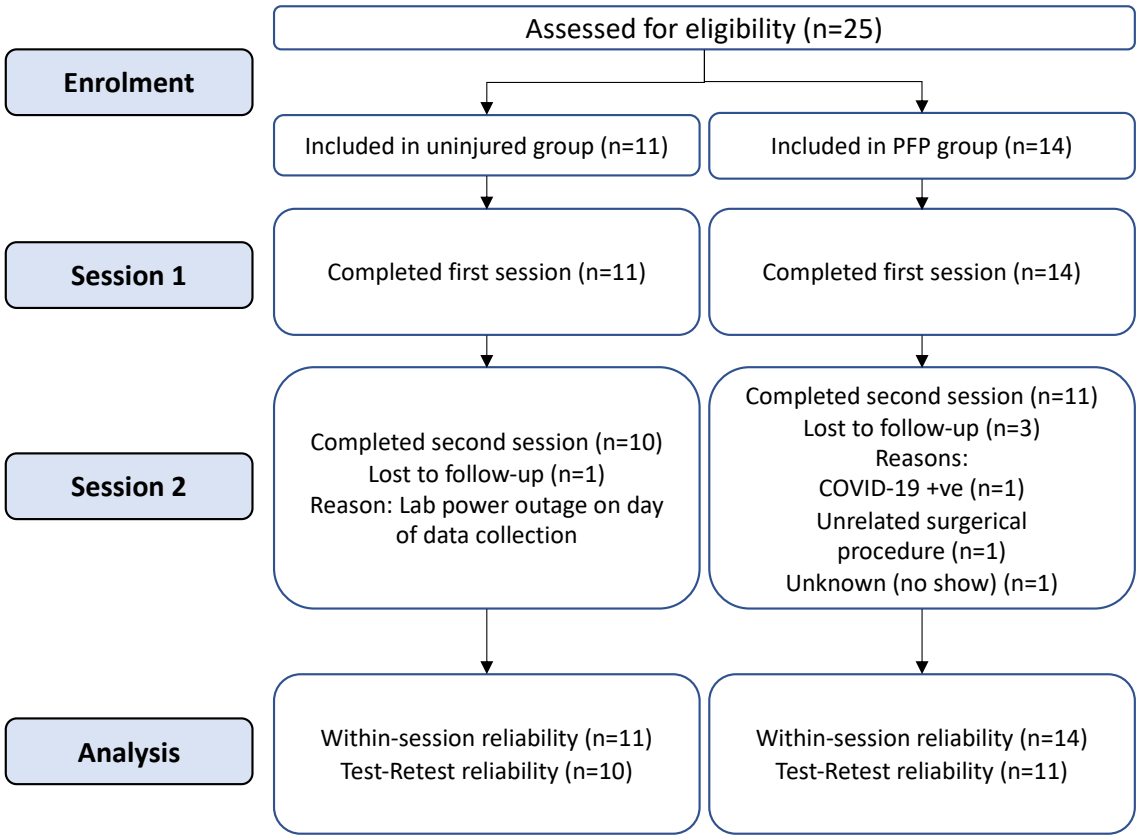


Figure 6.3: Study flow-chart.

Table 6.1: Demographics data for the whole sample (on which within-session reliability testing were conducted).

Within-Session		Mean	SD	Min	Max	Median	Male/ Female	Tested Side Rt/Lt	Dominant Side Rt/Lt	Symptomatic bilateral/ unilateral
PFP (n=14)	Age, yrs	27.14	4.28	19	34	27.50	10/4	6/8	13/1	8/6
	Height, m	1.72	0.09	1.58	1.86	1.72				
	Mass, Kg	72.58	17.12	53.80	117.80	67.68				
	BMI	24.47	4.11	19.93	34.05	23.08				
	VAS (0-10)	4.86	1.61	3.00	8.00	5.00				
	AKPS (0-100)	78.07	16.74	26.00	94.00	83.00				
Uninjured (n=11)	Age, yrs	27.73	4.45	19	35	27.00	5/6	11/0	11/0	NA
	Height, m	1.69	0.09	1.52	1.82	1.70				
	Mass, Kg	71.52	17.39	51.85	107.60	63.75				
	BMI	24.87	4.92	19.64	35.74	22.63				

Table 6.2: Demographics data for the samples on which test-retest reliability was conducted (attended test and retest sessions).

Test-Retest		Mean	SD	Min	Max	Median	Male/ Female	Tested Side Rt/Lt	Dominant Side Rt/Lt	Symptomatic bilateral/ unilateral
PFP (n=11)	Age, yrs	27.27	3.85	19	33	28.00	7/4	3/8	10/1	6/5
	Height, m	1.71	0.10	1.58	1.86	1.72				
	Mass, Kg	74.52	18.94	53.80	117.80	67.80				
	BMI	25.32	4.18	20.76	34.05	24.48				
	VAS (0-10)	5.00	1.73	3.00	8.00	5.00				
	AKPS (0-100)	74.91	17.58	26.00	90.00	82.00				
Uninjured (n=10)	Age, yrs	27.00	3.94	19	33	27.00	5/5	10/0	10/0	NA
	Height, m	1.69	0.10	1.52	1.82	1.72				
	Mass, Kg	72.30	18.12	51.85	107.60	64.58				
	BMI	25.14	5.10	19.64	35.74	22.95				

6.3.2 Reliability testing

6.3.2.1 Phase one

The within-session reliability results are presented in Table 6.3. It includes the results of all outcome measures except hamstrings flexibility, as data of flexibility testing was gathered once each session. The test-retest reliability results are presented in Table 6.4 and includes all outcome measures used in the protocol.

6.3.2.1.1 Reliability results of VM-VL onset timing in step-up (ms)

Reliability analysis of VM-VL EMG excitation onset timing show no agreement within-session (for PFP (0.312[0.09,0.615], SEM=108.02, CV=163.98%, MDC=299.4) and uninjured group (0.354[0.107,0.689], SEM=110.36, CV=59.75%, MDC=305.91). Test-retest reliability indicates poor reliability as well (for PFP (-0.276[-0.809,0.392],

SEM=120.93, CV=-63.39%, MDC=335.2) and uninjured group (-0.205[-0.772,0.473], SEM=131.47, CV=88.78%, MDC=364.41)).

The results indicate that the VM-VL excitation onsets detection method during a step-up task is not reliable in PFP and uninjured groups (Tables 6.3 and 6.4).

6.3.2.1.2 Reliability results of BF mean excitation amplitude in SLTHT (mV)

Results show that there are moderate to excellent within-session reliability for PFP (0.755[0.514,0.905], SEM=14.476, CV=14.689%, MDC=40.13) and uninjured group (0.997[0.992,0.999], SEM=36.578, CV=9.919%, MDC=101.39). Test-retest reliability is poor in both groups (PFP (0.049[-0.589,0.619], SEM=26.49, CV=25.44%, MDC=73.4) and uninjured (-0.019[-0.618,0.591], SEM=515.21, CV=28.93%, MDC=1428.1)). The protocol is not reliable in detecting BF mean excitation amplitude in both groups (Tables 6.3 and 6.4).

6.3.2.1.3 Reliability results of knee extensors peak isometric, concentric, and eccentric torques (Nm/kg)

For knee extensors peak torque tests, results indicate good to excellent within-session reliability for all peak torque types. The isometric, concentric and eccentric peak torque tests results were (0.962[0.902,0.987], SEM=12.85, CV=4.26%, MDC=35.63), (0.978[0.946,0.992], SEM=10.07, CV=4.02%, MDC=27.91), and (0.921[0.800,0.973], SEM=22.29, CV=7.06%, MDC=61.78), respectively. For the uninjured group, the results were (0.956[0.888,0.987], SEM=16.68, CV=5.78%, MDC=46.22), for isometric, (0.972[0.926,0.992], SEM=12.18, CV=4.80%, MDC=33.75) for concentric, and (0.951[0.871,0.985], SEM=30.02, CV=6.71%, MDC=83.2) for eccentric peak torque.

For the PFP, test-retest results show poor reliability for isometric peak torque (0.862[0.280,0.967], SEM=25.92, CV=9.36%, MDC=71.85) moderate reliability for concentric peak torque (0.903[0.694,0.972], SEM=20.44, CV=7.67%, MDC=56.65) and good reliability for eccentric peak torque (0.948[0.821,0.986], SEM=19.32, CV=6.21%, MDC=53.56). For the uninjured group, results show moderate reliability for isometric peak torque (0.905[0.681,0.975], SEM=25.68, CV=8.33%, MDC=71.18), and excellent reliability for concentric (0.976[0.911,0.994], SEM=12.28, CV=4.07%, MDC=34.03) and eccentric peak torque tests (0.974[0.900,0.994], SEM=23.44, CV=4.82%, MDC=64.97).

Concentric and eccentric peak torques can be reliably detected in PFP, unlike the isometric peak torque, which was unreliable in PFP only (Tables 6.3 and 6.4).

6.3.2.1.4 Rate of torque development to 30%, 60% and 90% of peak torque (Nm/s/kg)

For the PFP group, within-session analysis shows moderate reliability for RTD at 30% (0.825[0.638,0.933], SEM=131.86, CV=15.64%, MDC=365.5) and RTD at 60% (0.831[0.650,0.936], SEM=163.29, CV=19.36%, MDC=452.62) of peak torque. For RTD at 90% of peak torque, results indicate poor reliability (0.704[0.435,0.882], SEM=177.65, CV=36.99%, MDC=492.42). For the uninjured group, within-session analysis shows moderate reliability for RTD at 30% (0.891[0.729,0.966], SEM=130.07, CV=13.91%, MDC=360.53) and good reliability at 60% of peak torque (0.905[0.769,0.971], SEM=122.64, CV=15.22%, MDC=339.94). For RTD at 90% of peak torque, results were poorly reliable (0.354[0.019,0.719], SEM=158.97, CV=35.55%, MDC=440.65).

Regarding test-retest reliability, data of PFP group shows poor reliability for RTD at 30% (0.828[0.480,0.951], SEM=89.15, CV=13.52%, MDC=247.12) and RTD at 60% ((0.823[0.461,0.949], SEM=107.43, CV=12.21%, MDC=297.77) of peak torque. For RTD at 90% of peak torque, results indicate moderate reliability (0.915[0.724,0.976], SEM=52.50, CV=22.08%, MDC=145.53). For the uninjured group, test-retest analysis shows moderate reliability for RTD at 30% (0.923[0.556,0.983], SEM=99.79, CV=8.85%, MDC=276.6) and poor reliability at 60% (0.823[0.298,0.956], SEM=150.33, CV=15.91%, MDC=416.68) and 90% of peak torque (0.417[-0.123,0.804], SEM=99.08, CV=29.73%, MDC=274.65). therefore, results indicate the RTD tests were poorly reliable except for the RTD at 90% of peak torque (Tables 6.3 and 6.4).

6.3.2.1.5 Hamstrings flexibility (degrees °)

For hamstrings tightness test, results of test-retest reliability show excellent reliability in the PFP group (0.990[0.940,0.998], SEM=1.12, CV=14.54%, MDC=3.1) and moderate reliability for uninjured group (0.915[0.721,0.976], SEM=3.11, CV=9.60%, MDC=8.62), indicating a reliable detection of hamstrings flexibility deficits (Tables 6.3 and 6.4).

Table 6.3: Within-session reliability results of all outcome measures (except hamstrings flexibility). For reliability scores; $ICC_{3,1}$-Two-way mixed, absolute agreement, single measures with 95% confidence intervals, standard error of measurement (SEM), coefficient of variation % (CV) and minimal detectable change (MDC). Three repetitions were used for all except VM-VL timing (5 steps).

Groups	Repetition 1		Repetition 2		Repetition 3		Repetition 4		Repetition 5		Reliability scoring (Within-session)					
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	ICC	lower CI	Upper CI	SEM	CV	MDC
VM-VL EMG excitation onset in step-up task (ms) (mean + 3*SD of baseline and 25 ms for the double-thresholds method parameters)																
PFP n=14	-43.79	165.65	-24.50	74.81	-57.79	127.34	-69.79	138.33	-23.86	140.97	0.312	**0.090**	0.615	108.02	163.98	299.4
Uninjured n=11	-52.09	166.90	10.73	70.05	-23.00	71.09	-65.45	167.82	-85.36	172.05	0.354	**0.107**	0.689	110.36	59.75	305.91
BF mean excitation amplitude in single-leg triple hop-test (mV) normalised by MVC																
PFP n=14	92.03	30.44	88.42	28.51	91.98	30.79					0.755	**0.514**	0.905	14.476	14.689	40.13
Uninjured n=11	302.60	670.83	294.73	666.26	312.84	730.10					0.997	**0.992**	0.999	36.578	9.919	101.39
Knee extensors isometric peak torque (60° of flexion; Nm/kg)																
PFP n=14	238.91	68.74	226.31	64.56	228.35	68.70					0.962	**0.902**	0.987	12.85	4.26	35.63
Uninjured n=11	259.56	75.31	270.11	85.72	261.10	84.45					0.956	**0.888**	0.987	16.68	5.78	46.22
Knee extensors concentric peak torque (from 90° to 20°; Nm/kg)																
PFP n=14	197.59	68.11	204.08	69.48	205.54	70.93					0.978	**0.946**	0.992	10.07	4.02	27.91
Uninjured n=11	214.97	73.40	220.92	75.04	220.72	76.81					0.972	**0.926**	0.992	12.18	4.80	33.75
Knee extensors eccentric peak torque (from 20° to 90°; Nm/kg)																
PFP n=14	295.84	85.80	303.85	73.68	320.11	81.91					0.921	**0.800**	0.973	22.29	7.06	61.78
Uninjured n=11	332.94	141.26	341.57	134.73	360.13	142.50					0.951	**0.871**	0.985	30.02	6.71	83.2
Knee extensors rate of torque development to 30% of peak isometric contraction (Nm/sec/Kg)																
PFP n=14	728.87	358.10	673.12	324.95	646.24	275.15					0.825	**0.638**	0.933	131.86	15.64	365.5
Uninjured n=11	784.81	320.21	895.98	476.48	790.62	398.11					0.891	**0.729**	0.966	130.07	13.91	360.53
Knee extensors rate of torque development to 60% of peak isometric contraction (Nm/sec/Kg)																
PFP n=14	722.08	480.70	671.65	398.66	622.62	319.81					0.831	**0.650**	0.936	163.29	19.36	452.62
Uninjured n=11	760.44	341.39	803.03	503.61	713.05	363.30					0.905	**0.769**	0.971	122.64	15.22	339.94
Knee extensors rate of torque development to 90% of peak isometric contraction (Nm/sec/Kg)																
PFP n=14	314.64	454.65	306.64	287.76	262.36	212.23					0.704	**0.435**	0.882	177.65	36.99	492.42
Uninjured n=11	313.46	212.92	215.48	127.24	363.72	226.18					0.354	**0.019**	0.719	158.97	35.55	440.65

Reliability scores' colours (based on lower 95% CI of ICC)	ICC< 0.5 are considered poorly reliable	0.5 to 0.75 is moderately reliable	0.75 to 0.9 indicate good reliability	>0.9 indicate excellent reliability

Table 6.4: Test-retest reliability of all outcome measures within the protocol. For reliability scores; $ICC_{3,1}$-Two-way mixed, absolute agreement, single measures with 95% confidence intervals, standard error of measurement (SEM), coefficient of variation % (CV) and minimal detectable change (MDC).

Groups	Session 1		Session 2		Reliability scoring (Test-Retest)					
	mean	SD	mean	SD	ICC	lower CI	Upper CI	SEM	CV	MDC
VM-VL EMG excitation onset in step-up task (ms) (mean + 3*SD of baseline and 25 ms for the double-thresholds method parameters)										
PFP n=11	-34.62	98.02	-67.73	117.71	-0.276	**-0.809**	0.392	120.93	63.39	335.2
Uninjured n=10	-21.18	67.20	-68.74	156.55	-0.205	**-0.772**	0.473	131.47	88.78	364.41
BF mean excitation amplitude in single-leg triple hop-test (mV); normalised by MVC										
PFP n=11	88.87	26.88	81.31	28.21	0.049	**-0.589**	0.619	26.49	25.44	73.4
Uninjured n=10	327.65	721.32	100.15	29.65	-0.019	**-0.618**	0.591	515.21	28.93	1428.1
Knee extensors isometric peak torque (60° of flexion; Nm/kg)										
PFP n=11	227.18	72.22	254.52	67.80	0.862	**0.280**	0.967	25.92	9.36	71.85
Uninjured n=10	276.78	87.92	266.28	82.85	0.905	**0.681**	0.975	25.68	8.33	71.18
Knee extensors concentric peak torque (from 90° to 20°; Nm/kg)										
PFP n=11	195.28	72.29	205.92	61.27	0.903	**0.694**	0.972	20.44	7.67	56.65
Uninjured n=10	234.40	81.26	238.70	81.54	0.976	**0.911**	0.994	12.28	4.07	34.03
Knee extensors eccentric peak torque (from 20° to 90°; Nm/kg)										
PFP n=11	312.50	80.30	324.76	92.44	0.948	**0.821**	0.986	19.32	6.21	53.56
Uninjured n=10	359.52	145.75	358.84	152.84	0.974	**0.900**	0.994	23.44	4.82	64.97
Knee extensors rate of torque development to 30% of peak isometric contraction; (Nm/sec/Kg)										
PFP n=11	603.64	237.90	621.42	200.68	0.828	**0.480**	0.951	89.15	13.52	247.12
Uninjured n=10	851.96	399.41	753.96	328.85	0.923	**0.556**	0.983	99.79	8.85	276.6
Knee extensors rate of torque development to 60% of peak isometric contraction; (Nm/sec/Kg)										
PFP n=11	562.49	275.72	555.90	246.72	0.823	**0.461**	0.949	107.43	12.21	297.77
Uninjured n=10	786.86	406.27	642.37	304.75	0.823	**0.298**	0.956	150.33	15.91	416.68
Knee extensors rate of torque development to 90% of peak isometric contraction; (Nm/sec/Kg)										
PFP n=11	244.41	197.12	227.77	170.58	0.915	**0.724**	0.976	52.50	22.08	145.53
Uninjured n=10	307.76	153.10	194.34	70.46	0.417	**-0.123**	0.804	99.08	29.73	274.65
Hamstrings flexibility (popliteal angle in supine lying)										
PFP n=11	19.40	11.18	18.40	11.78	0.990	**0.940**	0.998	1.12	14.54	3.1
Uninjured n=10	16.82	12.14	14.91	9.49	0.915	**0.721**	0.976	3.11	9.60	8.62

Reliability scores' colours (based on lower 95% CI of ICC)	ICC< 0.5 are considered poorly reliable	0.5 to 0.75 is moderately reliable	0.75 to 0.9 indicate good reliability	>0.9 indicate excellent reliability

6.3.2.2 Phase two

6.3.2.2.1 VM-VL excitation onset timing in step-up (ms)

6.3.2.2.1.1 Within-session reliability of VM-VL timing

Threshold combination yielding highest reliability scores were 5 SDs and 25 ms for the PFP group (0.497[0.260,0.753], SEM=68.76, CV=16.88, MDC=190.59) and 11 SD and 50 ms for the PFP group (0.675[0.431,0.878], SEM=18.94, CV=171.80, MDC=52.49). Results indicate poor within-session reliability using all variations of thresholds in PFP and uninjured groups (Tables 6.5 and 6.6).

6.3.2.2.1.2 Test-retest reliability of VM-VL timing

Threshold combination showing highest reliability scores were 15 SDs and 25 ms for the PFP group (0.550[-0.120,0.868], SEM=30.24, CV=100.63, MDC=83.81), and 15 SDs and 25 ms for the uninjured group (0.220[-0.349,0.711], SEM=113.75, CV=204.9, MDC=315.30). Results indicate poor test-rest reliability using all variations of thresholds in PFP and uninjured groups (Tables 6.7 and 6.8).

Table 6.5: Within-session reliability results of phase two for VM-VL EMG excitation onset in step-up of the PFP group (n=14, n=13 from SD8) in milliseconds (ms). The double-thresholds method used with multiple thresholds' variations. "1st threshold" column shows the number of standard deviations (SD) used to define an onset. "2nd threshold" column shows the time-window variations used to define an onset (a signal exceeding SD(x) for at least (x)ms to be defined as an excitation onset). ICC; intraclass correlation coefficient. Lower 95% CI and Upper 95% CI; ICC's confidence interval. SEM; standard error of measurement in ms. CV; coefficient of variation in %. MDC; minimal detectable change. Original method (SD3 and 25ms) is underlined, and highest reliability scores are highlighted with grey. Based on the lower bound of the 95% CI of the ICC, all were poorly reliable.

Analysis type	1st threshold	2nd threshold	ICC	Lower 95% CI	Upper 95% CI	SEM	CV%	MDC
Within-session PFP (n=14, n=13 from SD8)	SD1	25ms	-0.061	-0.144	0.139	315.09	193.25	873.38
	SD1	50ms	-0.054	-0.139	0.150	314.90	202.08	872.87
	SD1	75ms	-0.052	-0.137	0.151	314.89	216.11	872.82
	SD1	100ms	-0.049	-0.134	0.155	314.27	213.09	871.11
	SD2	25ms	0.424	0.194	0.700	130.71	572.76	362.30
	SD2	50ms	0.430	0.200	0.705	129.69	567.52	359.47
	SD2	75ms	0.432	0.202	0.706	129.21	546.42	358.14
	SD2	100ms	0.431	0.201	0.705	128.37	599.84	355.83
	SD3	25ms	0.312	0.090	0.615	108.02	163.98	299.43
	SD3	50ms	0.306	0.086	0.610	107.78	58.44	298.76
	SD3	75ms	0.313	0.092	0.616	107.19	66.37	297.10
	SD3	100ms	0.293	0.075	0.599	109.58	44.81	303.73
	SD4	25ms	0.173	-0.012	0.480	108.33	67.73	300.28
	SD4	50ms	0.156	-0.024	0.463	108.77	110.27	301.50
	SD4	75ms	0.162	-0.020	0.469	109.58	89.14	303.74
	SD4	100ms	0.146	-0.032	0.452	111.41	93.92	308.81
	SD5	25ms	0.497	0.260	0.753	68.76	16.88	190.59
	SD5	50ms	0.472	0.234	0.737	70.47	58.82	195.34
	SD5	75ms	0.497	0.260	0.753	68.59	54.56	190.13
	SD5	100ms	0.462	0.224	0.730	71.57	59.12	198.37
	SD6	25ms	0.194	0.006	0.500	98.75	81.49	273.71
	SD6	50ms	0.206	0.012	0.514	99.25	34.19	275.10
	SD6	75ms	0.204	0.013	0.510	98.80	37.92	273.86
	SD6	100ms	0.224	0.029	0.531	104.28	27.55	289.05
	SD7	25ms	0.180	-0.007	0.488	86.03	58.54	238.46
	SD7	50ms	0.219	0.021	0.528	84.66	46.49	234.67
	SD7	75ms	0.243	0.043	0.548	85.29	65.62	236.41
	SD7	100ms	0.190	0.004	0.496	95.19	32.28	263.86
	SD8	25ms	0.247	0.034	0.570	81.61	67.73	226.22
	SD8	50ms	0.291	0.067	0.610	80.28	80.55	222.52
	SD8	75ms	0.300	0.078	0.616	81.66	56.27	226.34
	SD8	100ms	0.231	0.025	0.554	91.25	54.52	252.93
	SD9	25ms	0.332	0.099	0.645	70.23	47.22	194.66
	SD9	50ms	0.371	0.131	0.676	68.69	62.08	190.40
	SD9	75ms	0.382	0.142	0.684	68.33	38.20	189.39
	SD9	100ms	0.453	0.204	0.736	68.31	34.21	189.34
	SD10	25ms	0.193	-0.004	0.516	72.87	81.97	201.98
	SD10	50ms	0.211	0.009	0.535	74.00	73.18	205.13
	SD10	75ms	0.227	0.018	0.553	75.25	50.98	208.58
	SD10	100ms	0.260	0.049	0.579	74.26	49.28	205.83
	SD11	25ms	0.058	-0.092	0.359	88.02	133.77	243.97
	SD11	50ms	0.142	-0.034	0.458	89.52	145.88	248.14
	SD11	75ms	0.188	-0.005	0.509	89.40	168.64	247.79
	SD11	100ms	0.153	-0.027	0.470	88.81	167.83	246.17
	SD12	25ms	-0.017	-0.131	0.243	81.59	11.79	226.15
	SD12	50ms	0.106	-0.052	0.409	84.56	43.36	234.38
	SD12	75ms	0.169	-0.011	0.483	81.94	22.10	227.12
	SD12	100ms	0.169	-0.011	0.483	81.94	22.10	227.12
	SD13	25ms	0.128	-0.038	0.435	64.78	740.27	179.56
	SD13	50ms	0.329	0.107	0.636	65.71	701.07	182.14
	SD13	75ms	0.279	0.069	0.593	65.89	733.17	182.64
	SD13	100ms	0.279	0.069	0.593	65.89	733.17	182.64
	SD14	25ms	0.327	0.102	0.638	46.28	50.28	128.28
	SD14	50ms	0.490	0.249	0.756	49.30	10.97	136.66
	SD14	75ms	0.465	0.223	0.741	49.32	48.71	136.70
	SD14	100ms	0.398	0.159	0.694	49.65	60.60	137.63
	SD15	25ms	0.384	0.151	0.682	41.69	56.69	115.56
	SD15	50ms	0.442	0.198	0.726	44.14	73.24	122.36
	SD15	75ms	0.435	0.190	0.722	41.13	111.15	114.01
	SD15	100ms	0.394	0.150	0.693	44.39	37.83	123.05

Table 6.6: Within-session reliability results of phase two for VM-VL EMG excitation onset in step-up of the uninjured group (n=11) in milliseconds (ms). The double-thresholds method used with multiple thresholds' variations. "1st threshold" column shows the number of standard deviations (SD) used to define an onset. "2nd threshold" column shows the time-window variations used to define an onset (a signal exceeding SD(x) for at least (x)ms to be defined as an excitation onset). ICC; intraclass correlation coefficient. Lower 95% CI and Upper 95% CI; ICC's confidence interval. SEM; standard error of measurement in ms. CV; coefficient of variation in %. MDC; minimal detectable change. Original method (SD3 and 25ms) is underlined, and highest reliability scores are highlighted in grey. Based on the lower bound of the 95% CI of the ICC, all were poorly reliable.

Analysis type	1st threshold	2nd threshold	ICC	Lower 95% CI	Upper 95% CI	SEM	CV%	MDC
Within-session Uninjured (n=11)	SD1	25ms	0.482	0.210	0.778	189.16	123.16	524.32
	SD1	50ms	0.482	0.210	0.779	188.98	103.71	523.84
	SD1	75ms	0.482	0.210	0.779	188.98	103.71	523.84
	SD1	100ms	0.481	0.209	0.778	188.73	3.67	523.12
	SD2	25ms	0.493	0.228	0.783	124.19	85.64	344.23
	SD2	50ms	0.486	0.222	0.778	126.51	46.44	350.66
	SD2	75ms	0.486	0.222	0.778	126.51	46.44	350.66
	SD2	100ms	0.486	0.222	0.778	126.51	46.44	350.66
	SD3	25ms	0.354	0.107	0.689	110.36	59.75	305.91
	SD3	50ms	0.350	0.105	0.686	111.42	63.21	308.85
	SD3	75ms	0.350	0.105	0.686	111.42	63.21	308.85
	SD3	100ms	0.350	0.105	0.686	111.42	63.21	308.85
	SD4	25ms	0.243	0.036	0.587	67.32	86.75	186.60
	SD4	50ms	0.232	0.029	0.576	69.74	85.83	193.31
	SD4	75ms	0.232	0.029	0.576	69.74	85.83	193.31
	SD4	100ms	0.232	0.029	0.576	69.74	85.83	193.31
	SD5	25ms	0.218	0.010	0.569	52.65	174.51	145.93
	SD5	50ms	0.218	0.010	0.569	52.65	174.51	145.93
	SD5	75ms	0.225	0.015	0.576	51.52	138.36	142.81
	SD5	100ms	0.225	0.015	0.576	51.52	138.36	142.81
	SD6	25ms	0.309	0.068	0.656	36.07	148.58	99.97
	SD6	50ms	0.314	0.069	0.661	35.67	174.97	98.87
	SD6	75ms	0.346	0.093	0.686	35.07	45.27	97.21
	SD6	100ms	0.352	0.100	0.690	36.46	48.14	101.05
	SD7	25ms	0.301	0.058	0.651	38.47	64.43	106.62
	SD7	50ms	0.304	0.058	0.654	37.77	33.05	104.70
	SD7	75ms	0.339	0.089	0.680	38.37	33.67	106.37
	SD7	100ms	0.339	0.089	0.680	38.37	33.67	106.37
	SD8	25ms	0.421	0.158	0.739	31.51	60.51	87.34
	SD8	50ms	0.428	0.161	0.745	33.04	36.27	91.59
	SD8	75ms	0.441	0.176	0.752	32.15	33.96	89.13
	SD8	100ms	0.441	0.176	0.752	32.15	33.96	89.13
	SD9	25ms	0.581	0.319	0.832	22.69	49.62	62.89
	SD9	50ms	0.586	0.324	0.835	24.31	24.74	67.39
	SD9	75ms	0.496	0.228	0.786	25.95	29.32	71.94
	SD9	100ms	0.496	0.228	0.786	25.95	29.32	71.94
	SD10	25ms	0.568	0.303	0.826	22.42	35.57	62.15
	SD10	50ms	0.621	0.362	0.853	22.40	20.32	62.10
	SD10	75ms	0.573	0.306	0.829	23.33	22.70	64.67
	SD10	100ms	0.573	0.306	0.829	23.33	22.70	64.67
	SD11	25ms	0.585	0.317	0.835	19.59	166.60	54.30
	SD11	50ms	0.675	0.431	0.878	18.94	171.80	52.49
	SD11	75ms	0.626	0.368	0.855	19.82	169.69	54.93
	SD11	100ms	0.626	0.368	0.855	19.82	169.69	54.93
	SD12	25ms	0.615	0.354	0.850	18.57	68.31	51.49
	SD12	50ms	0.666	0.420	0.874	19.03	63.06	52.76
	SD12	75ms	0.634	0.380	0.859	19.40	64.65	53.77
	SD12	100ms	0.634	0.380	0.859	19.40	64.65	53.77
	SD13	25ms	0.557	0.294	0.819	19.79	71.07	54.84
	SD13	50ms	0.632	0.379	0.858	19.60	67.03	54.34
	SD13	75ms	0.575	0.312	0.829	21.82	69.95	60.49
	SD13	100ms	0.575	0.312	0.829	21.82	69.95	60.49
	SD14	25ms	0.538	0.275	0.808	20.30	74.14	56.28
	SD14	50ms	0.607	0.349	0.846	19.71	68.68	54.63
	SD14	75ms	0.585	0.324	0.834	21.63	70.61	59.95
	SD14	100ms	0.585	0.324	0.834	21.63	70.61	59.95
	SD15	25ms	0.529	0.267	0.803	21.80	81.35	60.43
	SD15	50ms	0.602	0.345	0.842	20.91	77.24	57.95
	SD15	75ms	0.568	0.310	0.824	22.75	80.94	63.05
	SD15	100ms	0.568	0.310	0.824	22.75	80.94	63.05

Table 6.7: Test-retest reliability results of phase two for VM-VL EMG excitation onset in step-up of the PFP group (n=11, n=10 from SD8) in milliseconds (ms). The double-thresholds method used with multiple thresholds' variations. "1st threshold" column shows the number of standard deviations (SD) used to define an onset. "2nd threshold" column shows the time-window variations used to define an onset (a signal exceeding SD(x) for at least (x)ms to be defined as an excitation onset). ICC; intraclass correlation coefficient. Lower 95% CI and Upper 95% CI; ICC's confidence interval. SEM; standard error of measurement in ms. CV; coefficient of variation in %. MDC; minimal detectable change. Original method (SD3 and 25ms) is underlined, and highest reliability scores are highlighted with grey. Based on the lower bound of the 95% CI of the ICC, all were poorly reliable.

Analysis type	1st threshold	2nd threshold	ICC	Lower 95% CI	Upper 95% CI	SEM	CV%	MDC
Test-retest PFP (n=11, n=10 from SD8)	SD1	25ms	0.235	-0.439	0.721	120.07	49.51	332.83
	SD1	50ms	0.208	-0.478	0.709	123.79	34.22	343.13
	SD1	75ms	0.207	-0.480	0.709	125.18	34.88	346.99
	SD1	100ms	0.215	-0.472	0.713	124.77	38.15	345.85
	SD2	25ms	-0.013	-0.634	0.580	143.36	35.33	397.38
	SD2	50ms	-0.011	-0.638	0.582	143.02	29.25	396.44
	SD2	75ms	-0.029	-0.658	0.573	144.07	31.82	399.34
	SD2	100ms	-0.033	-0.657	0.569	144.07	11.25	399.34
	SD3	25ms	-0.276	-0.809	0.392	120.93	63.39	335.20
	SD3	50ms	-0.312	-0.833	0.361	121.90	56.77	337.89
	SD3	75ms	-0.258	-0.813	0.411	126.23	62.51	349.89
	SD3	100ms	-0.263	-0.821	0.410	127.92	48.94	354.57
	SD4	25ms	-0.417	-0.927	0.286	87.46	126.93	242.43
	SD4	50ms	-0.464	-0.950	0.240	89.12	58.76	247.02
	SD4	75ms	-0.422	-0.929	0.281	95.22	77.10	263.93
	SD4	100ms	-0.440	-0.939	0.263	95.18	75.65	263.82
	SD5	25ms	0.000	-0.663	0.597	71.26	90.91	197.52
	SD5	50ms	0.151	-0.512	0.677	71.20	78.42	197.36
	SD5	75ms	0.093	-0.579	0.649	72.69	86.10	201.47
	SD5	100ms	0.072	-0.601	0.638	72.67	84.54	201.44
	SD6	25ms	-0.051	-0.703	0.566	63.52	168.42	176.07
	SD6	50ms	0.199	-0.472	0.702	62.85	161.03	174.20
	SD6	75ms	0.082	-0.597	0.645	63.09	166.82	174.88
	SD6	100ms	0.133	-0.564	0.674	61.17	167.55	169.55
	SD7	25ms	0.129	-0.551	0.669	52.44	26.07	145.37
	SD7	50ms	0.297	-0.354	0.748	54.05	24.11	149.81
	SD7	75ms	0.212	-0.476	0.712	54.80	33.04	151.89
	SD7	100ms	0.172	-0.528	0.694	52.79	34.24	146.32
	SD8	25ms	0.011	-0.691	0.630	54.19	278.41	150.20
	SD8	50ms	0.090	-0.613	0.669	54.52	285.73	151.13
	SD8	75ms	-0.147	-0.813	0.538	57.52	286.47	159.43
	SD8	100ms	-0.140	-0.812	0.543	56.96	284.36	157.88
	SD9	25ms	0.134	-0.582	0.693	50.65	393.10	140.40
	SD9	50ms	0.194	-0.524	0.721	50.61	391.17	140.28
	SD9	75ms	-0.091	-0.779	0.573	56.30	391.47	156.06
	SD9	100ms	-0.012	-0.720	0.619	59.58	395.26	165.14
	SD10	25ms	0.315	-0.389	0.775	41.55	7.69	115.18
	SD10	50ms	0.293	-0.428	0.767	44.37	9.08	122.99
	SD10	75ms	-0.010	-0.724	0.621	50.89	0.07	141.05
	SD10	100ms	0.024	-0.697	0.640	51.25	11.41	142.05
	SD11	25ms	0.243	-0.374	0.731	49.75	74.60	137.89
	SD11	50ms	0.339	-0.327	0.781	53.18	58.60	147.41
	SD11	75ms	0.152	-0.569	0.702	55.78	70.20	154.62
	SD11	100ms	0.037	-0.623	0.635	138.89	76.44	384.99
	SD12	25ms	0.323	-0.383	0.779	36.80	134.60	102.00
	SD12	50ms	0.379	-0.362	0.805	45.02	107.58	124.78
	SD12	75ms	0.104	-0.604	0.677	50.85	117.12	140.95
	SD12	100ms	0.019	-0.566	0.609	140.43	125.11	389.25
	SD13	25ms	0.237	-0.483	0.742	39.14	238.42	108.49
	SD13	50ms	0.369	-0.351	0.800	47.77	185.85	132.40
	SD13	75ms	0.107	-0.579	0.675	53.44	184.43	148.12
	SD13	100ms	0.067	-0.519	0.635	135.69	192.79	376.10
	SD14	25ms	0.236	-0.499	0.743	44.22	716.03	122.57
	SD14	50ms	0.331	-0.382	0.783	47.90	700.30	132.78
	SD14	75ms	0.039	-0.546	0.619	137.92	711.55	382.29
	SD14	100ms	0.077	-0.536	0.646	133.42	703.76	369.83
	SD15	25ms	0.550	-0.120	0.868	30.24	100.63	83.81
	SD15	50ms	0.368	-0.327	0.797	43.61	86.15	120.89
	SD15	75ms	0.037	-0.545	0.617	135.95	696.65	376.83
	SD15	100ms	0.068	-0.532	0.639	256.39	696.52	710.68

Table 6.8: Test-retest reliability results of phase two for VM-VL EMG excitation onset in step-up of the uninjured group (n=10) in milliseconds (ms). The double-thresholds method used with multiple thresholds' variations. "1st threshold" column shows the number of standard deviations (SD) used to define an onset. "2nd threshold" column shows the time-window variations used to define an onset (a signal exceeding SD(x) for at least (x)ms to be defined as an excitation onset). ICC; intraclass correlation coefficient. Lower 95% CI and Upper 95% CI; ICC's confidence interval. SEM; standard error of measurement in ms. CV; coefficient of variation in %. MDC; minimal detectable change. Original method (SD3 and 25ms) is underlined, and highest reliability scores are highlighted with grey. Based on the lower bound of the 95% CI of the ICC, all were poorly reliable.

Analysis type	1st threshold	2nd threshold	ICC	Lower 95% CI	Upper 95% CI	SEM	CV%	MDC
Test-retest Uninjured (n=10)	SD1	25ms	0.243	-0.400	0.734	210.53	723.6	583.55
	SD1	50ms	0.234	-0.410	0.730	211.72	579.6	586.86
	SD1	75ms	0.229	-0.413	0.728	212.57	776.8	589.22
	SD1	100ms	0.225	-0.416	0.726	212.59	766.9	589.26
	SD2	25ms	0.214	-0.359	0.709	111.33	394.9	308.58
	SD2	50ms	0.198	-0.378	0.701	113.79	227.6	315.41
	SD2	75ms	0.198	-0.384	0.703	114.26	239.4	316.71
	SD2	100ms	0.220	-0.349	0.711	113.75	204.9	315.30
	SD3	25ms	-0.205	-0.772	0.473	131.47	88.8	364.41
	SD3	50ms	-0.208	-0.781	0.474	132.23	87.3	366.52
	SD3	75ms	-0.212	-0.782	0.470	131.83	3610.8	365.42
	SD3	100ms	-0.188	-0.750	0.482	129.50	154.6	358.95
	SD4	25ms	-0.014	-0.573	0.583	103.72	81.6	287.48
	SD4	50ms	-0.017	-0.575	0.581	104.98	174.5	291.00
	SD4	75ms	-0.012	-0.582	0.587	103.76	175.4	287.60
	SD4	100ms	0.019	-0.555	0.605	101.11	175.8	280.26
	SD5	25ms	-0.064	-0.673	0.569	84.32	456.4	233.71
	SD5	50ms	-0.067	-0.667	0.564	85.43	458.5	236.79
	SD5	75ms	-0.085	-0.694	0.557	85.93	456.8	238.19
	SD5	100ms	-0.044	-0.661	0.582	82.52	458.7	228.73
	SD6	25ms	-0.001	-0.554	0.588	80.63	104.6	223.48
	SD6	50ms	0.022	-0.556	0.608	79.30	150.3	219.82
	SD6	75ms	0.050	-0.547	0.628	77.81	161.5	215.69
	SD6	100ms	0.078	-0.529	0.645	75.23	161.6	208.51
	SD7	25ms	-0.039	-0.569	0.560	68.88	62.2	190.92
	SD7	50ms	-0.030	-0.589	0.573	68.68	96.5	190.36
	SD7	75ms	0.163	-0.451	0.690	59.19	107.4	164.06
	SD7	100ms	0.152	-0.475	0.687	59.47	109.4	164.85
	SD8	25ms	-0.250	-0.782	0.433	50.14	153.2	138.97
	SD8	50ms	-0.180	-0.792	0.503	46.78	95.7	129.68
	SD8	75ms	-0.025	-0.674	0.600	41.30	88.8	114.47
	SD8	100ms	-0.025	-0.674	0.600	41.30	88.8	114.47
	SD9	25ms	-0.280	-0.806	0.410	50.69	248.5	140.49
	SD9	50ms	-0.140	-0.780	0.534	44.79	280.5	124.14
	SD9	75ms	-0.119	-0.736	0.539	41.03	284.2	113.74
	SD9	100ms	-0.119	-0.736	0.539	41.03	284.2	113.74
	SD10	25ms	-0.320	-0.818	0.373	50.03	121.0	138.66
	SD10	50ms	-0.082	-0.735	0.570	41.56	93.0	115.20
	SD10	75ms	-0.118	-0.732	0.540	41.37	88.2	114.68
	SD10	100ms	-0.118	-0.732	0.540	41.37	88.2	114.68
	SD11	25ms	-0.273	-0.802	0.416	46.67	78.0	129.37
	SD11	50ms	-0.118	-0.757	0.547	41.94	74.8	116.24
	SD11	75ms	-0.137	-0.742	0.526	41.31	69.4	114.52
	SD11	100ms	-0.137	-0.742	0.526	41.31	69.4	114.52
	SD12	25ms	-0.334	-0.839	0.367	47.94	77.2	132.90
	SD12	50ms	-0.252	-0.843	0.454	42.40	66.9	117.53
	SD12	75ms	-0.191	-0.768	0.485	40.88	62.9	113.30
	SD12	100ms	-0.191	-0.768	0.485	40.88	62.9	113.30
	SD13	25ms	-0.263	-0.787	0.421	44.00	84.4	121.97
	SD13	50ms	-0.153	-0.754	0.515	41.59	78.1	115.28
	SD13	75ms	-0.078	-0.659	0.553	198.02	69.4	548.88
	SD13	100ms	-0.032	-0.626	0.582	502.84	69.1	1393.80
	SD14	25ms	-0.307	-0.836	0.395	44.59	79.9	123.60
	SD14	50ms	-0.178	-0.761	0.495	40.97	67.5	113.55
	SD14	75ms	-0.082	-0.668	0.552	198.72	66.1	550.82
	SD14	100ms	-0.033	-0.629	0.582	503.47	65.8	1395.56
	SD15	25ms	-0.366	-0.878	0.349	43.65	83.6	120.99
	SD15	50ms	-0.202	-0.765	0.474	44.06	567.1	122.13
	SD15	75ms	-0.035	-0.629	0.581	508.63	565.4	1409.86
	SD15	100ms	-0.018	-0.616	0.591	989.01	565.3	2741.41

6.3.2.2.2 BF mean excitation amplitude in Single-leg triple-hop test (mV)

Within the uninjured group, the data of one participant (during SLTHT only, not MVC) were abnormal and was treated as an outlier in phase two (Appendix 6). Also, the unnormalised BF mean excitation amplitude and MVC data were analysed for reliability to help understand possible sources of poor reliability. Table 6.9 summarises all results from phases one and two.

6.3.2.2.2.1 Within-session reliability of BF mean excitation amplitude in SLTHT

Within-session reliability findings for the uninjured group showed excellent reliability (as presented in phase one), but moderate reliability with the outlier excluded (0.775[0.502,0.931], SEM=10.83, CV=10.42%, MDC=30.01). Therefore, the protocol is reliable within-session, in both groups (Table 6.9).

Within-session reliability of the unnormalised BF mean excitation amplitude and MVC data alone show higher reliability findings. The unnormalised BF mean excitation amplitude show good reliability for the PFP group (0.898[0.771,0.963], SEM=69.32, CV=14.69%, MDC=192.15). For the uninjured group excellent reliability was yielded with the outlier (0.996[0.989,0.999], SEM=52.18, CV=9.92%, MDC=144.65) and good reliability without outlier (0.955[0.873,0.988], SEM=31.56, CV=10.42%, MDC=87.48) (Table 6.9).

6.3.2.2.2.2 Test-retest reliability of BF mean excitation amplitude in SLTHT

Test-retest reliability showed poor results for both groups, except for the unnormalised data of the uninjured group. The unnormalised data of the PFP group showed poor reliability (0.59[-0.01,0.87], SEM=71.34, CV=16.77%, MDC=197.75). With the outlier included, the uninjured group showed poor reliability as well (-0.037[-0.647,0.583], SEM=653.38, CV=20.01%, MDC=1811.06). However, without the outlier, findings extremely improved reaching moderate reliability (0.967[0.686,0.994], SEM=27.58, CV=8.16%, MDC=76.45) for the unnormalised data of the uninjured group. The unnormalised data is moderately reliable in the uninjured group but unreliable in the PFP group (Table 6.9).

When MVC data were solely analysed, poor reliability was found in both groups (PFP (0.731[0.262,0.92], SEM=110.57, CV=18.39%, MDC=306.49) and uninjured (0.671[0.164,0.904], SEM=83.84, CV=21.87%, MDC=232.38)). This indicates that MVC is a possible source for poor reliability, but only in the uninjured group, and that the protocol is unreliable to detect BF mean excitation amplitude in PFP (Table 6.9).

Table 6.9: Reliability results of BF mean excitation amplitude during single-leg triple-hop test; within-session (PFP n=14 and uninjured n=11) and test-retest (PFP n=11 and uninjured n=10). One outlier (within the uninjured group) was removed, and data re-analysed. MVC; Maximum voluntary contraction. Original analyses are underlined.

Analysis type		BF mean excitation amplitude during SLTHT	ICC	Lower 95% CI	Upper 95% CI	SEM	CV%	MDC
Within-session	PFP n=14	Normalised	0.755	0.514	0.905	14.48	14.69	40.13
		Not normalised	0.898	0.771	0.963	69.32	14.69	192.15
		MVC only	0.953	0.892	0.983	44.10	7.911	122.232
	Uninjured n=11	Normalised	0.997	0.992	0.999	36.58	9.92	101.39
		and outlier removed	0.775	0.502	0.931	10.83	10.42	30.01
		Not normalised	0.996	0.989	0.999	52.18	9.92	144.65
		and outlier removed	0.955	0.873	0.988	31.56	10.42	87.48
		MVC only	0.988	0.966	0.996	19.80	7.63	54.87
Test-retest	PFP n=11	Normalised	0.05	-0.59	0.62	26.49	25.44	73.43
		Not normalised	0.59	-0.01	0.87	71.34	16.77	197.75
		MVC only	0.73	0.26	0.92	110.57	18.39	306.49
	Uninjured n=10	Normalised	-0.019	-0.618	0.591	515.21	28.93	1428.10
		and outlier removed	0.309	-0.49	0.796	20.50	17.45	56.82
		Not normalised	-0.037	-0.647	0.583	653.38	20.01	1811.06
		and outlier removed	0.967	0.686	0.994	27.58	8.16	76.45
		MVC only	0.671	0.164	0.904	83.84	21.87	232.38

6.3.2.2.3 Absolute rate of torque development (Nm/s/kg)

6.3.2.2.3.1 Within-session reliability of absolute RTD

For the PFP group, all absolute reliability tests were moderately reliable, from (0.802[0.598,0.924], SEM=183.85, CV=19.82%, MDC=509.62) for RTD to 75ms to (0.886[0.746,0.958], SEM=83.51, CV=11.97%, MDC=231.48) for RTD to 200ms. For the uninjured group, all findings showed moderate and good reliability, ranging from (0.807[0.563,0.938], SEM=138.07, CV=15.78%, MDC=382.72) for RTD to 25ms, to (0.929[0.813,0.979], SEM=68.46, CV=8.39%, MDC=189.77) for RTD to 200ms (Table 6.10).

6.3.2.2.3.2 Test-retest reliability of RTD

Data analysis yielded different results in both groups. Analyses from the PFP group showed moderate reliability in RTD to 25 and 50 ms, (0.862[0.562,0.961], SEM=80.87, CV=14.70%, MDC=224.16) and (0.846[0.522,0.956], SEM=103.24, CV=15.28%, MDC=286.15), accordingly. For the uninjured group, moderate reliability was found in RTD to 150 and 175 ms, (0.922[0.533,0.983], SEM=88.94, CV=8.99%, MDC=246.53) and (0.918[0.550,0.981], SEM=81.57, CV=8.70%, MDC=226.11), respectively. The rest of the RTD time-points showed poor reliability (Table 6.11).

Table 6.10: Within-session reliability results of isokinetic knee extension torque tests and rate of torque development (RTD). PFP n=14 and uninjured n=11. Underlined data represents phase one and were mentioned previously under phase one reliability results. PT; peak torque.

Analysis type		Peak torque and RTD	ICC	Lower 95% CI	Upper 95% CI	SEM	CV	MDC
Within-session	PFP n=14	Isometric PT (60d of flexion)	0.962	0.902	0.987	12.85	4.26	35.63
		Concentric PT (90d to 20d)	0.978	0.946	0.992	10.07	4.02	27.91
		Eccentric PT (20d to 90d)	0.921	0.800	0.973	22.29	7.06	61.78
		RTD to 30% of Iso.PT	0.825	0.638	0.933	131.86	15.64	365.50
		RTD to 60% of Iso.PT	0.831	0.650	0.936	163.29	19.36	452.62
		RTD to 90% of Iso.PT	0.704	0.435	0.882	177.65	36.99	492.42
		RTD to 25 ms (Absolute)	0.825	0.636	0.934	122.43	19.86	339.36
		RTD to 50 ms (Absolute)	0.806	0.605	0.926	164.24	20.45	455.26
		RTD to 75 ms (Absolute)	0.802	0.598	0.924	183.85	19.82	509.62
		RTD to 100 ms (Absolute)	0.807	0.607	0.926	181.05	18.56	501.86
		RTD to 125 ms (Absolute)	0.819	0.626	0.931	160.36	17.18	444.50
		RTD to 150 ms (Absolute)	0.837	0.657	0.939	131.90	15.65	365.60
		RTD to 175 ms (Absolute)	0.863	0.703	0.949	104.28	13.79	289.06
		RTD to 200 ms (Absolute)	0.886	0.746	0.958	83.51	11.97	231.48
	Uninjured n=11	Isometric PT (60d of flexion)	0.956	0.888	0.987	16.68	5.78	46.22
		Concentric PT (90d to 20d)	0.972	0.926	0.992	12.18	4.80	33.75
		Eccentric PT (20d to 90d)	0.951	0.871	0.985	30.02	6.71	83.20
		RTD to 30% of Iso.PT	0.891	0.729	0.966	130.07	13.91	360.53
		RTD to 60% of Iso.PT	0.905	0.769	0.971	122.64	15.22	339.94
		RTD to 90% of Iso.PT	0.354	0.019	0.719	158.97	35.55	440.65
		RTD to 25 ms (Absolute)	0.807	0.563	0.938	138.07	15.78	382.72
		RTD to 50 ms (Absolute)	0.849	0.643	0.953	147.70	15.06	409.39
		RTD to 75 ms (Absolute)	0.880	0.706	0.963	141.61	13.97	392.52
		RTD to 100 ms (Absolute)	0.903	0.758	0.970	126.17	12.72	349.73
		RTD to 125 ms (Absolute)	0.920	0.795	0.976	106.09	11.44	294.06
		RTD to 150 ms (Absolute)	0.928	0.811	0.978	89.23	10.26	247.34
		RTD to 175 ms (Absolute)	0.929	0.812	0.979	77.68	9.26	215.31
		RTD to 200 ms (Absolute)	0.929	0.813	0.979	68.46	8.39	189.77

Table 6.11: Test-retest reliability results of isokinetic knee extension torque tests and rate of torque development (PFP n=11 and uninjured n=10). PT; peak torque. Underlined data represents phase one and were mentioned previously under phase one reliability results. PT; peak torque.

Analysis type		Peak torque and RTD	ICC	Lower 95% CI	Upper 95% CI	SEM	CV	MDC
Test-retest	PFP=11	Isometric PT (60d of flexion)	0.862	0.280	0.967	25.92	9.36	71.85
		Concentric PT (90d to 20d)	0.903	0.694	0.972	20.44	7.67	56.65
		Eccentric PT (20d to 90d)	0.948	0.821	0.986	19.32	6.21	53.56
		RTD to 30% of Iso.PT	0.828	0.480	0.951	89.15	13.52	247.12
		RTD to 60% of Iso.PT	0.823	0.461	0.949	107.43	12.21	297.77
		RTD to 90% of Iso.PT	0.915	0.724	0.976	52.50	22.08	145.53
		RTD to 25 ms (Absolute)	0.862	0.562	0.961	80.87	14.70	224.16
		RTD to 50 ms (Absolute)	0.846	0.522	0.956	103.24	15.28	286.15
		RTD to 75 ms (Absolute)	0.823	0.465	0.949	115.40	14.82	319.86
		RTD to 100 ms (Absolute)	0.806	0.429	0.944	114.25	13.60	316.67
		RTD to 125 ms (Absolute)	0.808	0.442	0.944	101.12	13.24	280.30
		RTD to 150 ms (Absolute)	0.814	0.465	0.946	86.92	12.66	240.94
		RTD to 175 ms (Absolute)	0.816	0.473	0.946	77.17	11.98	213.89
		RTD to 200 ms (Absolute)	0.813	0.468	0.945	71.65	11.65	198.61
	Uninjured =10	Isometric PKT (60d of flexion)	0.905	0.681	0.975	25.68	8.33	71.18
		Concentric PKT (90d to 20d)	0.976	0.911	0.994	12.28	4.07	34.03
		Eccentric PKT (20d to 90d)	0.974	0.900	0.994	23.44	4.82	64.97
		RTD to 30% of Iso.PT	0.923	0.556	0.983	99.79	8.85	276.60
		RTD to 60% of Iso.PT	0.823	0.298	0.956	150.33	15.91	416.68
		RTD to 90% of Iso.PT	0.417	-0.123	0.804	99.08	29.73	274.65
		RTD to 25 ms (Absolute)	0.848	0.461	0.961	104.62	10.04	290.00
		RTD to 50 ms (Absolute)	0.885	0.447	0.973	114.32	10.09	316.89
		RTD to 75 ms (Absolute)	0.896	0.371	0.977	119.51	10.48	331.26
		RTD to 100 ms (Absolute)	0.900	0.361	0.978	117.71	10.43	326.26
		RTD to 125 ms (Absolute)	0.913	0.439	0.981	103.54	9.67	287.00
		RTD to 150 ms (Absolute)	0.922	0.533	0.983	88.94	8.99	246.53
		RTD to 175 ms (Absolute)	0.918	0.550	0.981	81.57	8.70	226.11
		RTD to 200 ms (Absolute)	0.904	0.495	0.978	79.12	8.82	219.30

6.3.2.3 Summary of reliability findings

The results of within-session and test-retest reliability were variable. Therefore, a summary of all findings of phases one and two are presented in table 6.12, and in figures 6.4 and 6.5.

Table 6.12: Summary of reliability results of analyses phases one and two.

Phase one of reliability analyses						
	outcome measures		Within-session		Test-retest	
Electromyography	VM-VL excitation onset in step-up	3 SD and 25 ms thresholds	PFP	Uninjured	PFP	Uninjured
	BF mean excitation amplitude in SLTHT (2nd hop landing)	normalised	PFP	Uninjured	PFP	Uninjured
knee extensors peak torque	Isometric		PFP	Uninjured	PFP	Uninjured
	Concentric		PFP	Uninjured	PFP	Uninjured
	Eccentric		PFP	Uninjured	PFP	Uninjured
Rate of torque development	Relative to peak torque	30% of peak	PFP	Uninjured	PFP	Uninjured
		60% of peak	PFP	Uninjured	PFP	Uninjured
		90% of peak	PFP	Uninjured	PFP	Uninjured
Flexibility	Hamstrings		NA		PFP	Uninjured

Phase two of reliability analyses						
	outcome measures		Within-session		Test-retest	
Electromyography	VM-VL excitation onset in step-up (from 1 SD to 15 SDs of baseline)	25 ms	PFP	Uninjured	PFP	Uninjured
		50 ms	PFP	Uninjured	PFP	Uninjured
		75 ms	PFP	Uninjured	PFP	Uninjured
		100 ms	PFP	Uninjured	PFP	Uninjured
	BF mean excitation amplitude in SLTHT (2nd hop landing)	No outlier	NA	Uninjured	NA	Uninjured
		Unnormalised	PFP	Uninjured	PFP	Uninjured
		No outlier	NA	Uninjured	NA	Uninjured
		MVC	PFP	Uninjured	PFP	Uninjured
Rate of torque development	Absolute	25 ms	PFP	Uninjured	PFP	Uninjured
		50 ms	PFP	Uninjured	PFP	Uninjured
		75 ms	PFP	Uninjured	PFP	Uninjured
		100 ms	PFP	Uninjured	PFP	Uninjured
		125 ms	PFP	Uninjured	PFP	Uninjured
		150 ms	PFP	Uninjured	PFP	Uninjured
		175 ms	PFP	Uninjured	PFP	Uninjured
		200 ms	PFP	Uninjured	PFP	Uninjured

Reliability scores' colours (based on lower 95% CI of ICC)	ICC< 0.5 are considered poorly reliable	0.5 to 0.75 is moderately reliable	0.75 to 0.9 indicate good reliability	>0.9 indicate excellent reliability

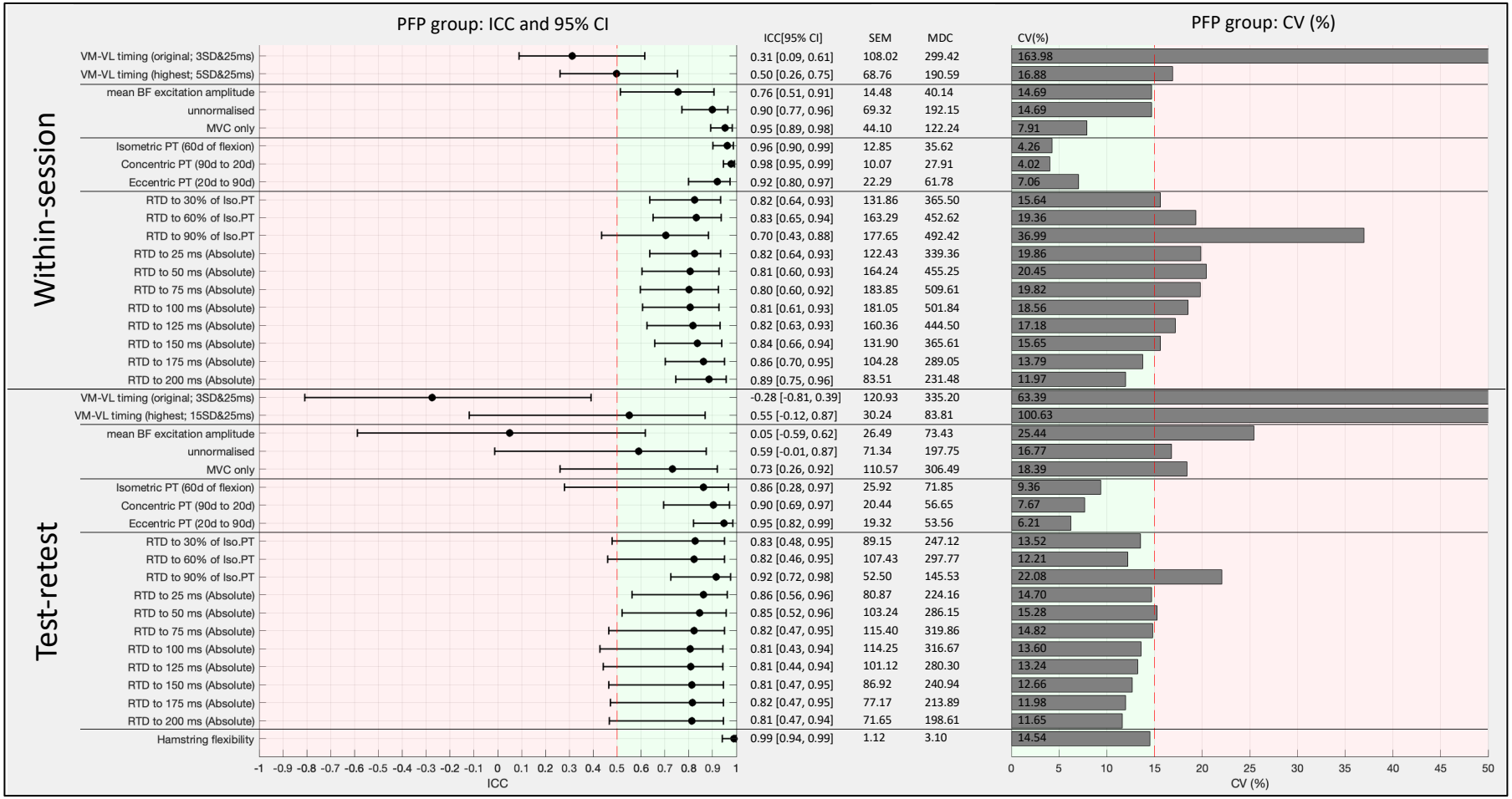


*Figure 6.4: Summary of reliability analyses of **PFP groups' data**. Within-session results are seen in the upper half of the figure, while test-retest data can be viewed at the bottom half. Outcome measures are listed on the left side, corresponding to the Intra-class correlation coefficient$_{3,1}$ and the 95% confidence intervals (ICC[95% CI]) seen in the first figure (left). The figure on the right shows the coefficient of variation (CV) in percentage, with a cut-off set at 15%. Data in the middle are titled, showing the ICCs and 95% CIs, the standard error of measurement (SEM) and the minimal detectable change (MDC). SEM and MDC are measured by the same units of the corresponding outcome measure. Unnormalised; unnormalised mean BF excitation amplitude. Iso.; Isometric. PT; Peak Torque. RTD; rate of torque development.*

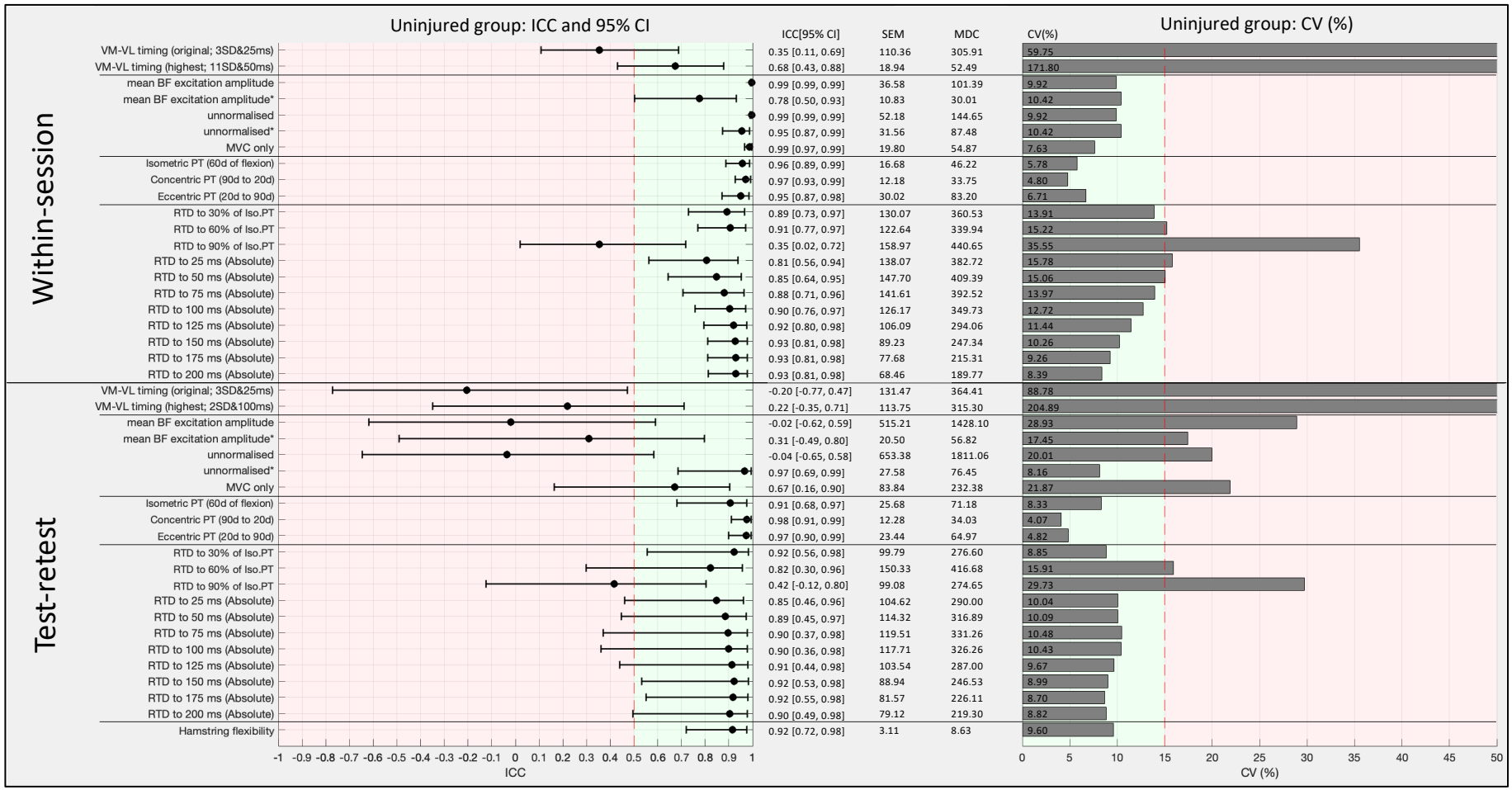


*Figure 6.5: Summary of reliability analyses of **uninjured groups' data**. Within-session results are seen in the upper half of the figure, while test-retest data can be viewed at the bottom half. Outcome measures are listed on the left side, corresponding to the Intra-class correlation coefficient$_{3,1}$ and the 95% confidence intervals (ICC [95% CI]) seen in the first figure (left). The figure on the right shows the coefficient of variation (CV) in percentage, with a cut-off set at 15%. Data in the middle are titled, showing the ICCs and 95% CIs, the standard error of measurement (SEM) and the minimal detectable change (MDC). SEM and MDC are measured by the same units of the corresponding outcome measure. Unnormalised; unnormalised mean BF excitation amplitude. Iso.; Isometric. PT; Peak Torque. RTD; rate of torque development. *= analysed with outlier removed.*

6.4 Discussion

The reliability analyses have clearly shown the importance of this chapter towards the overarching aim of the thesis. After thorough analysis, a reliable PFP deficit-detection protocol can include a) concentric and b) eccentric peak torques of the quadriceps, c) RTD to 25 ms and d) 50 ms, and e) hamstrings flexibility. The other outcome measures would require further reliability testing to ensure a sound progression into future studies in PFP.

6.4.1 Electromyography tests

6.4.1.1 VM-VL excitation onset timing in step-up

Although being one of the most investigated characteristics in the literature (72,75,103,133,196), this study failed to reach sufficiently reliable results for VM-VL excitation onset timing detection. We explored a spectrum of thresholds, above and beyond the derived method, but results remained the same.

In terms of reliability measures, results were high by Cowan et al. (249) (0.91 [0.67,0.98] (ICC [95%CI]), but Briani et al. (325) and Pazzinatto et al. (326) previously had unreliable results in the timing domain of VM and VL, similar to what we found. Briani et al. (325) had ICC scores of (0.26 [-1.95,0.45]) for the uninjured group and (0.59 [-0.02,0.83]) for the PFP group. With different thresholds, our highest ICC scores were (0.22 [-0.34,0.711]) for the uninjured group and (0.55 [-0.12,0.868]) for the PFP group, which are highly comparable. With the same thresholds (3SD and 25ms), we achieved lower scores (uninjured; -0.205[-0.772,0.473], PFP; -0.276[-0.809,0.392]). When SEMs are compared, Briani et al. (325) data yielded 49.5ms for the uninjured group and 40.9ms for the PFP group, while our data of the 3SD and 25ms show 131.4 ms (uninjured) and 120.93 ms (PFP). In addition to (195,249) also investigated VM-VL onset reliability in PFP in a step-down task, with reliable results and low SEM (0.7 [CI not reported], SEM= 4 ms). Our SEM calculations showed large values, indicating poor precision and a difficulty to exclude measurement error from any future results. The MDC is based on our large SEMs, indicating meaningless MDC scores for future implementations. The CVs exceeded the 15% limit, indicating large dispersion of data around the average. Our results contradict other reliability studies (195,249,325,326), but contradictions in VM-VL timing investigations are not unique to reliability studies. Cowan et al. (100) and Cavazutti et al. (106) investigated VM-VL onset in PFP

compared to uninjured group and only the former found significant differences. These contradictions might be due to reasons mentioned by Chester et al. (83) in their meta-analysis that investigated on VM-VL timing (e.g., sample characteristics). However, in the current study, considering the ICC, SEM, CV and MDC recommends taking extreme caution when investigating, interpreting and affirming conclusions based on similar VM-VL timing work in future.

We highlighted the weak reliability shown by our results, and there are multiple aspects that, if addressed, can enhance similar investigations.

The definition of the "baseline" was not clear in the referenced protocol. Briani et al. (196) referenced the work of Cowan et al. (100), in which it was defined as "200 ms before commencement of the trial". In our study, this was translated into asking participants to stand quietly relaxed (where a 200 ms period was used to determine baseline), after which the step-up task started. By tracing the methods referenced by Cowan et al. (100,249), the original was by Hodges and Bui (324) where the baseline was defined as "50 ms prior to the warning stimulus" and needle electrodes used on muscles other than the quadriceps. Baseline identification could be a confounder in our study. This is clearly seen in one of the participants within the PFP group, as the MATLAB script could not detect excitation onsets beyond 7 SDs. Participants cannot be expected to show same levels of muscle activity in quiet standing, especially in muscles that work against gravity, due to normal biomechanical or physiological differences (286,287,327).

Cowan et al. (100) and Briani et al. (196) used computerised onset detection, while only the former mentioned the use of visual inspection to confirm the points identified by the software. Visual inspection is considered as a gold-standard method to identify onsets (287,324). Automated detection was used in our study for two reasons. Firstly, maintaining the comprehensive derivation approach (Chapter five) by using automated detection through MATALB, as it was used by Briani et al. (196). Although their scripts were not published, our script should, theoretically, analyse the signal in the same way (same filters and 3SDx25ms thresholds used). Secondly, in our study, we explored a spectrum of thresholds' parameters, as multiple parameters have been used within the literature (76,104,203,324). Therefore, it was not feasible to visually inspect the data of each participant 120 times (two sessions, five steps), being a time-consuming

method (328). The automated detection method could be a possible source of the poor results that we obtained. Uliam Kuriki et al. (323) found that a cross-correlation analysis yielded best reliability results when compared to visual inspection, and least reliable results were yielded by the automated detection method.

Interestingly, the within-session analyses also yielded poor reliability results. Given that the sensors were not removed for the within-session analysis, and data were withdrawn from steps of the same task, we suspect systematic errors to play a larger part in being the source for poor reliability. Differences in SEMs between our study and Briani et al. (325) could be attributed the differences in the settings. Briani et al. (325) used a seven-steps stair case with a hidden force plate in the middle step to collect the data. This means that a similar setting to what was used by Briani et al. (325) might improve the large SEM that our data yielded.

In our study, a single 20 cm step was used with an individually chosen pace, which is different than the referenced study (196) that used a seven-step apparatus with an imbedded force plate (which is also different than Cowan et al. (100)). Similar differences in tasks are expected to differ between laboratories, and this topic was investigated by Cavazutti et al. (106), as they aimed to investigate the deficit in multiple tasks, including step-up. A double-threshold method was used with different types and values of thresholds (relative to peak excitation), but no differences were found between PFP and uninjured participants. This contradicts the findings of Cowan et al. 2001 (100) as we mentioned before. We are aware that validity was not assessed in this chapter, but if deficits existence is dependent on an extremely specific protocol, a question can be raised about the validity of the whole concept (of VM-VL delay).

Delsys sensors are constructed to obtain extremely low system noise of 5 µV per channel, and are “active parallel bar electrodes” with built in amplifiers to increase fidelity (329,330). We used these sensors, and followed the SENIAM guidelines as best as possible, especially in skin preparation and sensors placement. However, identifying signal-to-noise ratio (SNR) and skin impedance was needed. We adapted the methods (196), which did not include SNR calculation nor reliability results. This implies that an enhancement to the assessment tool we used to derive the methods from the systematic review is needed. For example, essential aspects like own-lab reliability and SNR identification should have a larger impact on total assessment scores.

The comprehensive progression from the systematic review (Chapters three and five) to the lab testing in this chapter necessitates that we do not recommend detection of VM-VL excitation onsets using the methods we tested.

6.4.1.2 BF mean excitation amplitude in SLTHT

The reliability analyses of BF mean excitation amplitude showed three types of differences in results; a) between phase one and phase two, b) between PFP and uninjured, and c) between the within-session and test-retest analyses.

Acceptable within-session reliability was maintained with all types of analyses (normalised, unnormalised and MVC). This was not the case for the test-retest results. The reliable within-session scores could be due to the test being undertaken without removal of the sensors between repetitions, a consequence of the addition of the within-session analyses a posteriori.

All test-retest results were poor, except the unnormalised EMG data for the uninjured group, with the outlier excluded. It indicates that the source of inconsistency in uninjured group's data is the MVC. However, the protocol is unreliable in PFP in our study, as unnormalised data showed poor reliability when PFP group's data were analysed. But unlike the VM-VL timing, which was unreliable within-session and between session, results indicate a possibility to enhance reliability scores.

The MVC procedure was an adaptation from the systematic review (194), except that the strap that provided the resistance during the MVC task was anchored to the bed (Chapter five). Hamstrings is one of the most common muscle groups to develop cramps (331), which in turn causes pain that can change the level of muscle activation in voluntary contractions (332,333). Our data were normalised to the peak of three MVC repetitions, which can minimise the effects of muscle cramps that were seen in some participants. A better interpretation can be reached if we are able to compare our reliability results to previous studies.

Within the systematic review (Chapter three), only six studies were found to be investigating EMG excitation amplitude in the hamstrings (118,194,206,215,216,219), none reported reliability results. Baellow et al. (118) investigated excitation amplitude of BF in drop-vertical jump normalised to quiet standing, with no reliability scores mentioned as well. Patil et al. (223) reported excellent reliability scores of the

excitation onset of medial against lateral hamstrings in seated extension (0.99 [0.958,0.998]), which is a different domain to what we investigated. No other PFP studies reporting reliability of BF mean excitation amplitude in a jumping task were found.

Other studies investigated the reliability of BF excitation amplitudes in hurdle-jump with single-leg landing (334) (0.943 [CI not reported] n=18), countermovement vertical jumping (335) (0.24 [CI not reported] n=15) and landing from a box (336) (0.89 [0.77,0.95], CV=36%, n=24). Our results of the unnormalised signal in uninjured group show moderate reliability (n=9, 0.967[0.686,0.994]) and acceptable CV (8.16%). Differences can be attributed to the various methodologies. Since these are the results of the unnormalised data of the uninjured group with an outlier excluded, the inconsistency is probably related to the conduction of the MVC data collection and to the knee pain complaint in the PFP group.

A correction (of the systematic review in chapter three) was published, mainly regarding the results of BF EMG meta-analysis (178). So, the test was included although it was not completely conforming to the process presented in this thesis. Nevertheless, the results show that BF mean excitation amplitude normalised (and unnormalised) by MVC in PFP is unreliable if it was analysed during the landing of the 2nd hop in a triple-hop test.

6.4.2 Muscle performance

6.4.2.1 Isometric, concentric, and eccentric knee extensors peak torque

Quadriceps weakness is a common deficit reported by previous meta-analyses as a risk factor (29,31) and an associated factor (81) with PFP, and accordingly, is a common target in PFP rehabilitation (4,15). Our protocol includes three types of peak torque testing, isometric, concentric and eccentric. Our protocol indicates that peak torque can be measured reliably in PFP using concentric and eccentric tests between 20° and 90° of flexion.

For the isometric test, the only apparent difference between PFP and uninjured results is the width of 95% CI of the ICC (PFP; 0.862[0.280,0.967], SEM=25.92, CV=9.36%, MDC=71.85 and uninjured; 0.905[0.681,0.975], SEM=25.68, CV=8.33%, MDC=71.18). Pain is an expected culprit in isokinetic tests in knee pain (274). Some PFP participants expressed feeling moderate pain spikes during isokinetic testing, which can be a source

for the difference in the 95% CI range. The CV was slightly higher in PFP as well, so we explored data variability, and the maximum-minimum value of the differences (of session two - session one of participants data from each group) was larger in PFP (114.4 Nm/kg) than the uninjured (94 Nm/kg). So, individual variability, which could be partially related to pain, can explain the difference between uninjured and PFP results. The concentric and eccentric tests were reliable in PFP and uninjured groups, but to further analyse the consistency of our data, comparisons to other studies should be made.

The systematic review (Chapter three) included a total of 17 studies that formed the peak torque meta-analyses (44,45,119,140,195,197,198,209,210,47,48,78,112,113,116–118), out of which nine used IKD (44,45,48,112,116,117,119,140,210), and only one reporting reliability results (119). Nunes et al. (119) used the IKD with PFP and uninjured groups, and reported the 95% CIs of ICC of a mixed-subgroup from the total sample (n=8 out of 52, 4 PFP and 4 uninjured). Their results ranged from (ICCs=0.91 to 0.95, SEMs=5.3 to 6.7 Nm/kg) for isometric, concentric, and eccentric peak torque tests (CV and MDC were not reported). These results showed better reliability compared to our results, which might not be the case if we analysed groups' data combined. Another possible reason is that we used the peak value (of three repetitions), while Nunes et al. (119) used an average (of five repetitions). Taking an average value can lead to higher reliability compared to single value (99). We chose that method because 'maximum effort' is what would be used in clinic to monitor a patient's progress, so that the tests are more suitable for translation into clinical work (if reliability was sufficiently achieved). However, our results show acceptable test-retest reliability (except the isometric in PFP), and differences between PFP and uninjured groups could be due to pain as it affects peak torque testing (337). Isokinetic reliability studies in people with PFP are rare (274). Therefore, our uninjured group results should be compared to previous studies.

Isometrically, Palmer et al. (338) analysed peak torque reliability using BIODEX at 60° on 20 recreationally active adults, and the results were (0.979[CI not reported], SEM=11.3 Nm, CV=4.8%) better than ours (0.905[0.681,0.975], SEM=25.68 Nm/kg, CV=8.33%). In another study, Mau-Moeller (339) investigated reliability (n=30 active adults) at the same angle and reported higher within-session (0.97[0.94-0.99],

CV=5.3%) and test-retest (0.94[0.88-0.97], CV=8.3%) reliability scores. Interestingly, our data showed very similar CVs (5.78% within-session and 8.33% test-retest uninjured results). Mau-Moeller (339) did not report the SEM, but our results show high SEMs. Regarding the concentric and eccentric torque tests, our uninjured group's data are comparable to other studies (339–341), but the SEMs of eccentric tests were clearly high as well. There are multiple sources that might explain the higher SEMs that our study show, and are required to be addressed.

The hand position was not standardised for all participants. Based on how they perceived it as a better stabilisation position, some participants chose to hold the chest belts, while others held the IKD chair side-grips. However, each participant's hand position was used for the retest session (it was standardised within-participants). This might introduce variability in participants results. Regarding participants position, Mau-moeller et al. (339) clearly mentioned that the seating specifications (how far the different parts of the IKD seat were set for each participant) were recorded, but Palmer et al. (338) did not clarify that aspect. Although the known procedures of BIODEX testing were carefully followed (342), we did not record these specifications as we assumed that alteration of some conditions of session two based on knowledge we gain from session one might introduce bias. Both are controllable sources of random and systematic errors that had possibly influenced our reliability measures. There are other IKD studies that record participants position specifications and had low SEMs (343,344), and it is a common method to control the testing settings. The within-session results might confirm the previous arguments, as our results were comparable to the within-session results in studies that had better test-retest findings than ours. For example, Maffiulitti et al. (340) and Mau-moeller et al. (339) reported their isometric tests within-session results, which yielded (0.983[no IC reported], CV=4.4%) and (0.97[0.94,0.99], CV=5.3%), respectively, showing results that are comparable to our PFP (0.962[0.902,0.987], CV=4.26%) and uninjured group (0.956[0.888,0.987], CV=5.78%).

Based on these results, concentric and eccentric peak torque tests can be used in future work. However, isometric peak torque test necessitates minimising multiple confounding sources previously mentioned, which are avoidable, to produce reliable and interpretable results.

6.4.2.2 Rate of torque development

All relative and absolute RTD outcome measures showed moderate to good within-session reliability (except the 90% to peak torque) for both groups. These results did not translate similarly into the test-retest results. The PFP group had moderate test-retest reliability of the 90% of peak, 25 ms and 50 ms, and the uninjured group had reliable results at 30%, 150 ms and 175 ms. Late absolute RTD was found to be reliable in uninjured groups in recent studies (345,346). The difference between PFP and uninjured groups in our study could be attributed to multiple sources.

In relative RTD, 2% of peak was used. A 3xSD + baseline mean was used for absolute RTD, but some participants had very low baseline causing the starting point to be identified before the start of the contraction (Appendix 6.5). The starting point was set at 7.5 N, a threshold used in previous studies (347,348). The isometric peak torque was reliable in the uninjured group and unreliable in the PFP group, this might partially explain the difference in RTD reliability results, as 7.5 N is a starting point that is independent of individual's torque data. Secondly, since the lower bound of the ICC was used to determine reliability, many other outcomes were deemed unreliable, which is different to what some studies do (345,349,350). The CV data demonstrated acceptable dispersion among the various RTD types, as only RTD to 90% of peak (in both groups), to 50ms (in PFP) and to 60% of peak (in uninjured) scored above 15%. A stable CV and a wide ICC's CI indicates that increasing sample sizes could enhance our results.

None of the studies included in the meta-analysis reported reliability of PFP groups' data (79,116,119), but our results are similar to other studies (338,346). Grindstaff et al. (346) investigated the reliability of absolute RTD at 50, 100, 150, and 200ms in 20 healthy participants, and reported the lower bound of 95% CIs (0.26 to 0.8), SEMs (95.8 to 266.3 Nm/s), CV (39.3 to 57.9%) and MDC (265.4 to 738.3 Nm/s). Our findings show better results in all measures except for the SEM at 50ms (and MDC) (114.32(316.89 Nm/s)), and a wider ICC 95% CI for the 100, 150 and 200ms, therefore, a larger sample size might play a role in narrowing our CIs. Being measured during the isometric tests, the sources of error that were mentioned previously can also influence the results of RTD.

Our results indicate that the protocol can reliably detect the early-phase absolute RTD in PFP. Neural dysfunctions within the quadriceps can be investigated using early RTD testing and enhanced with neuromuscular activation interventions (240,346). Given that it was unreliable within-session (for both), and test-retest (for uninjured), as well as showing the largest CV (for the PFP in test-retest), including the RTD to 90% should not be recommended without extreme caution.

Overall, our findings indicate that RTD deficits can be reliably measured at 25 and 50 ms, and at 90% of peak. Other variations would require further reliability testing.

6.4.3 Muscle flexibility

6.4.3.1 Hamstrings flexibility

Tightness in the hamstrings has been reported to be present in people with PFP (121–123). A treatment protocol that targets this deficit would require a reliable method to identify a mechanism of effect in future studies. In this study, we derived a method to specifically measure hamstrings flexibility, which yielded moderate to excellent reliability (in uninjured and PFP, respectively).

Although they conducted it on nine uninjured participants, excellent reliability was reported in the study from which our protocol was derived (121), and we had excellent reliability in the PFP group. In another study, Piva et al. (123) used straight leg raising to measure hamstrings length in thirty participants with PFP, and reported an ICC 95% CI of (0.92[0.82, 0.96]), with a SEM of 4.3°. Superior results were found in our PFP group's data (0.99[0.94,0.998], SEM=1.12°). Having higher reliability might be due to the differences in tests. For instance, we used a horizontal bar to stabilise the hip angle at 90°. Another study used a similar method (with hip stabilised at 90° with a horizontal bar) reported good inter-rater reliability (351). As our study yielded results in agreement with previous research (121,123,351), our MDC (3.1°) can be used to identify real change in future work. Therefore, the hamstring flexibility testing as conducted by this study is a simple and reliable method to be used in PFP groups.

6.4.4 Limitations

While this chapter represented the reliability analysis of a protocol derived from the literature (Chapters three and five), multiple limitations must be addressed.

As mentioned in discussion section 6.4.2.2, multiple measurement could be considered reliable if the ICC score was used to determine reliability levels. This could be a reason for any differences against previous studies, especially if data was not available for comparisons (i.e. the 95% CI of the ICC). The use of the lower limit is recommended (318,319), and was chosen to maintain robustness, if future studies to identify mechanisms of benefit of interventions are conducted using the resultant protocol. Increasing the sample size might play a role in enhancing the reliability results, with numbers of at least 30 being preferable (352).

Overall, higher reliability is present in the uninjured group's data, and combining both groups data might enhance the results. However, we analysed them separately for optimal adaptation of these results into future work on people with PFP. Moreover, having uninjured and PFP groups in the same reliability study provides knowledge about the effects of PFP as a condition on the reliability of such measures. The reliability of isokinetic tests are rarely performed in patients, and reliability work on healthy groups might present limited relevance when generalised to patient groups (274). In addition to the possible sources of error we mentioned previously (section 6.4.2.1), two other uncontrollable sources should be mentioned as well. The uninjured groups data were collected in two separate periods; eight participants were seen before COVID-19 related closures, and three were seen after that, in a goal to increase sample size. This relates to the second aspect, which is lack of practice due to laboratory closures. Large SEMs were yielded from the analyses (Appendix 6), which can be minimised with further practice. The EMG investigations yielded extremely poor relative (ICC) and absolute (SEM and CV) reliability results. This indicates that the mentioned sources of errors must be mitigated to improve data collection, and that established reliability is a priority for this domain before any future testing. Lastly, not including kinematics and outcome measures related to movement could present a future limitation. Such measures can play a key role in providing better governance of tasks and interpretation of results by associating aspects of movement to neuromuscular findings, as kinematic deficits are linked to PFP (353,354).

6.4.5 Recommendations

This chapter presented a comprehensive reliability phase of the thesis, which was conducted on uninjured, as well as PFP groups. Reliability investigations in PFP are

seldom found, and future reliability work is highly recommended to be performed on PFP groups, because reliability and error measures should be identified to subsequently establish clinically meaningful findings (123). Further optimisation of the MATLAB scripts to identify other subsidiary outcomes can improve results interpretation, like torque data at peak-percentage points to be analysed independent of time. The addition of a within-day analysis can clarify the results, especially in the EMG domain, as it mitigates the effects of the inherent sensors replacement errors that are acknowledged in EMG studies. Finally, the incorporation of kinematics is recommended for optimal understanding of neuromuscular changes in future.

6.5 Conclusion

The reliability of a protocol that targets local neuromuscular deficits based on a systematic review and meta-analysis was investigated in this chapter. A testing protocol that can be reliably used to identify the mechanism of effects of interventions in PFP includes concentric and eccentric peak torques of the quadriceps, RTD to 25 ms and 50 ms, and hamstrings flexibility.

7 Biomechanical testing of local deficits associated with patellofemoral pain: a preliminary feasibility study

In Chapter six, the reliability investigations of the derived testing protocol were presented. In this Chapter, we present a study designed to evaluate the feasibility of the testing protocol and enhance planning of future work. This study was initially planned to be conducted through the NHS, but due to difficulties related to COVID-19 that were mentioned in Chapter two, it was conducted at QMUL with ethical approval obtained through the Queen Mary University research ethics committee (QMREC) (Appendix 2).

7.1 Background

Patellofemoral pain acquired large input of exploratory and interventional studies (4,29,31,81,83,170,176), and optimal planning of similar research would require preliminary research, through piloting and feasibility. Although both terms are sometimes used interchangeably (355), a pilot study is a type of research that tests the feasibility or acceptability of methods or procedures, and identifies logistical aspects (356) in a small scale to be used in future on a larger scale (357). Feasibility and piloting can also inform study planning and accurate funding proposals (358,359). Such studies assess aspects that are critical for the success of future work, like recruitment rates, retention rates, and the participants' ability to tolerate proposed interventions or tests (360). Furthermore, assessing eligibility rates early through feasibility studies ensures that the target population is well-defined and that the subsequent research can produce meaningful results (361). Feasibility studies can also help in predicting factors that lead to poor retention and develop strategies accordingly, ensuring uninterrupted data collection (362).

Multiple feasibility studies can be found in the PFP literature which predominately focus on the feasibility of interventions (363–366) like exercise (241,367), exercise with education (368), taping (369), running retraining (365) and muscle electrical stimulation (370). In some cases, feasibility is investigated in specific patient groups, like exercise in female patients (366), and orthoses in adolescents (371) or adults (372). Other studies are being conducted to provide ways of detecting local, proximal and distal deficits, to allow individualising interventions to target these deficits (6,8). This body of research sets the basis for larger interventional studies, but whenever feasibility is investigated, it is often the feasibility of interventions, not the deficit-detection protocols.

Selfe et al. (11) investigated the possibility of subgrouping people with PFP using seven clinical tests combined with other factors identified through demographics and patient-reported outcomes. Their testing procedure included strength and/or flexibility tests of the quadriceps, hamstrings, and gastrocnemius. This assessment protocol was deemed as a novel and clinically feasible test to identify three subgroups of PFP (strong, weak and tight, weak and pronated foot) (11). Although the study was conducted with a goal of identifying PFP subgroups based on musculoskeletal tests

(11), to our knowledge, no other study investigated the feasibility of deficits-detection protocols. Other than Selfe et al. (11), most feasibility studies in PFP are mainly investigating the feasibility of an intervention (241,365,366,368,373,374). Moreover, a title and abstract search in PubMed and Embase directories for “patellofemoral pain” yielded 25 and 40 results when combined with “feasibility”. These numbers were 265 and 653 when “intervention” was used instead. So, when compared to interventional studies, feasibility studies are not as abundant in this field, and we did not find a similar study investigating the applicability of a testing protocol alone, especially with the same combination of targeted deficits.

A synthesis of current literature has identified a large number of studies demonstrating specific neuromuscular characteristics that are associated with PFP in Chapter three (176). The derivation and reliability testing of a protocol that investigates these deficits has been presented in Chapters five and six. The primary aim in this chapter is to assess the feasibility of the testing protocol, and evaluate recruitment and retention, and identify any adverse events from a testing procedure that combines multiple neuromuscular domains (EMG, peak and rate of torque, and flexibility). A secondary aim is to run analyses of the reliable outcome measures to find the relationship between the changes that occur in local deficits and PFP severity.

7.2 Methods

7.2.1 Ethical approval

The ethical application was approved on December 9th 2021 for the study on the PFP group (QMREC2018/48/082) (Appendix 2).

7.2.2 Research question

Is it feasible to test a group of people with PFP twice using a protocol that evaluates PFP specific local neuromuscular characteristics?

7.2.3 Study design

This study is part of a quasi-experimental study that investigated the reliability and feasibility of a lab-based testing procedure. The study included two parts, requiring three testing sessions, as follows:

- Reliability (Chapter six):

  Sessions one and two was performed one week apart, and statistical analyses to assess within-session and test-retest reliability.

- Feasibility (current Chapter):

After the second session, a third session was planned after six weeks to conclude the feasibility part of this protocol. A six-weeks period was chosen due to interventional studies frequently evaluating change over this time period (45,136,137,148,152,153,269,271,375). During the six weeks, the participants did not receive an intervention, but were referred to an online course (https://www.teampfp.com/my-knee-cap-pain). The course contains modules that explain PFP and provide treatment options. Study recruitment was open for six months.

7.2.4 Recruitment and protocol methodology

To avoid repetition, please refer to the methods section in Chapters five and six.

7.2.4.1 Eligibility criteria

We included adults ≤ 40 years of age, with pain in anterior part of the knee aggravated by at least two activities that involve loading the knee in a flexion position (step ascending or descending, squatting, jumping, sitting for long periods and kneeling). Worst pain felt within last month should be ≥3/10 on the visual analogue scale (VAS). We excluded any person diagnosed with any other knee problem (e.g., Meniscal injuries, Ligament injuries, Knee osteoarthritis, Osgood Schlatter's, Patellar tendinopathy). People with a history of cardiac problems/diseases, any respiratory problems/diseases, musculoskeletal or spinal injuries, previous musculoskeletal surgeries, and skin allergies were also excluded.

7.2.5 Data collection

7.2.5.1 Baseline data, eligibility and demographics

A pre-study screening was conducted, in which potential participants were screened using multiple yes/no questions. These questions included; a) are you aged between 18 to 40 years?, b) is your pain felt around and/or behind the knee-cap?, c) did your knee pain start due to trauma?, d) do you have pain during activities that load the knee in flexion (e.g climbing stairs, sit-to-stand, etc)?, e) have you had previous back or lower limb surgery?, f) have you had a previously diagnosed knee pathology?, g) do you have a history of breathing/chest problems or skin allergies? (Appendix 7.1). After signing the consent form, age, sex, height and mass were collected in the first session for all eligible participants. Next, a subjective and objective assessment was performed

to exclude any possible complaint other than PFP. This assessment includes questions about previous injuries/surgeries, as well as multiple orthopaedic knee tests of ligaments, menisci, fat-pads and tendons, and is based on a recent guideline (15). The assessment was performed by the main assessor, who has more than eight years of experience as a physiotherapist (Appendix 7.2). Upon study completion, participants were sent a survey about the completion of the online educational programme. This was done for a better interpretation of the results and explain any possible significant changes in the data. Participants were also given a £20 payment in the form of an Amazon voucher once they completed the study.

7.2.5.2 Primary outcomes measure: Feasibility

Feasibility outcomes include:

- Willingness of participation; the proportion of individuals that are eligible and submit an informed consent out of all participants that respond to the advertisement (>60%).
- The percentage of participants that meet eligibility criteria out of all consented participants (≥70%).
- Recruitment rate; the number of successful recruitments per week (minimum of two participants per week).
- Attendance to the testing sessions and drop-out rate was used to assess retention.

Being a feasibility study, no power analysis specific to this study was undertaken. However, we aimed to recruit a sample based on power calculations in which we used effect sizes from our previous meta-analysis. The optimal sample size is n=48, but at least n=16 is targeted (see Chapter six; section 6.2.4.7). We aimed to recruit 20% more participants, and targeted at least n=19. Exercise rehabilitation studies, in which this protocol would potentially be implemented, report 20 to 50% drop-outs (376). We set the drop-out limit to 40% for feasibility (deemed feasible if at least 11 out of the targeted n=19 complete the pre-post six weeks testing sessions). Although there are no specific guidelines, these limits were chosen to improve achievement of the desired precision of the results (361).

7.2.5.3 Secondary outcome measures

7.2.5.3.1 Local neuromuscular characteristics

All neuromuscular outcome measures described in Chapters five and six were collected in the feasibility sessions. The outcome measures that showed acceptable test-retest reliability of at least one of the groups (PFP or uninjured) were analysed in the current study:

1. Biceps Femoris non-normalised mean excitation amplitude
2. Knee extensors peak torque;
    a. Isometric (60° of knee flexion)
    b. Concentric (30°/second (from 90° to 20°))
    c. Eccentric (30°/second (from 20° to 90°))
3. Rate of torque development (RTD);
    a. RTD Relative to isometric peak torque
        i. at 30% of peak
        ii. at 90% of peak
    b. Absolute RTD
        i. at 25 ms
        ii. at 50 ms
        iii. at 150 ms
        iv. at 175 ms
4. Hamstrings flexibility.

7.2.5.3.2 Patient-reported outcomes

To identify the effects of PFP symptom severity on the neuromuscular outcome measures, two patient-reported outcomes were collected to evaluate pain and function:

1. Visual Analogue Scale (VAS):

A Horizontal 10-points scale, from 0 'no pain' to 10 which is 'worst pain imaginable', was used to measure worst pain over the previous week and after each test during the testing procedure. The minimal clinically meaningful difference (MCID) for the VAS is two points in PFP (259). Multiple studies show that pain severity influence biomechanical data (377–379). Therefore, pain scores were gathered nine times during each session; worst pain last week, before the session starts (when participant arrives

to the lab), after MVC test, step-up task, SLTHT, isometric, concentric, eccentric tests and after the testing ends.

2. Anterior knee pain scale (AKPS) (380):

A 13-item questionnaire assesses current knee function in activities of daily living, like using stairs, walking, running, jumping and sitting for prolonged periods. All items form a total score of 100 when calculated, and better function levels are represented with higher scores. A change exceeding 10 points is considered clinically meaningful (259).

7.2.5.4 Testing procedures

To avoid repetition, please refer to Chapters five and six for full description of the testing protocol, including the commencement of the protocol, tests' randomisation and signal processing. Figure 7.1 outlines the six tests performed by each participant; isometric, concentric and eccentric peak knee extension (on the IKD), hamstring flexibility, step-up and triple-hop tests.

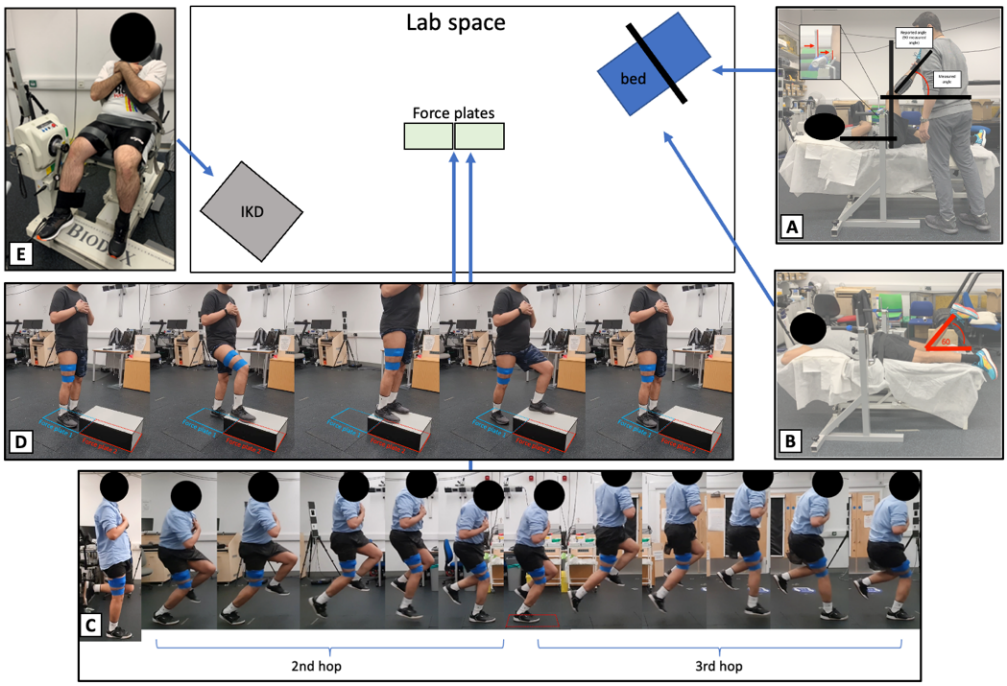


Figure 7.1: The flow of the testing session. The sequence is displayed from A to E which is the sequence of testing stations. C and D are randomised, and tests in station E. Tests are; a) hamstring flexibility, b) MVC of BF, c) BF mean amplitude in SLTHT, d) VM-VL onset in step-up task, e) Quadriceps peak torque and RTD tests. IKD; Isokinetic dynamometer. Although it was performed during data collection, VM-VL timing in step-up was not included in the current chapter as it was identified to be poorly reliable only after starting the pre-post six weeks data collection.

7.2.5.5 Statistical analysis

Statistical analyses for the secondary outcomes were conducted using SPSS (Version 29.0. Armonk, NY: IBM Corp.). Normal distribution test for within-group differences was conducted using Shapiro-Wilk test. To identify changes in each investigated

neuromuscular characteristic, paired samples T-test was used to analyse the normally distributed outcomes. If within-group differences were not normally distributed, Wilcoxon signed-ranks test was used to analyse pre-post differences (381). Wilcoxon test was also used to analyse the AKPS data and the 10-point VAS scale, as they were treated as ordinal scales (382,383). Changes over time in pain and AKPS were analysed to identify any possible association with the changes in the neuromuscular characteristics using Spearman's correlation coefficient. No cut-off limits were set for the correlation magnitude and r scores should be interpreted as a measure of relationship strength (384). Three types of correlation analyses were conducted i) on the data of session one (pre-six-weeks session), ii) on the data of session two (post-six-weeks session) and iii) using the mean difference between sessions one and two (mean difference = scores of session two – session one). An alpha score of ≤ 0.05 is considered significant difference for all analyses, and were conducted between local neuromuscular data and VAS and AKPS scores.

7.3 Results

The outcome measures that showed moderate to excellent test-retest reliability in any of the groups analysed in the previous chapter were investigated in this chapter.

7.3.1 Primary outcomes

7.3.1.1 Feasibility

Over the six-months recruitment period, 55 participants responded after seeing the study's advertisements; 17 participants consented, so targeted sample size (n=19) was not met. Out of the 17, 14 participants successfully enrolled as one did not attend, and two did not pass physical screening for eligibility criteria. This indicates an 82% eligibility rate, exceeding the ≥70% feasibility threshold. Total willingness-to-participate result was 25.5% (n=14/55) which did not meet the >60% a-priori feasibility threshold. Fourteen participants attended the first session, and three did not attend the second reliability session. To retain largest possible sample, all 14 were contacted to plan a testing session after six weeks from the time they were first seen. Eleven out of 17 completed the pre-post six weeks feasibility testing, showing a dropout rate of 35.2%, better than the <40% feasibility threshold. Recruitment rate was 0.5 participants per week for the full length of the study of six months, not achieving the minimum of two per week a-priori feasibility threshold. Testing duration was 1.25 to

1.5 hours each session. Figure 7.2 exhibits study flow, and Tables 7.1 and 7.2 present the demographic data.

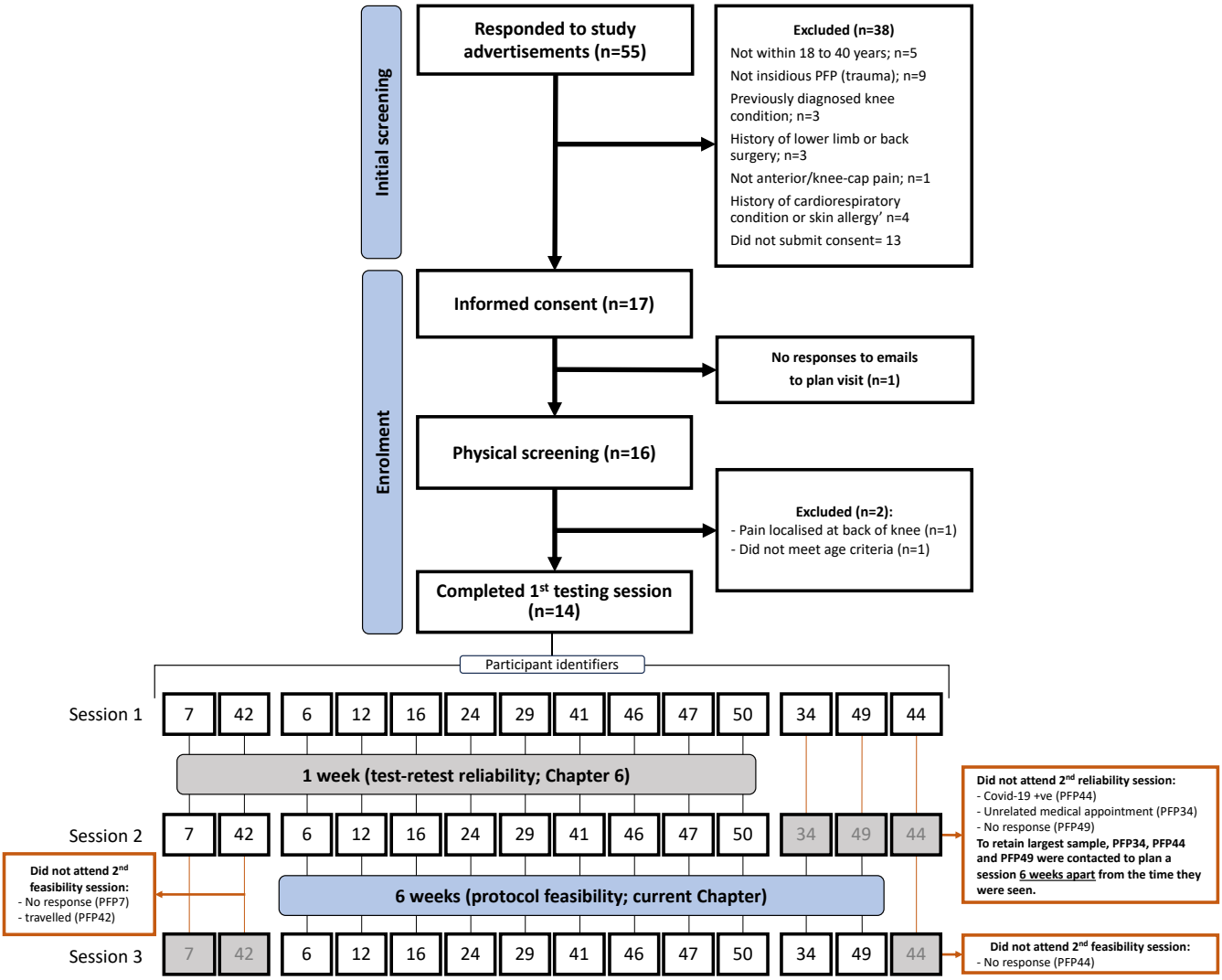


Figure 7.2: Study flow-chart, showing the recruitment process of each participant. Out of the 11 participants who attended the reliability session, nine attended the last testing session to be included in the feasibility analyses. Out of the three participants that did not attend the second reliability session, two completed a post-six weeks session (total n=11 completed pre-post six weeks testing).

Table 7.1: Demographic data of the included PFP sample

Total PFP sample		Mean	SD	Min	Max	Median	Male/ Female	Tested Side Rt/Lt	Dominant Side Rt/Lt	Symptomatic bilateral/ unilateral
n=14	Age, yrs	27.14	4.28	19	34	27.50	10/4	6/8	13/1	8/6
	Height, m	1.72	0.09	1.58	1.86	1.72				
	Mass, Kg	72.58	17.12	53.80	117.80	67.68				
	BMI	24.47	4.11	19.93	34.05	23.08				
	VAS (0-10)	4.86	1.61	3	8	5				
	AKPS (0-100)	78.07	16.74	26	94	83				
included in pre-post 6wks (feasibility)		**Mean**	**SD**	**Min**	**Max**	**Median**	**Male/ Female**	**Tested Side Rt/Lt**	**Dominant Side Rt/Lt**	**Symptomatic bilateral/ unilateral**
n=11	Age, yrs	26.73	2.97	21	31	27	8/3	5/6	10/1	7/4
	Height, m	1.71	0.09	1.58	1.86	1.72				
	Mass, Kg	73.42	19.28	53.8	117.8	67.55				
	BMI	24.81	4.40	19.93	34.05	23.49				
	VAS (0-10)	3.91	1.22	2	6	4				
	AKPS (0-100)	80.64	14.8	40	94	85				

*Table 7.2: individual demographic data. identifiers shown in **BOLD** are participants who completed the reliability part of the study (Chapter six) and highlighted in green are participants who completed the pre-post six weeks feasibility testing sessions.*

#	IDs	Sex	Age	Height (meter)	Bmass (Kg)	BMI	test	Dom.	EMG and Strength testing randomised sequence				
1	**PFP7**	F	33	1.59	67.8	26.82	Lt	Rt	SLTHT	SU	C	I	E
2	**PFP42**	M	19	1.84	75.5	22.30	Lt	Rt	SU	SLTHT	C	I	E
3	**PFP6**	F	30	1.61	58.5	22.57	Lt	Rt	SLTHT	SU	C	I	E
4	**PFP12**	F	24	1.61	53.8	20.76	Rt	Rt	SLTHT	SU	I	C	E
5	**PFP16**	M	31	1.81	80.2	24.48	Lt	Rt	SU	SLTHT	C	I	E
6	**PFP24**	M	27	1.77	89.3	28.50	Lt	Rt	SLTHT	SU	C	I	E
7	**PFP29**	M	27	1.72	63	21.30	Lt	Rt	SU	SLTHT	E	C	I
8	**PFP41**	M	28	1.58	56.6	22.67	Lt	Rt	SLTHT	SU	C	E	I
9	**PFP46**	M	24	1.72	89.65	30.30	Rt	Rt	SLTHT	SU	E	I	C
10	**PFP47**	M	29	1.86	117.8	34.05	Lt	Lt	SLTHT	SU	E	I	C
11	**PFP50**	F	28	1.65	67.55	24.81	Rt	Rt	SU	SLTHT	I	C	E
12	PFP34	M	21	1.72	69.5	23.49	Rt	Rt	SLTHT	SU	I	C	E
13	PFP49	M	25	1.76	61.75	19.93	Rt	Rt	SU	SLTHT	I	E	C
14	PFP44*	M	34	1.78	65.1	20.55	Rt	Rt	SU	SLTHT	I	C	E

*IDs; identifiers, Bmass; body-mass, BMI; body-mass index, test; tested side, Dom.; dominant side, F; female, M; male, Lt; Left, Rt; right, SLTHT; single-leg triple-hop test, SU: step-up, I; isometric, C; concentric, E; eccentric. *: attended one session only.*

7.3.2 Secondary outcomes

The figures from 7.3 to 7.9 show individual data alongside the mean and SD of data of pre-post six weeks.

7.3.2.1 Local neuromuscular characteristics

After normality testing, differences between session one and two were all normally distributed except for the data of RTD to 90% and hamstrings flexibility. No significant differences were found between session one and two within the local neuromuscular characteristics, except for the hamstrings flexibility (p=0.026). All results are presented in table 7.3.

7.3.2.2 Patient reported outcomes

Worst pain last week showed significant decrease (p=0.037). All other VAS and AKPS scores showed no significant differences (table 7.4).

7.3.2.3 Correlation analyses

7.3.2.3.1 Session one (pre-six weeks, table 7.5)

Significant correlations (p<0.05) were found between AKPS scores and multiple local neuromuscular characteristics. Isometric peak torque and RTD to 90% of peak torque showed largest correlation (r=0.81), followed by RTD at 25 ms, 150 ms and 175 ms (r=0.79), RTD at 50 ms (r=0.76), eccentric peak torque (r=0.75) and RTD to 30% of peak torque (r=0.69). Although insignificant and not reaching a MCID, the mean AKPS scores in this session were lower by 6.4 points than the second session (table 7.5).

7.3.2.3.2 Session two (post-six weeks, table 7.6)

Data pairs with significant correlations were different in session two. The non-normalised BF mean excitation amplitude data was significantly correlated with VAS scores collected after isometric test (r= -0.87), after concentric test (r= -0.85), after testing ended (r= -0.8), after eccentric test (r= -0.78), VAS before session started (r= -0.73), and after SLTHT (r= -0.72). Hamstrings flexibility showed significant correlations with VAS collected before session (r=0.77), AKPS score (r= -0.72), and VAS after eccentric test (r= 0.6).

7.3.2.3.3 Difference between sessions one and two (pre-post six weeks, table 7.7)

Hamstrings flexibility showed significant correlation with VAS collected before (r=0.81) and after session (r=0.67). Significant correlations were found between isometric peak

torque and both VAS before session started (r= -0.6) and after isometric test (r= -0.63). Rate of torque development scores showed multiple significant correlations with VAS after concentric test; RTD at 30% of peak torque (r= -0.67), at 150 and 175 ms (r= -0.64), and at 25 ms (r= -0.61).

7.3.2.4 Completion of the educational programme

After the study was completed, the 11 participants were sent a survey asking about the completion of the educational course in the six weeks period. Only eight participants responded, one did not start the course, six stated that they did not complete the course, and only one completed it (PFP29). The changes in each participant's data, arranged according to education programme completion, can provide an overview of the effects of the education programme for the participants, which can be found in table 7.8.

Table 7.3: The results of the investigations of local neuromuscular characteristics before and after a 6-weeks period.

Outcome measures		Descriptive statistics								Shapiro-Wilk test (for normality)	paired t-test results or ‡Wilcoxon signed-ranks test (for non-normally distributed within-group difference)				SEM and MDC from reliability study	Paired samples effect sizes Hedge's g and 95% confidence interval Or Z-score‡		
		Pre 6 weeks				Post 6 weeks												
		mean	SD	min	max	mean	SD	min	max	Sig.	mean	SD	Std Er	p-value	SEM (MDC)	ES	lower	upper
EMG (mV)	**Unnormalised BF mean excitation amplitude***	413.8	233.6	155.0	976.7	378.6	175.2	201.9	792.5	0.342	-35.1	89.2	26.9	0.221	71.3(198)	-0.363	-0.923	0.212
Muscle flexibility (degrees)	**Hamstrings*****	17.0	7.7	5.0	31.0	11.9	8.1	2.0	25.0	**<0.001**	-5.1	8.7	2.6	**0.026‡**	1.1(3.1)	-2.2‡	-1.121	0.065
Knee extensors Rate of Torque development (RTD) (Nm/sec/kg)	**RTD to 30% of peak T.***	704.8	242.4	450.1	1230.0	664.7	234.8	383.6	1072.8	0.352	-40.1	235.9	71.1	0.585	89(247)	-0.157	-0.703	0.396
	RTD to 90% of peak T.**	316.2	316.8	76.3	1123.6	213.7	136.6	76.3	492.9	**<0.001**	-102.4	271.8	81.9	0.139‡	52.5(145)	-1.4‡	-0.906	0.226
	RTD to 25 ms**	600.2	243.6	302.2	1092.1	545.0	204.7	278.7	874.7	0.065	-55.2	187.3	56.5	0.351	81(224)	-0.272	-0.823	0.292
	RTD to 50 ms**	726.0	305.5	382.0	1372.5	655.0	254.6	334.5	1113.4	0.031	-71.0	252.3	76.1	0.372	103(286)	-0.260	-0.810	0.303
	RTD to 150 ms*	732.6	251.9	474.1	1331.7	690.2	243.4	411.4	1105.8	0.216	-42.4	257.1	77.5	0.597	87(241)	-0.152	-0.698	0.401
	RTD to 175 ms*	696.4	210.9	470.4	1193.5	661.3	224.4	403.4	1031.0	0.408	-35.1	226.5	68.3	0.618	77(214)	-0.143	-0.688	0.409
Knee extensors peak torque (Nm/kg)	**Peak Isometric***	271.1	50.0	209.7	359.4	280.0	45.5	202.4	350.2	0.325	8.9	23.4	7.1	0.237	26(71.9)	0.350	-0.224	0.908
	Peak Concentric***	219.1	50.1	129.1	292.1	230.9	55.5	151.4	341.6	0.332	11.8	32.6	9.8	0.257	20.4(57)	0.334	-0.238	0.891
	Peak Eccentric***	351.5	59.2	273.2	422.6	384.7	83.4	272.1	548.4	0.677	33.2	69.5	20.9	0.144	19.3(53)	0.441	-0.146	1.009

- StdEr; standard error, ES; effect size, SEM; standard error of measurement, MDC; minimal detectable change.
** Outcome measures that showed acceptable reliability only in uninjured group (Based on Chapter six).*
*** Outcome measures that showed acceptable reliability only in PFP group (Based on Chapter six).*
**** Acceptable reliability found in each group (Based on Chapter six).*
- SEM and MDC are all from PFP results (Based on Chapter six).
- negative effect sizes represent a decrease over time.
- ‡; Wilcoxon signed-ranks test

Table 7.4: The results of change in pain (VAS) and knee function (AKPS) before and after a 6-weeks period.

Visual analogue scale and Anterior knee pain scale	Pre 6 weeks				Post 6 weeks				Difference (post-pre)	Wilcoxon results	
	mean	SD	min	max	mean	SD	min	max		Z	p-value
worst pain last week	**3.9**	**1.2**	**2.0**	**6.0**	**2.4**	**1.9**	**0.0**	**6.0**	**-1.5**	**-2.09**	**0.037**
before testing	0.3	0.5	0.0	1.0	0.5	0.7	0.0	2.0	0.2	-0.71	0.480
after MVC	0.3	0.6	0.0	2.0	0.2	0.4	0.0	1.0	-0.1	-0.38	0.705
after SLTHT test	0.8	0.9	0.0	2.0	0.6	0.8	0.0	2.0	-0.2	-0.51	0.608
after isometric peakT.	1.0	1.2	0.0	3.0	0.9	1.1	0.0	3.0	-0.1	-0.33	0.739
after concentric peakT.	1.1	1.4	0.0	4.0	0.6	0.8	0.0	2.0	-0.5	-1.67	0.096
after eccentric peakT.	2.6	1.8	0.0	5.0	1.4	1.4	0.0	4.0	-1.2	-1.88	0.061
pain after session	1.2	1.2	0.0	4.0	1.0	1.1	0.0	3.0	-0.2	-0.59	0.557
AKPS	80.6	14.8	40.0	94.0	87.0	8.1	67.0	96.0	6.4	-1.38	0.168

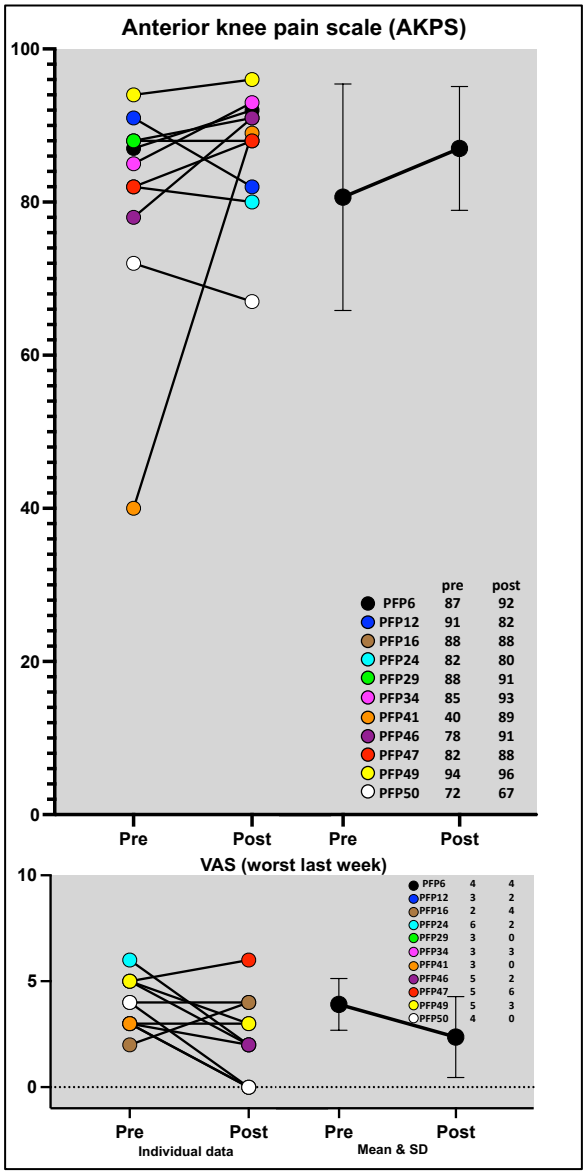


Figure 7.4: Pre-post 6 weeks data of AKPS and worst pain during the previous week ***(AKPS score increase = improvement)***

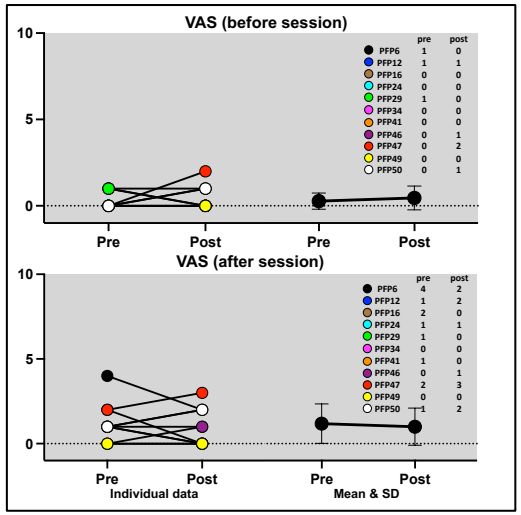


Figure 7.3: Pre-post 6-weeks data of pain before testing started and after testing finished.

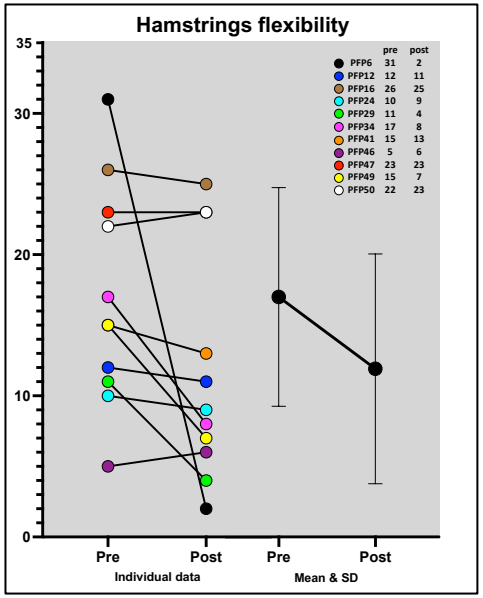


*Figure 7.5: Pre-post 6 weeks data of hamstrings flexibility (****Flexibility increases with a decrease in scores****)*

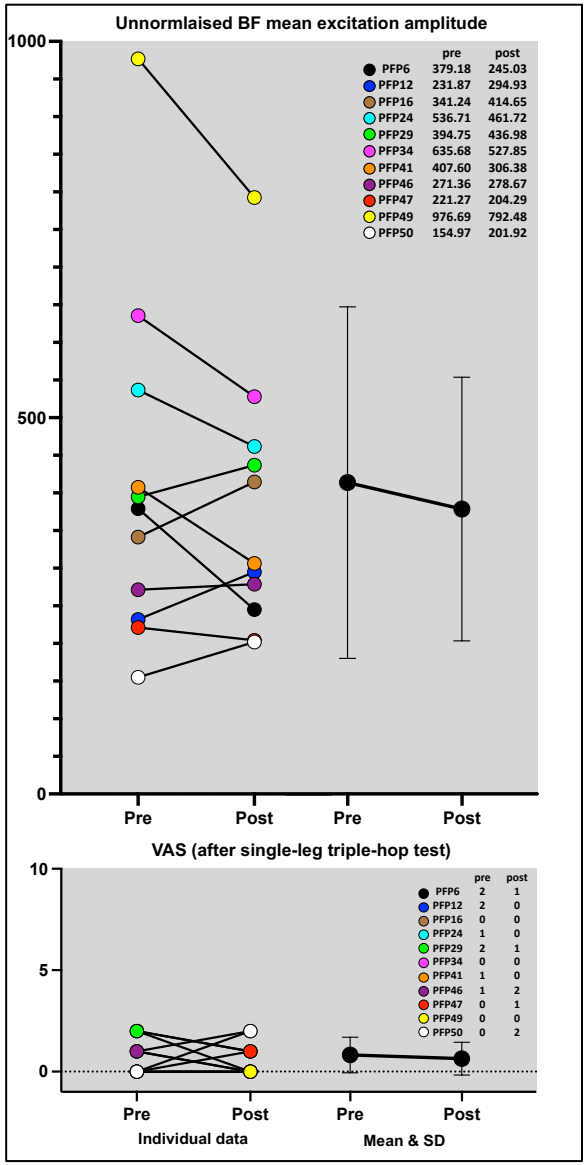


Figure 7.6: Pre-post 6 weeks data of BF mean excitation amplitude in single-leg triple-hop test (mV) and pain scores.

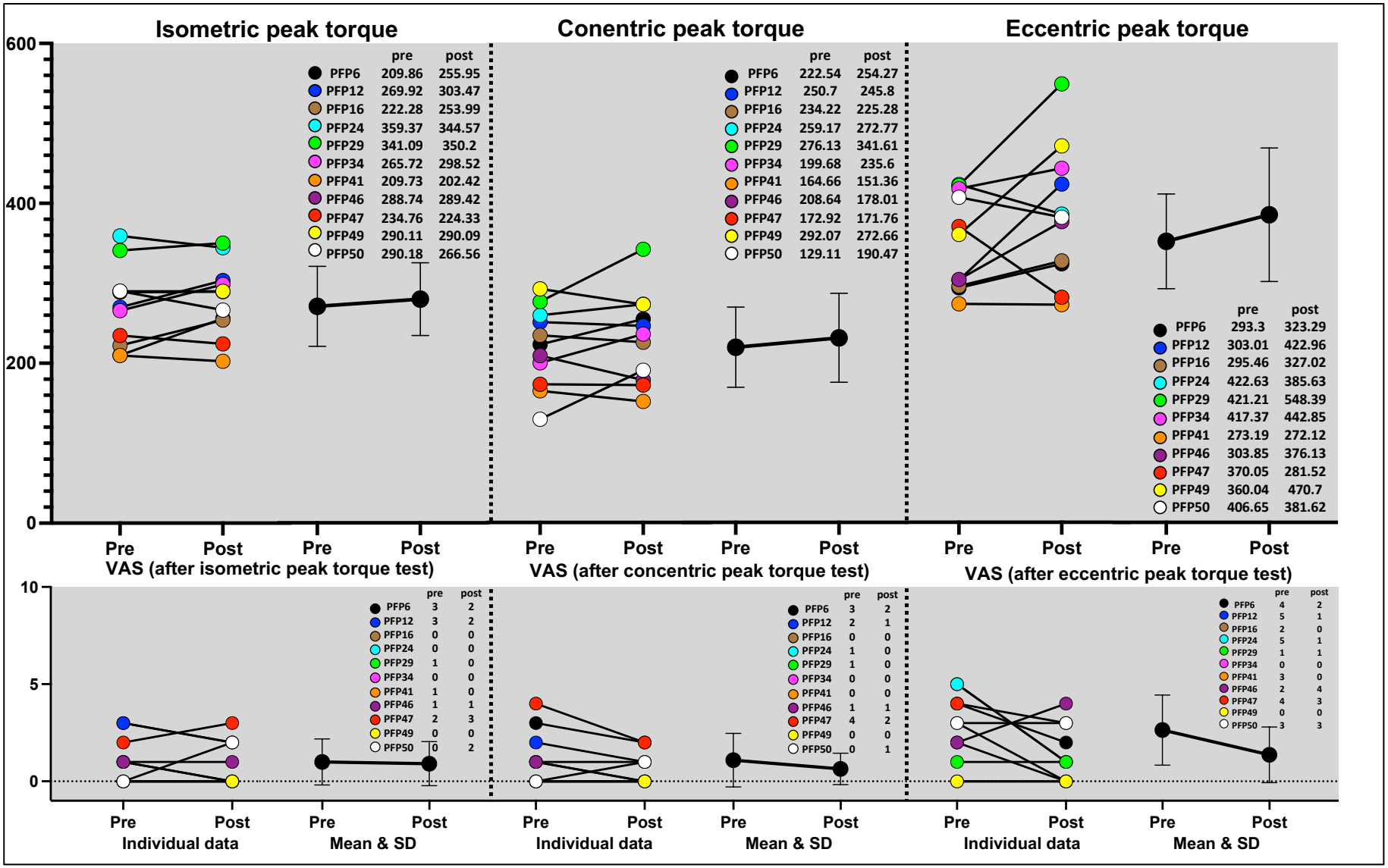


Figure 7.7: Pre-post 6 weeks data of peak torque tests (Nm/kg) and the corresponding pain scores taken after each test.

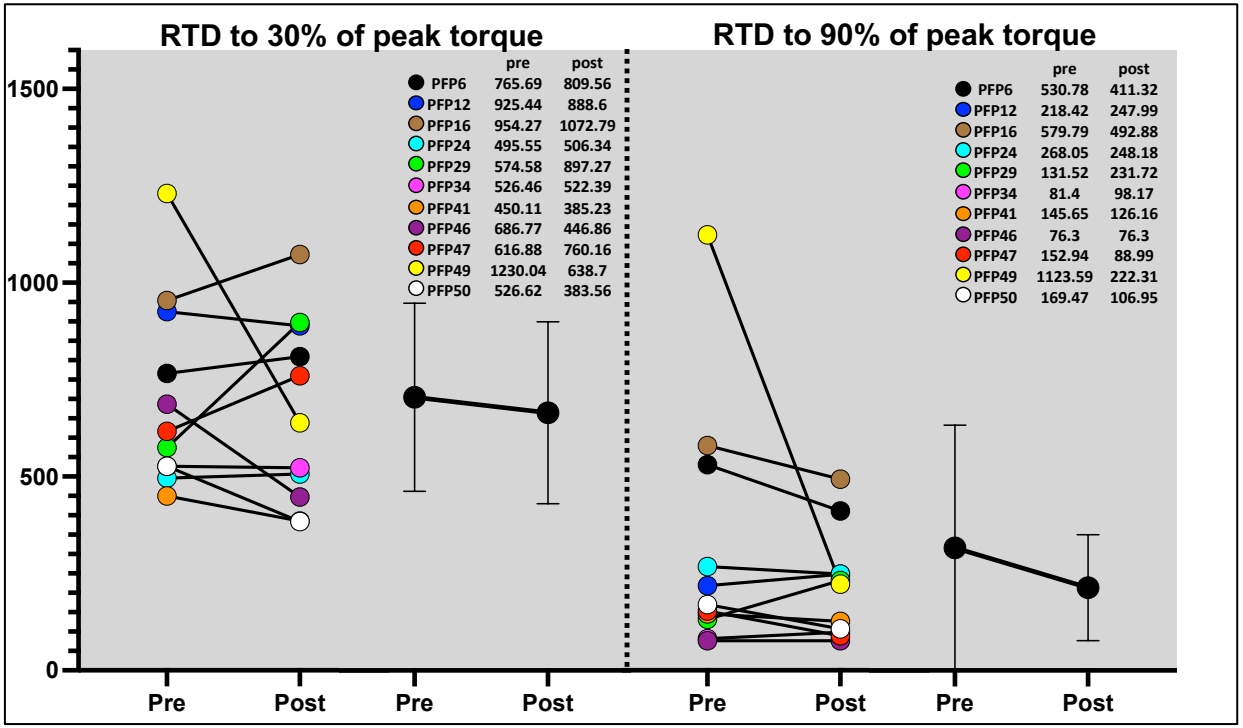


Figure 7.8: Rate of torque development data (RTD; Nm/sec/kg) pre-post 6 weeks.

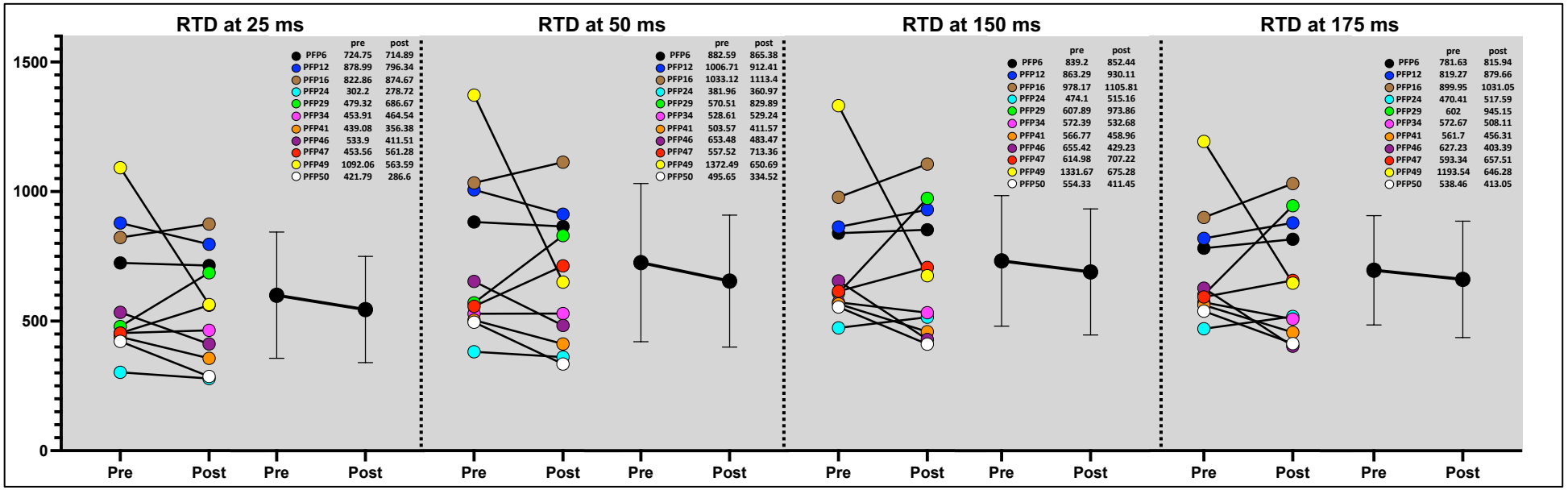


Figure 7.9: Absolute rate of torque development (RTD; Nm/sec/kg) data pre-post 6 weeks.

Table 7.5: Spearman's correlation analyses between the changes in patient reported outcomes and local neuromuscular investigations pre six weeks. Significant correlations are highlighted.

Spearman's Correlations of data of session 1 (pre 6 weeks)		AKPS		VAS													
				Worst pain last week		Pain before session started		Pain after single-leg triple-hop test		Pain after isometric peak torque test		Pain after concentric peak torque test		Pain after isometric peak torque test		Pain after session ended	
		Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.
Unnormalised BF MEA* (mV)		0.28	0.41	0.04	0.90	-0.13	0.71	-0.02	0.96	-0.41	0.21	-0.41	0.22	-0.46	0.15	-0.44	0.18
Peak torque (Nm/kg)	Iso.*	**0.81**	**0.00**	0.10	0.77	0.39	0.24	0.33	0.32	-0.07	0.84	0.12	0.74	-0.14	0.69	-0.15	0.67
	Con.***	0.01	0.97	0.37	0.27	-0.13	0.71	-0.18	0.61	-0.45	0.16	0.00	1.00	-0.14	0.69	-0.34	0.31
	Ecc.***	**0.75**	**0.01**	-0.07	0.85	0.26	0.44	-0.04	0.91	0.17	0.62	0.15	0.65	-0.15	0.66	0.12	0.73
Rate of torque development (Nm/sec/kg)	30%*	**0.69**	**0.02**	-0.28	0.40	0.19	0.57	-0.11	0.75	0.15	0.66	0.01	0.98	-0.06	0.85	0.35	0.29
	90%**	**0.81**	**0.00**	-0.27	0.42	0.39	0.24	0.14	0.69	0.24	0.48	0.06	0.87	-0.29	0.38	-0.06	0.86
	25ms**	**0.79**	**0.00**	-0.25	0.47	0.32	0.33	0.07	0.84	0.23	0.50	0.08	0.82	-0.29	0.40	0.04	0.90
	50ms**	**0.76**	**0.01**	-0.17	0.63	0.26	0.44	-0.04	0.91	0.21	0.54	0.12	0.74	-0.23	0.49	0.08	0.82
	150ms*	**0.79**	**0.00**	-0.25	0.47	0.32	0.33	0.07	0.84	0.23	0.50	0.08	0.82	-0.29	0.40	0.04	0.90
	175ms*	**0.79**	**0.00**	-0.25	0.47	0.32	0.33	0.07	0.84	0.23	0.50	0.08	0.82	-0.29	0.40	0.04	0.90
Hamstrings flexibility*** (degrees)		-0.47	0.14	0.27	0.42	-0.39	0.23	-0.24	0.48	-0.06	0.86	0.09	0.80	0.33	0.33	-0.01	0.98

: outcome measures that were reliable in the PFP group, **: reliable in uninjured group, *: reliable in each group (Chapter six).*

Table 7.6: Spearman's correlation analyses between the changes in patient reported outcomes and local neuromuscular investigations post six weeks. Significant correlations are highlighted.

Spearman's Correlations of data of session 2 (post 6 weeks)		AKPS		VAS													
				Worst pain last week		Pain before session started		Pain after single-leg triple-hop test		Pain after isometric peak torque test		Pain after concentric peak torque test		Pain after eccentric peak torque test		Pain after session ended	
		Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.
Unnormalised BF MEA* (mV)		0.48	0.14	-0.01	0.97	**-0.73**	**0.01**	**-0.72**	**0.01**	**-0.87**	**<.001**	**-0.85**	**<.001**	**-0.78**	**0.01**	**-0.80**	**0.00**
Peak torque (Nm/kg)	Iso.*	0.21	0.54	-0.06	0.87	-0.51	0.11	-0.22	0.52	-0.35	0.29	-0.32	0.34	-0.20	0.55	-0.22	0.52
	Con.**	0.26	0.45	-0.27	0.42	-0.25	0.47	-0.16	0.64	-0.39	0.24	-0.45	0.17	-0.24	0.49	-0.37	0.27
	Ecc.**	0.17	0.62	0.47	0.15	-0.19	0.57	-0.25	0.47	-0.03	0.93	-0.02	0.97	-0.24	0.49	-0.09	0.79
Rate of torque development (Nm/sec/kg)	30%*	-0.01	0.97	0.34	0.31	-0.25	0.47	-0.32	0.34	-0.05	0.90	-0.06	0.86	-0.30	0.38	-0.07	0.84
	90%**	0.28	0.41	0.48	0.14	-0.11	0.76	-0.20	0.56	0.10	0.78	0.12	0.72	-0.24	0.49	-0.06	0.86
	25ms**	0.23	0.50	0.54	0.09	-0.09	0.80	-0.22	0.51	0.12	0.74	0.15	0.67	-0.20	0.55	-0.01	0.98
	50ms**	0.23	0.50	0.54	0.09	-0.09	0.80	-0.22	0.51	0.12	0.74	0.15	0.67	-0.20	0.55	-0.01	0.98
	150ms*	0.02	0.95	0.39	0.24	-0.25	0.47	-0.32	0.34	-0.05	0.90	-0.06	0.86	-0.30	0.38	-0.07	0.84
	175ms*	0.02	0.95	0.39	0.24	-0.25	0.47	-0.32	0.34	-0.05	0.90	-0.06	0.86	-0.30	0.38	-0.07	0.84
Hamstrings flexibility*** (degrees)		**-0.72**	**0.01**	-0.21	0.54	**0.77**	**0.01**	0.46	0.16	0.42	0.20	0.32	0.35	**0.60**	**0.05**	0.45	0.16

: outcome measures that were reliable in the PFP group, **: reliable in uninjured group, *: reliable in each group (Chapter six).*

Table 7.7: Spearman's correlation analyses between the changes in patient reported outcomes and local neuromuscular investigations pre-post six weeks. Significant correlations are highlighted.

Spearman's Correlations of differences between session 1 and 2 (using mean differences = session 2-session 1)		AKPS		VAS													
				Worst pain last week		Pain before session started		Pain after single-leg triple-hop test		Pain after isometric peak torque test		Pain after concentric peak torque test		Pain after eccentric peak torque test		Pain after session ended	
		Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.	Corr.	Sig.
Unnormalised BF MEA* (mV)		-0.48	0.13	0.01	0.99	0.24	0.48	0.08	0.83	0.12	0.73	0.04	0.9	-0.11	0.75	0.22	0.51
Peak torque (Nm/kg)	**Iso.***	0.06	0.85	0.59	0.054	**-0.6**	**0.05**	-0.49	0.13	**-0.63**	**0.04**	-0.21	0.55	-0.09	0.8	-0.41	0.22
	Con.***	-0.27	0.42	-0.14	0.69	-0.32	0.34	-0.08	0.83	0.02	0.94	-0.19	0.57	0.04	0.91	-0.11	0.74
	Ecc.***	-0.15	0.67	0.07	0.83	-0.51	0.11	-0.38	0.25	-0.57	0.07	0.03	0.92	0.23	0.5	-0.18	0.6
Rate of torque development (Nm/sec/kg)	**30%***	-0.03	0.94	0.42	0.19	-0.34	0.31	-0.25	0.45	-0.18	0.61	**-0.67**	**0.02**	-0.27	0.42	-0.42	0.2
	90%**	0.08	0.81	-0.3	0.36	-0.11	0.75	-0.33	0.32	-0.36	0.27	-0.11	0.74	0.04	0.9	0.26	0.45
	25ms**	0.12	0.73	0.51	0.11	-0.3	0.37	-0.2	0.55	-0.17	0.62	**-0.61**	**0.046**	-0.15	0.67	-0.37	0.26
	50ms**	0.14	0.69	0.46	0.15	-0.3	0.37	-0.17	0.63	-0.13	0.7	-0.54	0.09	-0.15	0.65	-0.43	0.19
	150ms*	-0.25	0.47	0.39	0.23	-0.31	0.35	-0.38	0.25	-0.25	0.46	**-0.64**	**0.03**	-0.41	0.21	-0.31	0.36
	175ms*	-0.25	0.47	0.39	0.23	-0.31	0.35	-0.38	0.25	-0.25	0.46	**-0.64**	**0.03**	-0.41	0.21	-0.31	0.36
Hamstrings flexibility* (degrees)**		-0.21	0.53	-0.3	0.37	**0.81**	**0**	0.53	0.1	0.58	0.06	0.15	0.66	0.11	0.76	**0.67**	**0.02**

: outcome measures that were reliable in the PFP group, **: reliable in uninjured group, *: reliable in each group (Chapter six).*

Table 7.8: Data used in the correlation analyses of the differences between sessions one and two pre-post six weeks. Improvement (VAS and AKPS) as well as increases in data (local characteristics) are highlighted with green, and red for the worsening scores (VAS and AKPS) and decreases in data. Negative hamstring flexibility scores represent increases in flexibility.

Difference between pre-post 6 weeks scores for each participant; each score = session 2 (post6weeks) – session 1 (pre6weeks)													
online course	**completed**	**not completed**						**no response**					
	PFP29	**PFP12**	**PFP24**	**PFP41**	**PFP46**	**PFP47**	**PFP50**	**PFP6**	**PFP16**	**PFP34**	**PFP49**	**mean**	**SD**
AKPS	3	-9	-2	49	13	6	-5	5	0	8	2	6.4	15.4
VAS (worst pain last week)	-3	-1	-4	-3	-3	1	-4	0	2	0	-2	-1.5	2.1
VAS (before session)	-1	0	0	0	1	2	1	-1	0	0	0	0.18	0.9
VAS (after SLTHT)	-1	-2	-1	-1	1	1	2	-1	0	0	0	-0.2	1.2
VAS (after IsoPT.)	-1	-1	0	-1	0	1	2	-1	0	0	0	-0.1	0.9
VAS (after ConPT.)	-1	-1	-1	0	0	-2	1	-1	0	0	0	-0.5	0.8
VAS (after EccPT.)	0	-4	-4	-3	2	-1	0	-2	-2	0	0	-1.3	1.9
VAS (after session)	-1	1	0	-1	1	1	1	-2	-2	0	0	-0.18	1.2
BF MEA (unnormalised)*	42.23	63.06	-74.99	-101.22	7.31	-16.98	46.95	-134.15	73.41	-107.83	-184.21	-35.1	89.2
Peak IsoPT.*	9.11	33.55	-14.8	-7.31	0.68	-10.43	-23.62	46.09	31.71	32.8	-0.02	8.9	23.4
Peak ConPT.***	65.48	-4.9	13.6	-13.3	-30.63	-1.16	61.36	31.73	-8.94	35.92	-19.41	11.8	32.6
Peak EccPT.***	127.18	119.95	-37	-1.07	72.28	-88.53	-25.03	29.99	31.56	25.48	110.66	33.2	69.5
RTD to 30% of IsoPT.*	322.69	-36.84	10.79	-64.88	-239.91	143.28	-143.06	43.87	118.52	-4.07	-591.34	-40.1	235.9
RTD to 90% of IsoPT.**	100.2	29.57	-19.87	-19.49	0	-63.95	-62.52	-119.46	-86.91	16.77	-901.28	-102.4	271.8
RTD at 25 ms**	207.35	-82.65	-23.48	-82.7	-122.39	107.72	-135.19	-9.86	51.81	10.63	-528.47	-55.2	187.3
RTD at 50 ms**	259.38	-94.3	-20.99	-92	-170.01	155.84	-161.13	-17.21	80.28	0.63	-721.8	-71	252.3
RTD at 150 ms*	365.97	66.82	41.06	-107.81	-226.19	92.24	-142.88	13.24	127.64	-39.71	-656.39	-42.4	257.1
RTD at 175 ms*	343.15	60.39	47.18	-105.39	-223.84	64.17	-125.41	34.31	131.1	-64.56	-547.26	-35.1	226.5
Hamstrings flex.***	-7	-1	-1	-2	1	0	1	-29	-1	-9	-8	-5.1	8.7

: outcome measures that were reliable in the PFP group, **: reliable in uninjured group, *: reliable in each group (Chapter six).*

7.4 Discussion

In this chapter, we aimed to determine the feasibility of the testing protocol in a group of people with PFP. To our knowledge, no previous study investigated a battery of tests targeting a similar combination of local neuromuscular deficits that are associated with PFP (176). Therefore, this feasibility study provides specific factors to aid future study planning to explore mechanisms of effects of interventions through changes in local neuromuscular deficits, that are evidently associated with PFP.

7.4.1 Feasibility

Identifying aspects that impact participation is important to inform future research planning (385). Findings of this study indicate that a protocol administered to detect changes in local neuromuscular deficits is partially feasible. This is due to the partial agreement with the feasibility parameters that were set a-priori.

Out of the 55 responses to the screening survey, only 14 consented and were eligible, indicating a low willingness-to-participate rate (25.5%, less than half of the a-priori target of 60%). Although a total of 17 participants consented, six were lost; two were ineligible, one did not respond to plan session time, and three did not attend the second session (6/17=35% drop-out). This indicates that a total retention rate of 65% was achieved (with less than 40% a-priori drop-out rate). The high eligibility rate (82%) versus the low willingness-to-participate rate (25.5%) is a consequence of the screening that was performed to identify potential eligible participants.

Our results are not very different than an interventional feasibility study that was performed during the pandemic. In their two-armed randomised feasibility trial, O'Sullivan et al. (371), reported that approximately 87.1% of the potential (screened) participants were not included (compared to 74.5% in our study). The drop-out rate at six weeks was 36% (13 out of 36), which is similar to what we obtained (35%). O'Sullivan et al. (371) had n=36 total sample size and a recruitment rate of 1.2 participants per week over 7.5 months. We had a smaller sample, a lower recruitment rate (0.5 per week) in a shorter period (six months) indicating that neither using one-site nor study length were sufficient. O'Sullivan et al. (371) targeted adolescents, and recruitment was conducted in two cities (Brisbane and Gold Coast) in community and schools sports events, as well as multiple social media platforms (Instagram and

Facebook). The recruitment in our study was mainly through flyers that were present in Mile-End campus (in the Gym, Engineering and post-graduates buildings) and in Whitechapel (in the Experimental Medicine and Rheumatology Centre, and a QMUL affiliated coffee-shop), in addition to QMUL bulletin (emailed) and twitter. Six clinics were administering the intervention (foot orthoses) in O'Sullivan et al. (371), and we performed the tests in one laboratory in Mile-End, London. So, having multiple sites for data collection, in addition to increasing study length, can increase exposure to study advertisements and improve the recruitment rate to allow obtaining a larger sample in future (386). Another interesting finding, O'Sullivan et al. (371) had 11% participants' losses that were covid-related (4/36), we had one participant lost for a similar reason (tested +ve, 1/11=9%). Therefore, we suspect that Covid-19 had a direct influence on the feasibility outcomes, and a post-pandemic study would achieve a larger sample size, especially after enhancing recruitment pathways.

Supervised interventions can increase adherence in knee pain research (387). So, it is reasonable to assume that a study offering an intervention that aims to improve participants' condition would help retain or recruit a larger sample. However, we retained the minimum targeted sample of n=11. A small incentive, that was not presented in study advertisements, was provided to the participants who completed all sessions (£20 voucher). This could have had a positive impact on retention rate (388). However, this incentive was received by only nine participants (who attended all three session's), so it is reasonable to assume that the incentive only had minimal impact on feasibility outcomes. We contacted three participants whom attended only one reliability session, to be tested six weeks apart from the time they were present to analyse our protocol's feasibility. Two attended, indicating that it was a successful method to retain a larger sample (18%). Our sample eventually had nine participants that had one session before the pre-post six weeks tests. This might cause a 'testing effect', which means that participants performance can be affected by their familiarity with the test (99).

Most importantly, no adverse events following testing were seen, and no dropouts were reported due to any test within the protocol. This finding is similar to the clinical local-deficits identification protocol by Selfe et al. (11), although our protocol included

multiple lab-based tests and potentially took longer to be performed. So, the tests were well-tolerated by the recruited sample.

Our primary outcomes; willingness-to-participate, eligibility rate, recruitment rate and retention rate, were identified. In the recommendations section, an explanation of how these results would inform planning of a future study with a similar testing protocol can be found.

7.4.2 Secondary outcomes

Except for hamstrings flexibility, secondary analyses showed anticipated insignificant changes, that could be attributed to participants' knee condition, in addition to multiple significant correlations between the investigated characteristics and clinical outcomes.

Multiple interventional studies include arms investigating wait-and-see (164,389,390) or sham interventions (148,150) in PFP. The sham group in Ma et al. (148) showed an increase of 9.8 points in AKPS scale in a testing session after six weeks. Our group showed an increase of 6.4 points. Pain scores can change during session, especially if testing includes knee loading. Song et al. (150) collected worst pain score of last week (4.16 VAS) and pain during single-leg squat (SLS; 3.78 VAS). So, their sham arm showed difference of 0.38 VAS between two different pain scores in the same session. Although our study did not include SLS, we had larger results in both sessions between worst pain last week and VAS after SLTHT (table 7.4). The changes our group exhibited are also larger than the changes that were seen in wait-and-see arms in previous studies (164,389,390). In our study, only eight responded when asked about the completion of the online programme, one completed the programme while six did not, and one did not start the course. So, these changes could be attributed to the educational programme that we referred our group to during the six weeks period, as seven out of 11 participants were exposed to the education programme in our study. Education was found to be superior to wait-and-see in a recent systematic review (4). Recommending education programmes alone to treat PFP remains challenging, but it might produce improvements that are similar to exercise (391) and can promote active management (15). So, the fact that only one participant completed the education programme explains the insignificant but minimal changes we found. However, there was an exception in hamstrings flexibility, as results show significant changes and

surpassed the MDC. It is important to note that the observed changes in VAS and AKPS did not reach MCID, which is expected, as an exercise intervention was not provided. These variations in results require an explanation, which is demonstrated next.

By visually inspecting hamstrings flexibility data in Table 7.3 and Figure 7.5, its apparent that there is a potential outlier (PFP6). To investigate the impact of this, a sensitivity analysis was undertaken by removing the data point. Although PFP6's data significantly influenced the group's average, the change in hamstrings flexibility remained significant without it (p=0.047) but did not pass the MDC of 3.1° (change=2.7° without the outlier, and 5.1° with the outlier). Hamstrings flexibility data was not normally distributed, which required the analysis using Wilcoxon signed-ranks test. The difference in conclusion between the Wilcoxon test and MDC analysis could be due to the violation of the normality assumption, as the MDC was calculated using 1.96 multiplier, which corresponds to the 95% confidence interval under a normal distribution (99). Most importantly, PFP6 verbally mentioned undertaking extensive stretching exercises in the six-weeks period, which likely contributed to their marked flexibility improvement. This is a reasonable explanation of the results, especially that the reliability of the hamstrings flexibility test was excellent in the previous chapter.

Increased hamstrings flexibility was associated with an increase in function in session two (AKPS scores, table 7.6) and a decrease in pain collected before sessions started (in session two and pre-post changes (tables 7.6 and 7.7)) and after session ended (pre-post changes (table 7.7)). This is an expected, further confirmation of our previous findings (in Chapter three) suggesting tighter hamstrings to be associated with PFP. Overall, the correlations between AKPS and multiple deficits seen in session one were all diminished in the second session, where there was minimal overall increase in torque. This relationship is expected as less torque is associated with PFP (31,81,176). However, correlation analyses require large samples to be accurate (381). Due to the small sample, we could be presenting over-fitted results (392,393). A 100-point VAS scale would be preferrable in future to implement interval scores that can present more detailed variance in pain levels (259,394).

Pain can show statistically significant changes while being below a MCID. Pre-post analyses showed significant difference in worst pain scores of previous week, although the difference was -1.5, less than a two-point MCID change (259) (tables 7.3 and 7.4).

Being less than a MCID is expected as no intervention was introduced, but this warrants minimising reliance on statistical significance and instead, rely on well-established MCIDs. So, the effects of PFP as a condition (in absence of interventions) on reported pain and AKPS scores should be anticipated in future. Studies seeking to identify a mechanism of benefit through the deficits we investigated should set the MCIDs for chosen patient reported outcomes a-priori.

7.4.3 Limitations

The small area and population category targeted (mainly students and staff within a University) might have negatively influenced the recruitment aspect of the study. A thorough screening process would enhance future recruitment plans and present further understanding of the population exposed to our study advertisements. Secondly, the sample size allows our results to inform protocol feasibility but was not sufficient to inform the secondary analyses conducted on the outcome measures. Due to the small sample, the outcomes of this study cannot be used to calculate sample size for future work. However, feasibility study results are generally not recommended to be used for sample power calculation (395).

Not all outcome measures investigated in this study showed acceptable reliability in PFP, as some outcomes showed acceptable reliability in uninjured group only (Chapter six). So, the results should be treated with caution for the outcome measures that were unreliable in PFP, and further reliability analyses are recommended. Pain levels were gathered at nine different time-points to allow an understanding of the potential effects of PFP symptoms on local characteristics (377–379). However, most VAS scores were of pain felt after a task not during it. This could have implications on the interpretation of PFP-deficits relationship and the gradual pain exacerbation that can occur through performing multiple tasks that consecutively load the knee.

The testing sessions included a task used for a test that was not reliable (step-up for the VM-VL) and can increase joint loads or exacerbate pain, which might affect the detection of deficits. This is especially important in scenarios where tasks with physical demands higher than repetitive step-ups are required. This was due to unavailable reliability results before the start of data collection. In particular, the signal analyses procedures through MATLAB took extra time, which prevented the exclusion of these tests before the pre-post six-weeks feasibility part of the study was conducted. The

time was limited as well, as this study was conducted during COVID pandemic, near the end of the PhD programme.

7.4.4 Recommendations

To conduct a study that aims to identify a mechanism of benefit of interventions in PFP, multiple recommendations should be mentioned. A future study should recruit at least 35% more than the targeted sample. Studies in PFP sometimes recruit samples that suffice the 'rule of ten' (ten participants for each investigated variable), which is not always appropriate as it is based on logistic regression models (396), and some statistical studies recommend larger numbers (n=50 per variable) (397). Even when some PFP reviews considered the 'rule of ten' to be sufficient, they found that most studies in PFP had smaller samples (29,31,81). Moreover, different types of statistical analyses should influence the sample size planning procedures (398) and some statistical analyses require large samples to be accurate (399). For example, Van Voorhis and Morgan (398) mentioned general sample size limits that can be considered in relation to statistical analysis types (n=30 for each cell for t-test/ANOVA, n=50 for correlation/regression, n=20 for chi-square, and n=300 for factor analyses). Conducting feasibility studies to provide an expected drop-out rate, consulting statisticians, and providing published effect sizes for sample size calculation, especially when different types of analyses (e.g., pre-post changes and regression) are planned, is vital.

Secondly, if the reliability of the outcome measures were not established by the same assessors of the study, planning should involve implementing a reliability aspect for a proportion of the recruited participants. This might affect the length of the study. We objectively showed that reliability established in previous studies might not be completely generalisable, especially in a protocol that includes a combination of different domains (EMG, torque and flexibility). Moreover, reliability studies conducted on participants diagnosed with PFP are uncommon (274), which is another layer of what future studies should consider before investigating protocols' feasibility.

Scripts and codes used in programming applications like MATLAB are rarely published, which affects reproducibility of results (400). So, another important aspect that this study provided is the development of the analysis scripts in MATLAB. Similar procedures could take time and effort to be sufficiently optimised, and a future study

that implements similar neuromuscular investigations can derive their signal analysis procedures from the scripts provided in Appendix 5. We did not find any published signal analyses scripts in the studies from which our testing protocol was derived, and we contacted some of the authors but failed to obtain any script.

Future interventional feasibility studies should equally focus on feasibility of the testing protocol, as some tests can present discomfort which might affect the results a clinician (and a patient) might seek following intervention. By establishing reliability in a PFP sample, effects of similar discomfort can be identified. However, reliability studies are usually short in duration. A true wait-and-see period would have presented a clearer interpretation about the effects of the natural course of the disease on the deficits in our study. Multiple PFP studies have wait-and-see groups (164,389,390), and systematically reviewing such studies to identify the effects of PFP on data collection without intervening is recommended. However, the ethical challenge of recruiting a PFP group with a present complaint without intervening must be considered. This ethical issue of not providing an intervention for an eligible group (401) made it required to add the online education programme to our study, which was targeting the feasibility of a testing protocol.

Application to major organisations, like NHS in the UK, would allow a larger exposure of affected populations to recruitment pathways. Use of incentives should be evaluated and carefully planned as it affects recruitment rates and adherence (402). Although the AKPS is valid and reliable, and is supported in the literature (15,259,383), other questionnaires could be used additionally to provide further details about functional levels. A recent systematic review indicates that the Knee injury and Osteoarthritis Outcome Score - Patellofemoral subscale (KOOS-PF) had higher validity compared to other patient reported outcomes' tools (403).

Lastly, length of study and the use of one site to collect data was a limitation that should be mitigated in future. A multi-site study is needed to recruit enough participants for a study of a similar period, otherwise, length of study will need a substantial increase to provide optimal recruitment.

7.5 Conclusion

This feasibility study was conducted to improve the chances of success in a future larger-scale study (362). It was specifically targeting a protocol that included a novel combination of tests that detect local neuromuscular deficits evidently associated with PFP (176). The current study highlighted aspects that can improve recruitment in future, including drop-outs rate with reasons, recruitment rate, and duration. It also identified that the combination of multiple neuromuscular tests for deficits associated with PFP can be tolerated. A future study should include methods to increase exposure to study advertisements and increase the sample by using multiple sites. With the limitations and recommendations carefully considered, this study provided important information that aid conducting future research that aim to identify mechanisms of benefit of interventions via local neuromuscular deficits associated with PFP.

8 Implementing the outcomes of the thesis for a future project to identify the mechanisms of effects of interventions in patellofemoral pain

As demonstrated through the chapters, the thesis as a whole presents a novel method to provide what is needed to identify the mechanisms of effects of interventions using local neuromuscular characteristics associated with PFP. In this chapter, we demonstrate how a future interventional study would be planned based on the outcomes of the thesis.

8.1 Background

Specific deficits associated with PFP have been identified (Chapter three), some have been shown to be reliable (Chapter six) and few of these deficits have been investigated for change following specific interventions (Chapter four). Future work needs to fill this knowledge gap, through delivery of an intervention that specifically targets known deficits and identifying the magnitude of change of these deficits to be correlated with the change in symptoms.

8.2 What are the deficits associated with PFP that should be investigated?

There are two categories of deficits to be included in a future interventional study, dependent on whether further reliability work will be nested in study's design. Category one deficits have proven reliability of measure and shown to be associated with PFP. Category two are either deficits that were identified to be associated with PFP in Chapter three but were not included in the testing protocol due to poor methods reporting (Chapter five), or characteristics observed to have changed following specific interventions delivered to PFP populations (Chapter four) but were not identified to be associated with PFP in Chapter three (Table 8.1).

Table 8.1: All outcome measures, or characteristics, that can be implemented in a future interventional study.

	Category of investigations	Deficits to be investigated
Category 1	**Ready for investigations** (associated with PFP and reliable)	Knee extension isometric peak torque* at 60° of knee flexion
		Knee extension concentric peak torque at 30°/sec from 20° to 90°
		Knee extension eccentric peak torque at 30°/sec from 90° to 20°
		RTD at 25ms of isometric MVC at 60°
		RTD at 50ms of isometric MVC at 60°
		Hamstrings flexibility by measuring popliteal angle in supine position with a horizontal bar to hold hip at 90°
Category 2	**Deficits that were identified in Chapter three but were not included in testing due to poor methods reporting****	Knee extensors total work
		Knee flexors concentric peak torque
		Knee flexors total work
	Can be changed with interventions based on Chapter four, but were not identified in Chapter three	Quadriceps flexibility
		Gastrocnemius flexibility
		Iliotibial-band flexibility

**; isometric peak torque was only reliable in the uninjured group, but as the RTD to 25 and 50ms are to be conducted in isometric peak torque test, including this test is recommended with caution.*
- RTD to 90% of peak torque was reliable in PFP, but the 95% confidence interval of the intraclass correlation coefficient (ICC) was large, with large SEM and MDC, so further reliability testing would be required, and can be added to category two.
***; would require methods development.*

8.3 Which study design would be suitable to identify a mechanism of effects of interventions through local neuromuscular deficits?

Planning a quasi-experimental study (similar to Chapter seven) would present a gradual progression into a larger RCT since we did not implement an exercise intervention that targets these deficits. However, an experimental pre-post intervention randomised controlled trial (RCT) would be the optimal choice. A study with this design is needed to truly ascertain if a mechanism of effects of interventions using local neuromuscular deficits can be identified. The experimental arm would receive an intervention that targets the collected deficits, which would be adapted from the results of Chapter four. The control group receiving an intervention recommended by best-practice guidelines and consensus statements (can be derived from, or built in a similar manner, to the work of Greaves et al. (127)). So, a single-blinded RCT can be performed to identify if targeting local neuromuscular deficits that are associated with PFP with a specific intervention in an experimental PFP group show superior improvement against a PFP control group.

With within-group and between-groups comparisons, the goal would be to see if these deficits change with improvement. If they exhibit changes with superior improvements when targeted by a specific intervention, it will indicate that these deficits can guide intervention choices, and a mechanism of effects can be identified through these deficits. The null hypothesis would be that there are no significant differences in interventional outcomes between experimental and control groups (i.e., no between-group differences in changes of deficits and clinical outcomes).

8.4 What would be the sample size?

There are two reasons to use the effect sizes yielded by the meta-analyses (from Chapter four) and not the outcomes of the feasibility study (Chapter seven) to conduct a sample power calculation. First, there were no exercise intervention prescribed in our feasibility study, and it is generally not recommended to use the outcomes of a such study for subsequent sample size calculation (362). Secondly, pooling data from several studies improves effect size estimation, which is offered by meta-analyses (99).

Looking at the findings in Chapter four, there are multiple pooled effects that can be used to calculate the sample size. The significant pooled effect of deficits associated with PFP were as follows:

- Figure 4.4 showing strong evidence of a change in isometric extension peak torque; 0.660 from hip and knee exercises that showed a MCID in pain (VAS) and function (AKPS) (third and last plot; Page 94).
- Figure 4.6 showing very limited evidence of a change in concentric extension peak torque; 0.923 from hip and knee strengthening and stretching exercise that only showed a MCID in pain (VAS) (last plot; Page 96).
- Figure 4.7 showing very limited evidence of a change in concentric flexion peak torque; 1.038 from hip and knee strengthening and stretching exercise that only showed a MCID in pain (VAS) (last plot; Page 97).
- Figure 4.10 showing very limited evidence of a change in hamstrings flexibility; 0.874 from knee strengthening exercise that only showed a MCID in function (AKPS) (last plot; Page 100).

Being of a strong evidence, pooled from two samples that showed MCID in pain and function, and smaller than all other effect sizes, the pooled effect of a change in isometric peak torque in PFP, which equals 0.66 was used to calculate sample size for a future RCT using G*power (Version 3.1.9.4; t-tests, difference between two independent means (two groups), two-tailed, alpha=0.05, and power set to 0.8). Outcomes showed a total required sample of n=76 (n=38 in each group). Using the feasibility outcomes, the sample size can be planned, incorporating the willingness-to-participate percentage and drop-out rates we identified from Chapter seven.

The study advertisements should seek to obtain an expression of interest from 459 potential participants, as based on feasibility study, 25.5% (n=117) of people would be eligible and willing to participate. Then, with a calculated drop-out of n=41 (as an expected drop-out rate of 35.2% was obtained from the feasibility study) a sample of n=76 would be retained. We achieved a recruitment rate of 0.5 participants per week during the pandemic, and enhancing that rate should be targeted in future. With an enhanced recruitment rate of at least 2 participants per week, conducting a single-centre RCT would require 10 months to be completed.

8.5 What interventions should be used?

The intervention of the experimental group can be derived from Chapter four's results. Strong evidence indicated that a significant change in isometric peak torque can be associated with a MCID in pain and function, by pooling the data of two studies with

low risk of bias (162,268). As the programme used by both studies was for four weeks and did not target hamstrings flexibility and rate of force development, these elements were added (power element derived from (309)). The resultant programme is a six-weeks hip and knee exercise programme that targets strength (generally), power, and hamstrings flexibility. Being a hip and knee targeted programme, it is in-line with recent recommendations of using such programmes to treat PFP (4,15). The programme can be found in Appendix 8.

An intervention that should be derived from published guidelines (15,127,128) would be given to the control group. Basically, the control group should receive an evidence-based intervention programme that is not built specifically to target the identified deficits. Consequently, we can accurately find if targeting such deficits would produce improvement that is superior to other interventions, affirming the use of local neuromuscular characteristics to guide intervention choices.

8.6 Conclusion

This concise chapter contained an objective implementation of the outcomes of the thesis in a potential future interventional study. It applies the findings of Chapters three, five and six to justify the choice of deficits to be investigated, and uses parameters for recruitment from Chapter seven. An intervention programme that targets local neuromuscular deficits that are associated with PFP is also presented, through the adaptation of the findings of Chapter four. Therefore, Chapter eight exhibits a summarised potential plan for an interventional study that can identify a mechanism of effects of interventions through local neuromuscular deficits associated with PFP.

9 Discussion and Conclusion

This chapter presents a general discussion of the outcomes of the thesis, followed by a final conclusion. A diagram representing the different phases of the thesis is supplemented in this section to visually highlight the thesis progression (Figure 9.1).

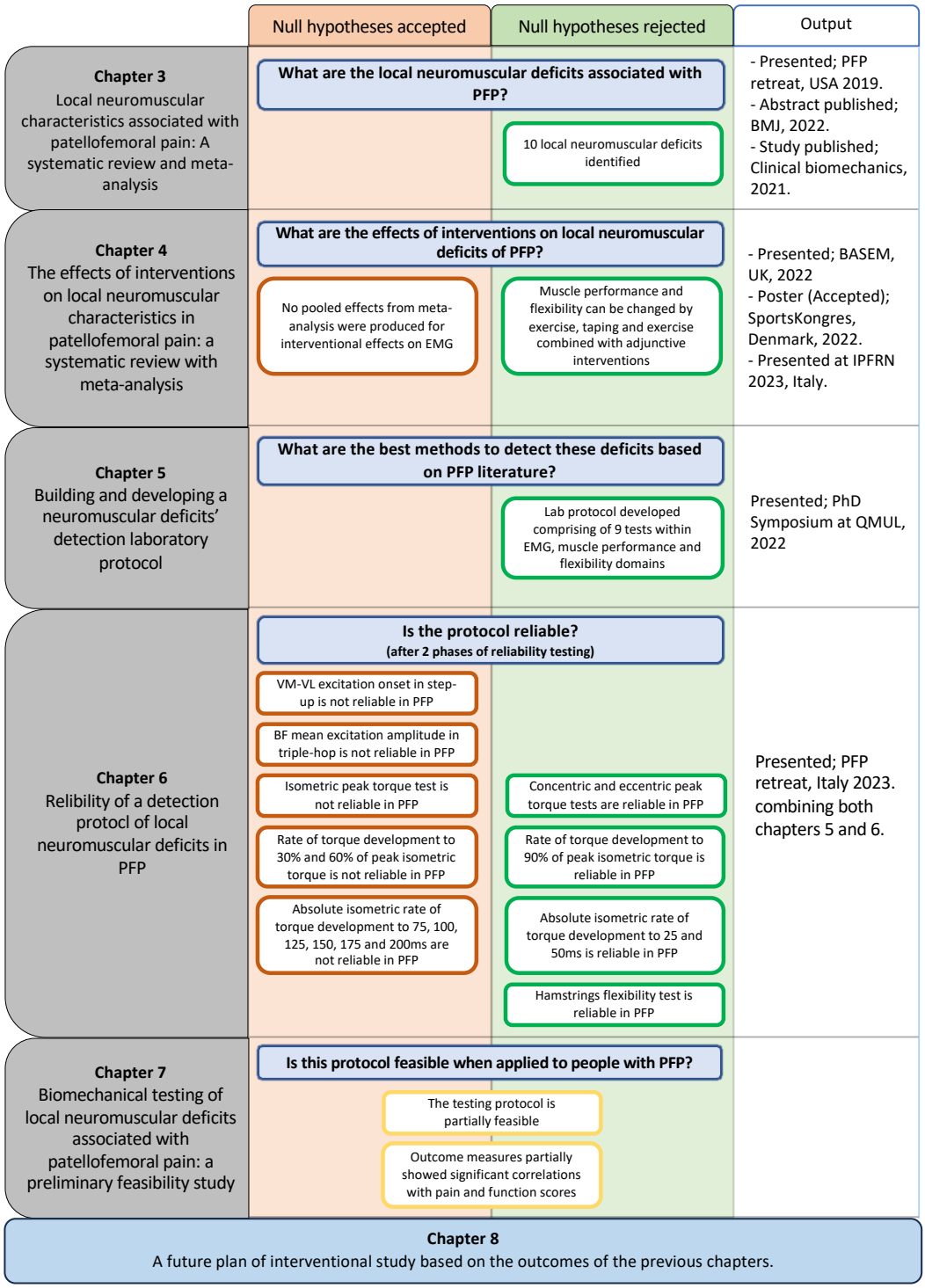


Figure 9.1: Diagram presenting the progression and outputs of the thesis.

9.1 Aspects of novelty within the thesis

In seeking to answer our research question - 'How can we identify and measure local neuromuscular characteristics associated with PFP, in order to investigate mechanisms of effects for specific interventions?' – a series of interlinking studies were conducted to provide insight into the mechanisms of effects of interventions for people with PFP. Five areas can be identified where this thesis shows novelty and adds to the literature.

9.1.1 The large syntheses of the literature

To equip the thesis with a solid base of high level of evidence (99), two reviews were conducted, and are the largest available syntheses on local neuromuscular deficits to date. The systematic review in Chapter three was conducted to synthesise the literature for local neuromuscular deficits that are associated with PFP, to identify which deficits should be tested. The systematic review in Chapter four was a synthesis of interventional studies, to identify which interventions can target local neuromuscular deficits and should be included in a future interventional study. There were no previous systematic reviews that focused solely on local neuromuscular characteristics. Therefore, establishing a foundation for the thesis by systematically reviewing and meta-analysing the literature was reasonable. Although we had strict inclusion criteria, both reviews included a large number of studies (46+67=113; but five cohort studies with a case-control element were included in both reviews). This is an indication about the amount of research output specifically within local characteristics, and that an objective synthesis using meta-analyses was needed for the thesis to reach its goal (302).

9.1.2 The methods development process

The methods development process was novel. No previous studies or theses to our knowledge determined their practical laboratory methods objectively by a novel scoring system of meta-analyses results. The benefit of such approach is to minimise methodological inconsistency which might be the cause of the inconsistent results around PFP characteristics within the literature (these inconsistencies were highlighted in Chapter one).

9.1.2.1 Finding an evidence-based local neuromuscular deficits-detection protocol in PFP by assessing meta-analyses results

In an attempt to enhance the robustness of the thesis, Chapter five comprised of a detailed extraction of the methods that formed the quantitative agreements (i.e. significant pooled effects). To our knowledge, this is the first attempt to empirically extract (by methods scoring) a testing protocol from meta-analyses.

This unique approach required developing assessment tools that evaluate the reproducibility of each variable investigated within a forest plot. The reproducibility of biomechanical testing procedures can be assessed to further inform the outcomes of a systematic review (273). By adapting this approach, we intended to minimise the effects of paucity seen in local neuromuscular characteristics reporting (12). No other attempts were found to be analysing the reporting details of local neuromuscular tests in PFP. The closest example can be found only in a recent systematic review of kinematic gait variables in PFP (273). By deciding to progress with protocols that sought empirical agreement in deficit detection, we are minimising arbitrary inclusion of tests. But for our assessment tools, a validation, like a delphi study, is needed before general research implementation (273).

Being a novel approach, a discussion about the challenges we faced is needed. We sought better research integrity (404) by publishing a corrigendum of our systematic review (178), as we discovered that the meta-analysis of BF EMG outcomes were erroneous, due to methodological differences, although both studies measured excitation amplitude in single-leg triple-hop test. This can change the meta-analyses on which our protocol was based. Additionally, journals' reviewers might request search-updates during peer review. So, we identified two sources that can modify outcomes; possible errors, and updated searches. Researchers should be aware about this in future similar adaptations.

We mentioned previously that the method we used to categorise each variable in the meta-analysis (functional/isolated tasks; Chapter three) aided the test-extraction method proposed in Chapter five. However, we found a different categorisation method that could better inform progression into similar biomechanical testing in future. Dischiavi et al. (405) conducted a systematic review on types of interventions in PFP. In that study, the interventions were categorised based on their kinematic task-

specific and planar elements (e.g. single-leg squat is multi-planar; sagittal and frontal). Although it was about interventions, their methods of variables' categorisation could be adapted for deficit-detection procedures (i.e. the findings of our review in Chapter three), and better inform subsequent biomechanical research.

Overall, Chapter five was a justified approach that was needed to provide the thesis with an evidence-based testing protocol to detect local neuromuscular characteristics associated with PFP.

9.1.3 The methodological assessment tools

The produced lists of methodological assessment tools that were used to score how studies reported their practical methods are original as well. A study can be determined as a "high quality" or "low risk of Bias" study using available methodological and risk of bias assessments, but the level of study quality and risk of bias are usually unrelated to the reporting quality of the laboratory investigations. Such a step of methodological assessment is needed in biomechanical studies, and the thesis provides three assessments for EMG, muscle performance and flexibility tests. Being original, however, necessitates carefully considering the limitations and recommendations that are related to this work, that were mentioned in Chapter five.

9.1.4 New findings and gaps revealed by the systematic reviews

The findings of both reviews add to the knowledge in PFP literature. The review in Chapter three identified deficits within EMG, muscle performance and muscle flexibility that were not produced by meta-analyses previously. The second review (Chapter four) identified interventions with effects that can target specific deficits. Surprisingly, that review showed a clear gap around the overlap of investigations between studies that aimed to find deficits (testing PFP against uninjured groups) and studies that aimed to identify changes within such deficits pre-post interventions. This means that some interventional studies have used a characteristic that might not be associated with PFP. For example, table 4.3 (page 90) includes 62 investigated characteristics that we found within interventional studies (pre-post intervention). These outcome measures intersected with the studies that aimed to find deficits (testing PFP against uninjured) in only 20 out of the 62.

The thesis also produced unique gap-maps that clearly highlight the research areas where most of the evidence is situated. Gap-maps are being increasingly presented in

recent studies of PFP (4,273,406). Our gap-maps showed the areas where there is the least evidence, further guiding this thesis to avoid investigations less supported by the literature.

Since the aim of the thesis was to provide a specific protocol that can be used to identify a mechanism of effects of interventions through local neuromuscular characteristics that are associated with PFP, it took an approach of objectively synthesising what has been identified. In a relevant paper (80), Callaghan referred to the methods used to sub-classify PFP groups (based on deficits) to being conducted in a "scatter-gun" approach, as they are adopted into clinical work without fulfilling preliminary research phases (i.e., reliability and validity). A novel way to prevent another 'scatter-gun' approach, was to use the highest levels of evidence (systematic reviews and meta-analyses) to determine what deficits to choose and how they can be detected, then perform reliability and feasibility studies (in PFP), progressing towards planning a future large-scale interventional study. As we mentioned, PFP groups with specific deficits are often dealt with through non-systematic methods (80), and conducting investigations of characteristics that were not sufficiently tested (from our gap-maps) would cause a risk of continuing to deal with PFP in a similar manner.

9.1.4.1 The syntheses do not disprove the existence of other local deficits in PFP

Within muscle flexibility, the first review in Chapter three indicates that hamstring tightness is a deficit associated with PFP. However, the review does not disprove existence of flexibility deficits in other local structures. Two other structures were tested in included studies, but were not meta-analysed due to lack of similar investigations (gastrocnemius and ITB) (77,201). In the second review (Chapter four), we found limited and very limited evidence showing that increased gastrocnemius and ITB flexibility was associated with improvement in pain and function.

Conversely, quadriceps tightness, but not hamstrings, was found to predispose young adults to PFP in a prospective study (69), yet, it was not investigated in any of the 67 studies included in Chapter three. There are other studies that investigated quadriceps flexibility in PFP and control groups. Smith et al. (122) and Piva et al. (123) reported quadriceps tightness in Individuals with PFP, but were not included in our first review (Chapter three) as there samples had previous injuries and different age range, respectively. We identified very limited evidence of increased quadriceps flexibility in a

PFP group with improvement in AKPS scores (in Chapter four) but our findings showed tightness as a deficit in hamstrings (in Chapter three). This shows that there might be flexibility deficits that were not sufficiently investigated in case-controls, but were identified pre-post interventions. Flexibility of other local structures require further investigations to produce quantitative syntheses.

The eligibility criteria might have had an impact on our results of EMG deficits. Cowan et al. (100) is one of the earlier studies that supplemented the knowledge around VM-VL delays in PFP. That study was not included due to their exclusion criteria, as they only excluded surgeries performed within last three months. The onset difference between VM and VL is investigated mostly in functional tasks (104,195,196,203). We included three studies that were not meta-analysed for methodological reasons. In these studies, VM-VL timing detection through afferent pathways using knee-jerk reflex was performed (75,103,192). The results in Voight and Weider (103) and Witvrouw et al. (75) showed changes in VM timing. Bevilaqua-Grossi (193) did not find significant differences between PFP and controls. In a different study, Karst and Willet (110) compared between onset data of knee-jerk reflex and functional tasks. Although they found delays in the in knee-jerk reflex, these delays did not carry over in the functional task data. This indicates that type of task or method of data collection might dictate the results, which is another indication that choosing tests based on meta-analyses with tasks' categories was reasonable. Despite the lack of agreement, our meta-analyses indicated that VM-VL timing can be used to detect muscle imbalance deficits in PFP, in stepping and stair negotiation. So, it is obvious that there are fields within local deficits in PFP that sought more research than others. This is an important point of interpretation, and future research are recommended to cover the gaps shown in the gap-maps presented in Chapters three and four.

9.1.4.2 The clinical importance of identifying muscle performance deficits in PFP

Willy et al. (15) reported that exercise was found to be effective but poorly reproducible, and that clinicians must explore muscle performance aspects in each patient for better exercise tailoring. The importance of determining muscle performance testing types was highlighted previously. Boling et al. (111) conducted a study to explore concentric and eccentric hip strength differences between uninjured and PFP groups, and discussed the inconsistency and mixed reporting of isometric,

concentric and eccentric testing in PFP literature. In our systematic reviews (Chapters three and four), the included studies reported strength tests in multiple angles and speeds, used different tools for data collection, and showed mixed levels of reporting of the details of their analyses (i.e. normalisation). This lack of agreement might have implications on the transfer of these results into clinical practice. However, our syntheses provided specific muscle performance tests that can be used in PFP to guide exercise choices (407).

The power aspect in muscle performance is currently under research focus. Barton et al. (241) published their feasibility study in 2019 on power-targeting exercise programme for the hip (with optional quadriceps exercises), and was found to be feasible and beneficial. Similarly, de Vasconcelos et al. (309) published a protocol in 2021 for a power-focused hip and knee exercise programme. Our findings support evaluating RTD and are in line with these preliminary research outputs (241,309). Our results also complement the interventional guidelines that is provided by the international patellofemoral pain retreat website that included power as a recommended treatment target (275). Multiple aspects of muscle performance are targeted within these guidelines, and the thesis provides the methods that can be used to monitor changes in these aspects, solving the issue raised by Boling et al. (111) of the need to specify which muscle performance aspects need to be investigated to be subsequently targeted by intervention.

Finding deficits in quadriceps muscles' performance has a unique importance as they are found within studies of risk factors (29,31), in which quadriceps weakness was found to predispose some populations to PFP development. This makes weakness a viable target for interventions. Our findings present a clear path for any further investigation in local muscle performance deficits in PFP. Overall, we found several deficits that can be used to identify potential mechanisms of benefit in future interventional studies.

9.1.5 Reliability in PFP, and preparation for a large-scale study through feasibility

The reliability study (in Chapter six) was conducted in PFP and uninjured groups, giving a clear idea about the effects of the disease on the consistency of measures. The lack of reliability studies conducted specifically on PFP groups were highlighted in the year

2000 (274). Twenty-two years later, biomechanical studies in PFP are still lacking in terms of reliability investigations (273).

Chapter six provided two important aspects for the thesis; a) that we do not continue with a deficits-testing protocol with poor or unknown reliability, and therefore, b) identify the tests that require further reliability before going further. So, another unique step into maintaining a succinct approach towards the thesis goal, was conducting the reliability on a PFP group. The feasibility study, despite the pandemic, was able to provide key factors to aid planning a future interventional study, which is presented in Chapter eight.

9.1.5.1 The importance of conducting lab-specific reliability and feasibility investigations

Adequate reliability testing is vital in research (319), and the sixth chapter formed an imperative phase in the thesis. The list of deficits that were included in the testing protocol were comparable to what the literature indicates (12,81–83). Despite of the rigorous pathway to include and test the reliability of the protocol components, multiple tests showed unreliable results. Poor reporting and reliability testing of research methods in PFP is frequently declared in multiple papers (80,89,98,273). Therefore, we objectively demonstrated the difficulty to reproduce the findings that are commonly seen in PFP literature. Interestingly, Bazett-Jones et al. (273) showed that the least reported aspect of kinematic testing was lab-specific reliability. This indicates that our process in developing a lab protocol and conducting extensive reliability investigations, especially in a single study on PFP and uninjured groups, was viable.

The additional aspect in our work is the exploration of the different thresholds of baseline SDs and time-windows to identify onsets for the VM-VL timing deficit. To our knowledge, no previous work investigated such spectrum of thresholds for onsets' identification. This was performed for two reasons. First, the study we adapted the protocol from did not justify the choice of a double-threshold method of 3 SD x 25ms (196). This is seen previously. Wong et al. (109) systematically reviewed the literature of VM-VL timing investigations in PFP, and multiple types of onset detection thresholds were found. The only study that justified the choice of 3 SD and 25ms is Cowan et al. (100), by comparing the data to visually-identified onsets. The second reason is that

we wanted to explore the effects of signal processing on the findings. Aminaka et al. (191) noted that the high baseline excitation amplitude prevented a proper detection of VM onset using the double-threshold method. To solve that, Aminaka et al. (191) changed the detection method to percentage of peak activity, and subsequently managed to detect the onsets. This could be due to the poor description of how baseline EMG excitation was collected, which is a limitation we found in EMG studies and was thoroughly discussed in Chapter six.

Electromyography studies require sufficient standardisation to be interpretable and comparable. For example, muscle movement under the skin is a normal and expected confounder (287). This is minimised in knee-jerk reflex, and not as much in stepping up, especially if different heights of steps are used between different studies. Clinical classification tests in PFP is recommended to be performed during weight-bearing (13), and that could be the reason why more studies are conducted during functional tasks. However, differences in settings might be the cause of VM-VL timing reports to be inconsistent in PFP, and the difficulty to control possible confounders, especially in functional EMG studies, could be a reason for poor reproducibility.

In some investigations, changes in signal processing can allow different interpretations of the results. The RTD was adapted as a relative measure (to peak torque) from the studies included in Chapter three. Maden-Wilkinson et al. (408) investigated the relationship between absolute and relative RTD with several musculoskeletal variables of the quadriceps. Their correlation analyses yielded different results between relative and absolute RTDs, as only absolute RTD showed significant correlations with some of the investigated variables. We were able to analyse relative and absolute RTD by modifying signal processing procedures. This might be important to be considered early in reliability phases, and especially if a specific type of RTD can be better linked to clinical goals in future. There are multiple indications of evident inconsistency within local deficits in PFP, and our reliability testing partially showed poor results. Any future study must sufficiently establish the reliability of such protocols before further investigations.

A feasibility study was needed to test the applicability of our protocol in a PFP cohort, and has offered various important points (Chapter seven). The feasibility analyses related to sample recruitment presented clear parameters for future study planning.

These thresholds, alongside the effect sizes from strong evidence provided by the second systematic review (Chapter four), can help obtain a minimum sample that is required to accurately identify a mechanism of effect of intervention using local neuromuscular deficits that are associated with PFP.

Important outcomes of Chapter seven can be withdrawn from the pre-post changes analyses. The effects yielded by the analyses can be used to set thresholds to identify true effects of interventions. For example, the insignificant change in concentric peak torque presented an effect size of 0.334. Any future true effects should surpass that threshold. These effects, however, can be considered biased by the educational programme given to the participants. We decided to minimise any ethical challenges by providing the group with an online PFP educational programme, as we asked them to wait for six weeks. Since only one participant finished the course, it can be considered as a conservative decision to set these effects as thresholds for true changes in deficits following intervention. Moreover, the effect sizes taken from Chapter four were smaller than what we generally found from the analyses in the feasibility study. So, sufficient power can be achieved using the effect size from the meta-analysis, especially that it is from groups that showed MCID in PFP symptoms (Chapter four). Feasibility studies are conducted to inform future planning (409), and Chapter eight demonstrates an overview of a future study plan based on the outcomes of the entire thesis.

9.2 Recommendations

Future studies are recommended to maintain a high degree of details reporting of various aspects. Within sample characteristics, we analysed the reporting of PFP criteria that was used to include PFP groups in interventional studies (255) (Chapter four). Only 25 and 24 studies (out of 46) clearly defined pain location and the insidious onset of PFP, respectively, and in total, 13 studies scored ≤ 50% in the 7-point checklist, which was built by experts in the field (255). However, a consensus paper was published in 2021 following a patellofemoral pain retreat meeting, highlighting the most essential items to be reported in future studies (98). Reporting the recommended methodological items have direct implications on research that aim to identify specific deficits and subgroups of PFP. This is especially important for meta-analyses. As there are three types of heterogeneity; clinical (in samples, interventions

and outcome measures), methodological (design and risk of bias) and statistical (difference in calculated effects), sufficient homogeneity is required for a meta-analysis to be conducted, and for statistical homogeneity analyses to be accurate (167). Pre-planning a detailed eligibility criteria would minimise the lack of agreement of these items in PFP research, and allow accurate syntheses.

For studies investigating local EMG deficits, there are gaps in research regarding structures other than the quadriceps, and tasks that gained more investigation than others. In general, timing investigations are less conducted compared to excitation amplitudes (176). Sufficient planning for such studies, and reliability testing, is required for a clear interpretation of any outcomes. Similarly, muscle performance is mostly investigated in the quadriceps.

9.3 Conclusion

The thesis provided a succinct exploration into the prominent aspect of local neuromuscular characteristics in people with PFP. The thesis targeted an overarching aim of understanding the mechanisms of effects for interventions in PFP. However, this was not completely possible due to pandemic-related repercussions. Consequently, the thesis provided an approach that implements a variety of methods including meta-analyses and lab-based work to provide the needs to reach that aim. The systematic reviews were conducted to synthesise all available literature and provide solid foundations for subsequent testing. They identified the local neuromuscular deficits associated with PFP and interventions that have demonstrated meta-analysed changes in such local deficits. A testing protocol was required to be developed based on a synthesis of all studies that aimed to find deficits in PFP compared to uninjured groups. The methods adoption process minimises the effects of inconsistency in existing reports of local neuromuscular factors in PFP. Reliability and feasibility of the developed test protocol was completed in PFP as well as an uninjured group to inform future research. The lab-based work identified tests that are readily implementable in future research and investigations that require further testing for a scientifically sound progression. There are numerous indications of interventional effects in PFP, and with the methods used to conduct the thesis and the outcomes, this PhD project provided best means needed to successfully identify the mechanisms of effects of interventions through local neuromuscular characteristics associated with PFP.

10 References

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Appendices

1 Disseminated work

1.1 The systematic review from Chapter 3

Contents lists available at ScienceDirect

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Review

Local neuromuscular characteristics associated with patellofemoral pain: A systematic review and meta-analysis

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Keywords:
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meta-analysis

ABSTRACT

Background: Local neuromuscular deficits have been reported in people with patellofemoral pain. We synthesised the neuromuscular characteristics associated with patellofemoral pain to help identify interventional targets and potential mechanisms.

Methods: Five databases were searched for local neuromuscular characteristics in case-control studies. Electromyography, flexibility, muscle performance and cross-sectional area data were derived from functional or isolated task investigations and synthesised accordingly. An evidence gap map was constructed.

Findings: Sixty-seven studies were included. In functional tasks, electromyographic investigations showed moderate evidence of small effect for vastus medialis onset-delays relative to vastus lateralis (0.44 [0.03, 0.85]) during stepping/stair negotiation tasks, and higher biceps femoris mean excitation amplitudes (0.55 [0.06, 1.04]) in single-leg triple-hop test. In isolated tasks, we found moderate evidence of medium effect for lower Hoffman-reflex amplitude of vastus medialis (−1.12 [−1.56, −0.67]). Muscle performance investigations showed; strong evidence with medium and small effects for lower extensors concentric (−0.61 [−0.81, −0.40]) and eccentric (−0.56 [−0.79, −0.33]) strength, and moderate evidence of medium effect of lower isometric (−0.64 [−0.87, −0.41]) strength, moderate evidence with small effect for rate of force development to 30% (−0.55[−0.89, −0.21]), 60% (−0.57[−0.90, −0.25]) and medium effect to 90% (−0.76[−1.43, −0.10]) of maximum voluntary contraction, and small effect for lower flexors concentric strength (−0.46 [−0.74, −0.19]) and extensors total work (−0.48 [−0.90, −0.07]). Flexibility investigations showed tighter hamstrings (−0.57 [−0.99, −0.14]).

Interpretation: Differences within quadriceps and hamstrings motor-control, hamstrings tightness, and quadriceps and hamstrings weakness are associated with patellofemoral pain, and can be used to guide investigations of treatment effects.

https://doi.org/10.1016/j.clinbiomech.2021.105509

1.2 The systematic review from Chapter 3 was accepted and presented at the international patellofemoral pain retreat in Milwaukee, WI, USA, 2019

1.3 Accepted abstract of the systematic review from Chapter 3 (SportsKongres 2022)

100 **LOCAL NEUROMUSCULAR CHARACTERISTICS ASSOCIATED WITH PATELLOFEMORAL PAIN: A SYSTEMATIC REVIEW AND META-ANALYSIS**

Saleh Alsaleh*, Nicholas Murphy, Stuart C Miller, Dylan Morrissey, Simon Lack. *Sports and Exercise Medicine, William Harvey Research Institute, Barts and the London School of Medicine and Dentistry, Queen Mary University of London, Mile End Hospital, E1 4DG, UK*

10.1136/bmjsem-2022-sportskongres.19

Introduction Local neuromuscular deficits have been reported in people with patellofemoral pain. To help identify interventional targets, we synthesized the neuromuscular characteristics associated with patellofemoral pain persistence.
Materials and Methods Five databases were searched for case-control studies. Muscle electromyography, flexibility, performance and cross-sectional area data were extracted from reports of functional or isolated tasks and synthesised. An evidence gap map was constructed.
Results Sixty-seven studies were retained. In functional tasks, electromyographic investigations showed moderate evidence of small effect for vastus medialis onset-delays relative to vastus lateralis (0.44 [0.03, 0.85]) during stepping/stair negotiation tasks, and higher biceps femoris mean excitation amplitudes (0.55 [0.06, 1.04]) in single-leg triple-hop test. In isolated tasks, we found moderate evidence of medium effect for lower Hoffman-reflex amplitude of vastus medialis (-1.12 [-1.56, -0.67]). Muscle performance investigations showed: strong evidence with medium and small effects for lower extensors concentric (-0.61 [-0.81, -0.40]) and eccentric (-0.56 [-0.79, -0.33]) strength; and moderate evidence of medium effect of lower isometric (-0.64 [-0.87, -0.41]) strength; moderate evidence with small effect for rate of force development to 30% (-0.55[-0.89, -0.21]), 60% (-0.57[-0.90, -0.25]) and medium effect to 90% (-0.76[-1.43, -0.10]) of maximum voluntary contraction; and small effect for lower flexors concentric strength (-0.46 [-0.74, -0.19]) and extensors total work (-0.48 [-0.90, -0.07]). Flexibility investigations showed tighter hamstrings (-0.57 [-0.99, -0.14]).
Conclusion Quadriceps and hamstring motor-control, flexibility and weakness are robustly associated with patellofemoral pain, so these parameters should be used to guide investigations of treatment effect mechanisms.

https://bmjopensem.bmj.com/content/bmjosem/8/Suppl_1/A7.2.full.pdf

1.4 A corrigendum to the systematic review

Corrigendum

Corrigendum to "Local neuromuscular characteristics associated with patellofemoral pain: A systematic review and meta-analysis"[Clinical Biomechanics 90 (2021) 105509]

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The authors would like to apologise for any inconvenience caused for the below corrections.

In this paper (Alsaleh et al. 2021), the authors have pooled data of Biceps Femoris and Vastus Lateralis activity in a triple-hop test (Fig. 4, page 10). However, it has latterly become apparent to us that the phases in which muscle activity were analysed were not consistently at the start of the third hop. Moreover, they differed to a point that we think it is sound to remove the meta-analysis of these outcomes, although both used the single-leg triple-hop test:

- Bley et al. (2014) analysed muscle activity in the window between initiation of the first jump (of triple-hop) until leaving the force plate.
- Kalytczak et al. (2016) analysed the muscle activity before and during the stance phase of the first landing of the triple-hop test.

As a result, multiple parts of the manuscript require amendment and we suggest they should be removed:

- The plots figure (Fig. 4, page 10).
- Multiple phrases and paragraphs should be removed:
  - **A sentence in the abstract:**
    "and higher biceps femoris mean excitation amplitudes (0.55 [0.06, 1.04]) in single-leg triple-hop test".
  - **Last paragraph in page 3:**
    "During SLTHT (Fig. 4), moderate evidence (1 HQ and 1 MQ) of small effect indicates higher BF mean excitation amplitudes during propulsion phase of the 3rd hop. Evidence is conflicting regarding VL mean excitation amplitude."
  - **A sentence in 1st paragraph, page 11:**
    "higher BF mean amplitudes".
  - **The 3rd paragraph in page 11:**
    "For the findings regarding the BF muscle, 2 studies (Bley et al., 2014;Kalytczak et al., 2016) investigated the muscle's excitation, during SLTHT, and presented significant pooled effect suggesting higher BF mean excitation amplitudes to be associated with PFP. Single leg hops require higher demands on the knee joint (Willson and Davis, 2008), and a higher muscle activity might indicate that higher demands were needed to stabilise the knee, especially when manifesting in an antagonist knee muscle (Solomonow et al., 1987). Interestingly, VL mean excitation amplitude in the same task was investigated by both studies, but did not present a significant pooled effect, further confirming the importance of choosing the best method of detection for these neuromuscular deficits. Moreover, future research is recommended to investigate the co-contraction requirements within PFP patients. Overall, higher BF mean excitation amplitudes during SLTHT is associated with PFP".
  - **A sentence in 2nd paragraph, page 12:**
    "higher mean excitation amplitude of BF during propulsion of the 3rd hop during SLTHT"
  - **A sentence in the conclusion paragraph, page 13:**
    "Furthermore, a higher mean amplitude of BF was present in PFP during SLTHT".

Electromyographic Activity Domain (***Functional Tasks***)																		
Muscles / Tasks	VM	VL	RF	BF	ST	GRA SAR POP	TFL	Gast. M	Gast. L	VM	VL	RF	BF	ST	GRA SAR POP	TFL	Gast. M	Gast. L
Total Excitation **Timing** investigations										Total Excitation **Amplitude** Investigations								
Stepping and stair negotiation	❹⑤1	❸⑤1					❶			❸④2	❸④2							
Squatting and leg presses	❷②1	❷②1	❶①	①						❸⑦2	❸⑥1	❶②2	①1	①1			①	1
Jumping tasks	❶	❶								❶①	❷③		❶③					
balance during standing	❶①	❶①	①							❷①	❶①	①						
Gait (walking)	②	②								①	①	①						
Gait (running)	②	②								①	①	①						
Meta-analysis results (**Timing** investigations)										**Meta-analysis** results (**Amplitude** investigations)								
Stepping and stair negotiation	EO ↔	EO ↔								MEA	MEA							
	ED									MEA-R ↔								
	EO-R ⇧																	
Squatting and leg presses										MEA	MEA (VL)							
											MEA(VLO) ↔							
Single-leg triple-hop test																		

Pooled effect	⇧⇩ Small effect	↑↓ Medium effect	↔ No difference	Study numbers	Example: ❹⑤1 4 HQ, 5 MQ and 1 LQ studies investigated VM timing EMG in stepping and stair negotiation	Evidence Level	Strong evidence	Moderate evidence	Conflicting evidence	No pooled data

Modifications:

- **Table 5, the meta-analysis gap map, page 9:**
  The cell showing the result of the meta-analysis of single-leg triple-hop test within excitation amplitudes investigations should be empty. The modified version is attached below:

After dismantling the mentioned plots, this systematic review presents limited evidence of a higher mean excitation amplitude of Biceps femoris and Vastus lateralis in pre-stance and stance phases at end of first hop (Kalytczak et al. 2016), and very limited evidence of a higher mean excitation amplitude of Vastus lateralis during initiation (propulsion phase) of first hop (Bley et al. 2014) in single-leg triple-hop test. Therefore, this warrants further investigation into electromyographic deficits of hamstrings during jumping tasks in people with PFP. The gap map shows a clearer gap within local neuromuscular investigations in patellofemoral pain, with predominant focus on the medial and lateral Vasti muscles within available literature.

As we focused on the results of pooled effects from multiple studies, the reader is encouraged to interpret these outcomes of single studies in similar manner to the supplementary file that was submitted at the time the paper was published.

https://doi.org/10.1016/j.clinbiomech.2022.105718

1.5 Acceptance of the systematic review from Chapter 4 as a poster presentation at SportsKongres 2022

#SPORTSKONGRES 2022
FEB 3 - FEB 5 | COPENHAGEN

SCANDINAVIAN SPORTS MEDICINE CONGRESS

WWW.SPORTSKONGRES.DK @SPORTSKONGRES **APP**: #SPORTSKONGRES

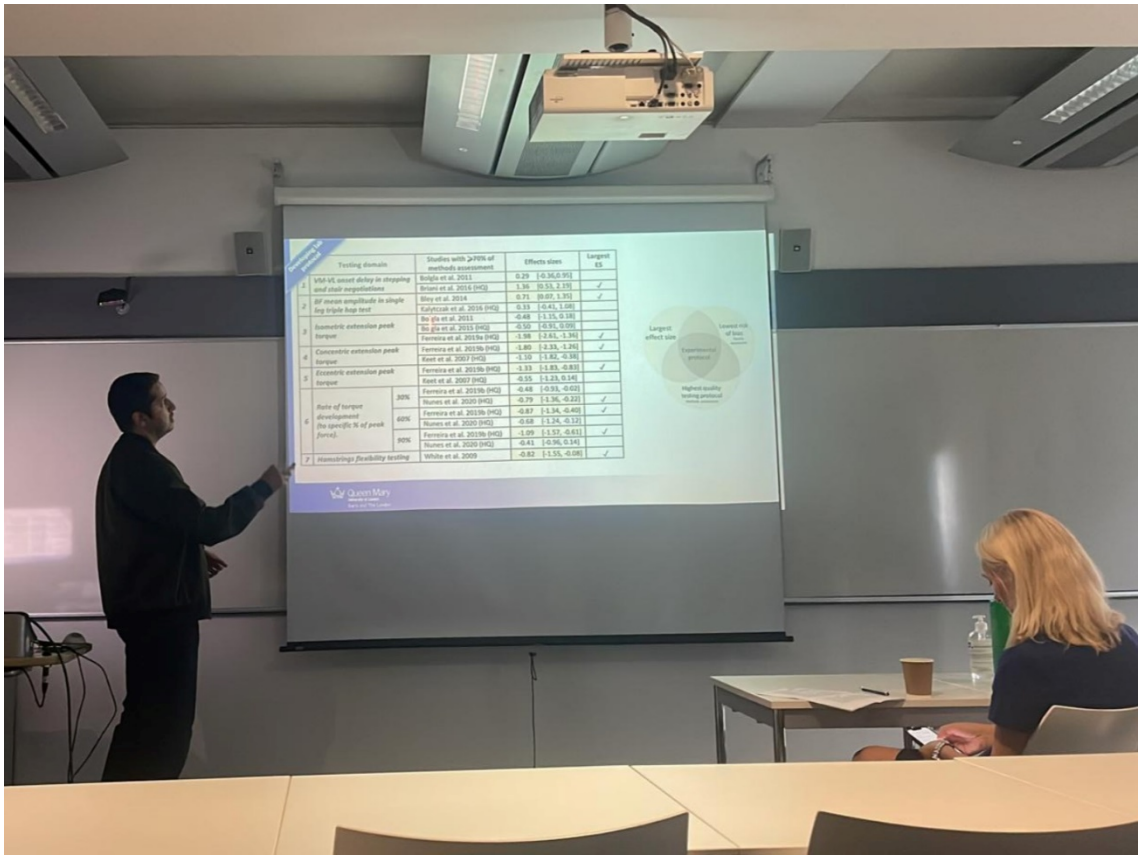
Dear Saleh Alsaleh

Thank you for submitting your abstract to the Scandinavian Sports Medicine Congress 2022 (#sportskongres). This year, we received 195 abstracts.

Your abstract has been selected for poster presentation.

Title	The effects of interventions on local neuromuscular characteristics in patellofemoral pain: a systematic review with meta-analysis
Paper Number	101
Presentation Type	Poster
Session Details	torsdag, feb 3, 2022 08:15 - 09:00
Presenting Author	Mr. Saleh Alsaleh Affiliations: Sports and Exercise Medicine, William Harvey Research Institute, Barts and the London School of Medicine and Dentistry, Queen Mary University of London

1.6 The work of Chapter 5 was presented at QMUL PhD Symposium



1.7 Oral presentation of the systematic review from Chapter 4 at BASEM 2022

Redacted; a screenshot from BASEM 2022 conference video recording showing the author of the thesis presenting Chapter 4. Reason; Unable to gain permission from the copyright holder.

2 Ethics approvals

2.1 Reliability study approval

QMREC2018/48/038 Saleh Al-Saleh Testing the consistency of leg muscle function measures in people with and without knee cap pain

DM **Dylan Morrissey <d.morrissey@qmul.ac.uk>** Monday, 17 February 2020 at 2:38 PM

To: Simon Lack; Saleh Alsaleh; **Cc:** Hazel Covill

Dear Saleh,
I am happy to approve this as: QMREC2018/48/038 Saleh Al-Saleh Testing the consistency of leg muscle function measures in people with and without knee cap pain.

Good luck with the work (data to be collected before end of March please).

Ha
zel, fyi

Best wishes
Dylan

thanks for follow @DrDylanM

Dr Dylan Morrissey

Professor of Sports and Musculoskeletal Physiotherapy

Consultant Physiotherapist

Academic Lead

Sports and Exercise Medicine

William Harvey Research Institute

Bart's and the London School of Medicine and Dentistry

Queen Mary University of London

2.2 Feasibility study approval

RE: QMREC2018/48/082 Biomechanical testing of local deficits associated with patellofemoral pain: a pilot feasibility and reliability study

RE **[Shared] Research Ethics <research-ethics@qmul.ac.uk>** Wednesday, 8 December 2021 at 6:38 PM

To: Saleh Alsaleh; **Cc:** [Shared] Research Ethics; Dylan Morrissey; Simon Lack; Stuart Miller

This message is flagged for follow up. Mark Complete

Dear Salah

Apologies for the delay. I have managed to open all the documents and have gone through. I can see that this is a measurement / pilot study and clearly described.

I am also happy for this to be approved and have noted this for my file.

Hope it all does well.

Kind regards

Hazel

Hazel Covill
Research Ethics Facilitator

3 Appendix of Chapter 3

3.1 Modified Newcastle-Ottawa Scale (NOS); CASE-CONTROL STUDIES

Note: A study can be awarded a maximum of one star (*) for each numbered item within the Selection and Exposure categories. A maximum of two stars can be given for Comparability.

Selection

1) Is the case definition adequate?

a) yes, with independent validation – *well-defined inclusion and exclusion criteria WITH external validation (references)* *****

b) yes, e.g., record linkage or based on self reports

c) no description

2) Representativeness of the cases

a) consecutive or obviously representative series of cases – *comprehensive representation of well-defined population* *****

b) potential for selection biases or not stated

3) Selection of Controls

a) community controls – *cases derived from same population as controls* *****

b) hospital controls

c) no description

4) Definition of Controls

a) no history of disease (endpoint) *****

b) no description of source

Comparability

1) Comparability of cases and controls on the basis of the design or analysis

a) study controls for *sex* *****

b) study controls for *another additional factor* *****

Exposure

~~1) Ascertainment of exposure~~ – *does not apply*

~~a) secure record (eg surgical records) *~~

~~b) structured interview where blind to case/control status *~~

~~c) interview not blinded to case/control status~~

~~d) written self report or medical record only~~

~~e) no description~~

1) Same method of ascertainment for cases and controls

a) yes – *same protocol for both groups* *****

b) no

2) Non-Response rate *(equal sample size)*

a) same rate for both groups – *if same number of controls and cases OR more controls than cases* *****

b) rate different and no designation – *if less controls than cases*

3.2 Supplementary data

The next tables contain all data that were not eligible for meta-analysis **due to presentation** (mean (SD) not reported and/or no answer from authors) or when presented graphs were not clear for the use of WebPlotDigitzer. Other studies were not meta-analysed due to having **unique methodologies** of data collection that prevented pooling (i.e. when a study performed an investigation that was not performed by another study).

3.2.1 Significant findings

Table 1: Significant findings in other included studies within EMG domain during functional tasks (not pooled due to having unique methods/variables):

	Authors	Task	variable	SMD (CI %95)	*P*-value
1	McClinton et al. 2007	Step-up/down	VMO/VL EMG activity duration ratio	0.43 [0.15, 0.71]	*P*=0.043 (significantly higher duration ratio in PFP (longer VMO activity) across all step heights)
2	Freddolini et al. 2017	Walking	VM onset (point in gait cycle)	-2.21 [-2.77, -1.65]	*P*<0.05 (significantly earlier in PFP)
			VL onset (point in gait cycle)	-1.45 [-0.95, -1.94]	*P*<0.05 (significantly earlier in PFP)
			VL activity duration	1.53 [1.03, 2.04]	*P*<0.05 (significantly longer in PFP)
			VM activity duration	2.56 [1.96, 3.16]	
			RF activity duration	0.88 [0.42, 1.34]	
			VL offset	1.42 [0.93, 1.91]	*P*<0.05 (significantly later deactivation in PFP)
			VM offset	2.45 [1.87, 3.04]	
			RF offset	-0.77 [-1.22, -0.31]	
3	Liebensteiner et al. 2008	Leg-press	ST Mean EMG amplitude (stable footplate)	-0.76 [-1.42, -0.10]	*P*=0.002 (significantly lower amplitude in PFP)
			ST Mean EMG amplitude (unstable footplate)	-1.06 [-1.75, -0.38]	*P*=0.017 (significantly lower amplitude in PFP)
4	Gawda et al. 2019	decrease of median frequency in half squat position (static for 1 minute)	VMO (mean of bilateral limbs)	1.69 [0.95, 2.42]	*P*<0.05 (significantly greater decrease of median frequency in PFP)
			RF (mean of bilateral limbs)	0.93 [0.27, 1.58]	
5	Mostamand et al. 2011	Single leg squat (start of squat (eccentric phase))	VMO-VL onset	0.85 [0.16, 1.53]	*P*<0.05 *(VMO delay vs VL in PFP)*
6	Santos et al. 2017	Walking on treadmill (inclined)	VLO (Vastus Lateralis Obliquus) mean amplitude	1.04 [0.22, 1.85]	*P*=0.04 (higher amplitude in PFP versus control)
7	Brindle et al. 2003	Stair ascent	VL activity duration	-4.20[-5.60,-2.79]	*P*<0.05 (less activity duration in PFP)
8	Kalytczak et al. 2016	Single leg triple hop test (mean EMG amplitudes)	BF; before foot contact	0.53 [-0.23, 1.28]	*P*<0.05 (reported significantly higher mean amplitudes in PFP by authors)
			BF; stance phase	0.83 [0.05, 1.60]	
			VL before foot contact	0.53 [-0.23, 1.28]	
			VL stance phase	0.78 [0.00, 1.55]	
			VL eccentric phase (before mid-stance)	0.70 [-0.07, 1.46]	
9	Miller at al. 1997	Step up/step down	VMO/VL average RMS ratio	-1.19 [-2.34, -0.05]	*P*<0.05 (Higher ratio in control group)
		Modified wall slides		-1.18 [-2.32, -0.03]	
10	Baellow et la. 2020	Drop-vertical jump (normalised to quiet standing)	VMO mean excitation amplitude	0.36 [-0.37, 1.10]	*P*=0.01
			BF mean excitation amplitude	-0.41 [-1.14, 0.33]	
11	Santos et al. 2017	walking on treadmill (inclined)	VLL mean amplitude	0.87 [0.07, 1.67]	*P*=0.04 (higher amplitude in PFP versus control)
			VLO mean amplitude	1.04 [0.22, 1.85]	*P=0.01* (higher amplitude in PFP versus control, but was not reported significant in study, and SMD was generated by computing using Revman)

12	Felicio et al. 2019	Straight leg raise (SLR)	Quadriceps EMG combined (VMO+VLL+VLO)	0.52 [-0.06, 1.11]	*P*<0.05 (significantly higher quads excitation amplitude in PFP during SLR)
13	de Almeida Britto et al. 2021	Running	VMO excitation onset-time	0.84 [0.09, 1.59]	*P*=0.023 (significant delay in VMO excitation onset in PFP during running)
			VMO excitation total-time	0.81 [0.06, 1.56]	*P*=0.030 (significantly longer duration of VMO excitation during running)
			VMO excitation amplitude at onset-time	0.92 [0.17, 1.68]	*P*=0.029 (significantly higher excitation amplitude of VMO at onset-time during running)
			VMO excitation amplitude at end-time	0.69 [-0.05, 1.43]	*P*=0.041 (significantly higher excitation amplitude of VMO at end-time during running)
			VMO excitation amplitude during total-time	1.34 [0.54, 2.13]	*P*=0.004 (significantly higher VMO excitation amplitude during total-time in running)

Table 2: Significant findings in other included studies within EMG domain during functional tasks (not pooled due to data presentation):

	Authors	Task	Variable	*P*-value
1	Christou 2004	Leg press	VMO mean EMG amplitude	*P*<0.01 (significantly higher activation of VMO in PFP)
2	Thomee et al. 1996	Isometric leg press (standing position)	VM mean EMG amplitude	*P*<0.01 (significantly lower in PFP)
3	Rathleff et al. 2013	Stair descent	VM mean EMG amplitude	*P*=0.049 (significantly higher in PFP)
			VL mean EMG amplitude	*P*=0.003 (significantly higher in PFP)
			VL EMG sample entropy	*P*=0.005 (significantly higher sample entropy in PFP)
4	Stensdotter et al. 2008	anterior and posterior perturbations while standing on a moveable surface	VML/RF anterior translation mean amplitude ratio	*P*=0.01 (significantly smaller ratio in PFP)
			VL/RF anterior translation mean amplitude ratio	*P*=0.02 (significantly smaller ratio in PFP)
			VML/VL overall mean amplitude ratio	*P*=0.002 (significantly larger in PFP)
			overall VMO-VL onset	*P*=0.02 (significantly earlier VMO onset in PFP)
			overall VMO-RF onset	*P*=0.03 (significantly earlier VMO onset in PFP)
			VMO ant translation onset	*P*=0.03 (significantly earlier in PFP)

Table 3: Significant findings in other included studies within EMG domain during isolated tasks (not pooled due to having unique methods/variables):

	Authors	Task	Variable	SMD (CI %95)	*P*-value
1	Pazzinatto et al. 2019	Patellar tendon reflex	VM Patellar Tendon reflex EMG peak amplitude (% Max M-wave)	-0.68 [-1.21, -0.16] (mean difference; -0.09 [-0.16,-0.02])	*P*<0.05 (significantly lower amplitude of VM)
2	Patil et al. 2011	Knee extension (OKC)	Lateral hamstring (LH)-medial hamstring (MH) EMG activity onset ratio	-0.68 [-1.35, -0.01]	*P*=0.043 (LH onset significantly earlier than MH in PFP group. Contrarily, control group had MH activated before LH)
3	Chen et al. 2012	Electromechanical delay (EMD)	VMO EMD	16.04 [12.79, 19.29]	*P*<0.001 (significantly longer in PFP)
			VL EMD	-13.20 [-15.89, -10.50]	*P*<0.001 (significantly shorter in PFP)

Table 4: Significant findings in other included studies within EMG domain during isolated tasks (not pooled due to data presentation):

	Authors	Task	Variable	*P*-value
1	Mellor and	isometric knee	Proportion of peaks: Rectified mean proportions of significant peaks in distal VL EMG averages, triggered by a motor unit in VMO	*P*<0.01

	Hodges 2005	extension at 30º of flexion	Proportion of peaks: Rectified mean proportions of significant peaks in proximal VL EMG averages, triggered by a motor unit in VMO	(significantly lower proportions of peaks of VL in PFP)
			Proportion of peaks: Rectified mean proportions of significant peaks in (proximal or distal) VL EMG averages, triggered by a motor unit in VMO	
			Proportion of peaks: Unrectified mean proportions of significant peaks in distal VL EMG averages, triggered by a motor unit in VMO	
			Proportion of peaks: Unrectified mean proportions of significant peaks in proximal VL EMG averages, triggered by a motor unit in VMO	
			Proportion of peaks: Unrectified mean proportions of significant peaks in (proximal or distal) VL EMG averages, triggered by a motor unit in VMO	
2	Voight et al. 1992	knee jerk reflex	VL onset	*P*<0.001 (significantly earlier in PFP)
3	Gallina et al. 2019	knee extension against constant resistance (high definition EMG on VM and VL)	principal components (PC) during concentric phase	*P*<0.05 (less number of PC needed to explain 90% of variance in PFP)
			redistribution of VM/VL activation between concentric and eccentric phases	*P*<0.05 (significantly lower in PFP; more coactivation)

Table 5: Significant findings in other included studies within muscle performance domain during isolated tasks (not pooled due to having differing methods/variables):

	Authors	Task	Variable	SMD (CI %95)	*P*-value
1	Thomee et al. 1996	Knee extension (OKC)	Additional torque after stimulation during maximal isometric contraction	1.68 [0.62, 2.73]	*P*<0.004 (significantly higher additional torque with stimulation (larger torque deficit) in PFP)
2	Duffey et al. 2000	Knee extension (OKC)	Extension work last 6 reps (240°/s)	-4.16 [-4.71,-3.62]	*P*=0.043 (significantly less work output in PFP)
		Knee flexion (OKC)	Flexion work 1st 6 reps (240°/s)	-3.84 [-4.36,-3.33]	*P*<0.05 (significantly less work output in PFP)
			Flexion work last 6 reps (240°/s)	-2.87 [-3.30,-2.43]	*P*=0.029 (significantly less work output in PFP)
		OKC torque ratio	Flexion/extension peak torque ratio at 240°/s	-2.87 [-3.30, 2.43]	*P*=0.034 (significantly lower ratio in PFP)
3	Ferreira et al. 2019a	submaximal isometric force-matching task	knee extension Force steadiness at 60° and 10% target	2.01 [1.39, 2.64]	*P*<0.001 (significantly less steady in PFP)
4	Ferreira et al. 2019b	Rate of Force development (RoFD) *(Reported as mean difference by authors)	concentric extension up to 30% max	0.58 [0.38–0.78]*	*P*<0.05 (significantly slower rate in PFP)
			concentric extension up to 60% max	0.38 [0.23–0.53]*	
			concentric extension up to 90% max	0.31 [0.18–0.43]*	
			eccentric extension up to 30% max	0.41 [0.08–0.75]*	
			eccentric extension up to 60% max	0.39 [0.17–0.60]*	
			eccentric extension up to 90% max	0.28 [0.10–0.46]*	
5	Stensdotter et al. 2008	anterior and posterior perturbations while standing on a moveable surface	VML/RF anterior translation mean amplitude ratio	Reported in graph (were not extracted from graph due to unique task used, and data were not inputted into Revman to calculate SMD)	*P*=0.01 (significantly smaller ratio in PFP)
			VL/RF anterior translation mean amplitude ratio		*P*=0.02 (significantly smaller ratio in PFP)
			VML/VL overall mean amplitude ratio		*P*=0.002 (significantly larger in PFP)
			overall VMO-VL onset		*P*=0.02 (significantly earlier VMO onset in PFP)
			overall VMO-RF onset		*P*=0.03 (significantly earlier VMO onset in PFP)
			VMO ant translation onset		*P*=0.03 (significantly earlier in PFP)
6		Knee flexion (OKC)	Isometric at 60°	20.4 [10.1-30.7]*	*P*<0.001

	Briani et al. 2021	*(Reported as mean difference by authors)	Eccentric from 90° to 20° at 30°/s	22.9 [10.7-35.1]*	(less peak torque in PFP)
		Flexion rate of force development (RoFD) *(Reported as mean difference by authors)	Isometric flexion up to 30% max	0.37 [0.19-0.55]*	*P*<0.001 (significantly slower rate in PFP)
			Isometric flexion up to 60% max	0.11 [0.02-0.21]*	*P*=0.011 (significantly slower rate in PFP)
			concentric flexion up to 30% max	0.32 [0.19-0.46]*	*P*<0.001 (significantly slower rate in PFP)
			concentric flexion up to 60% max	0.12 [0.05-0.20]*	*P*=0.008 (significantly slower rate in PFP)
			eccentric flexion up to 30% max	0.33 [0.20-0.46]*	*P*<0.001 (significantly slower rate in PFP)
			eccentric flexion up to 60% max	0.31 [0.03-0.23]*	*P*=0.009 (significantly slower rate in PFP)

Table 6: Significant findings in other included studies within Flexibility domain:

	Authors	Task	Variable	SMD (CI %95)	*P*-value
1	Earl et al. 2005	Ober's test	ITB flexibility	-1.10 [-1.85, -0.35]	*P*=0.004 (significantly less flexible in PFP)

Significant findings in other included studies within Cross-sectional area (CSA) domain:

	Authors	Task	Variable	MD (CI %95)	*P*-value
1	El Sawy et al. 2021	CSA using MRI (reported by authors)	VMO; lower end of shaft	-17.2±11.0%	*P*<0.05 (significantly less CSA in PFP)
			VMO; upper border of Patella	-21.1±6.0%	
			VMO; mid-patellar level	-36.7±11.0%	
		CSA using Ultrasound (calculated using Revman)	VMO; upper border of Patella	-3.80 [-4.24, -3.36]	
			VMO; mid-patellar level	-4.10 [-4.60, -3.60]	

3.2.2 Insignificant findings

Table 7: Variables investigated within functional tasks

	Authors	Task	variable	SMD (CI %95)	*P*-value
1	Freddolini et al. 2017	Walking	RF onset at toe-off	-0.11 [-0.55, 0.32]	*P*>0.05
			RF offset at toe-off	0.14 [-0.30, 0.58]	
2	Kalytczak et al. 2018	Single-leg triple-hop test	VL peak amplitude	0.39 [-0.36, 1.14]	*P*=0.10
			BF peak amplitude	0.10 [-0.64, 0.84]	*P*=0.96
			VL time of peak amplitude	-0.51 [-1.26, 0.25]	*P*=0.19
			BF time of peak amplitude	0.12 [-0.63, 0.86]	*P*=0.76
3	Liebensteiner et al. 2008	Leg-press	Gastrocnemius Medialis Mean EMG amplitude (stable footplate)	-0.42 [-1.06, 0.22]	*P*≥0.05
			Gastrocnemius Medialis Mean EMG amplitude (unstable footplate)	-0.33 [-0.79, 0.12]	
4	Earl et al. 2005	Side Step down (tested leg is not lead leg)	VMO EMG onset after foot contact of ipsilateral leg	0.52 [-0.21, 1.25]	*P*≥0.05
			TFL EMG onset after foot contact of ipsilateral leg	-0.06 [-0.78, 0.66]	*P*≥0.05
5	Pal et al. 2011	walking	VM-VL onset	0.20 [-0.40, 0.79]	*P*≥0.05
		running	VM-VL onset	0.11 [-0.48, 0.70]	*P*≥0.05
6	Orozco-Chavez and Mendez-Rebolledo 2018	Single leg squat (start of squat (eccentric phase))	VM onset	-0.33 [-0.90, 0.24]	*P*≥0.05
			VL onset	0.27 [-0.30, 0.84]	*P*≥0.05
7	Santos et al. 2017	walking on treadmill (flat)	VMO mean amplitude	-0.57 [-1.34, 0.21]	*P*≥0.05
			VLL mean amplitude	-0.04 [-0.80, 0.72]	
			VLO mean amplitude	0.19 [-0.57, 0.95]	
		walking on treadmill (inclined)	VMO mean amplitude	-0.03 [-0.78, 0.73]	
8	Brindle et al. 2003	Stair descent	VL activity duration	-0.78[-1.56,0.00]	*P*≥0.05
9	Goto et al. 2019	Star Excursion balance test	Mean VMO activity	0.70 [-0.07, 1.47]	*P*≥0.05
10	Song et al. 2015	Single-leg squat (0-45º)	RF mean EMG amplitude	-0.12 [-0.76, 0.52]	*P*≥0.05

11	Baellow et la. 2020	Drop-vertical jump (normalised to quiet standing)	VL mean excitation amplitude	-0.12 [-0.84, 0.61]	*P*=0.51
12	Felicio et al. 2019	Squat	Quadriceps EMG combined (VMO+VLL+VLO)	-0.16 [-0.74, 0.42]	*P*≥0.05
		Squat + hip abduction		0.03 [-0.54, 0.61]	
		Squat + hip adduction		-0.07 [-0.65, 0.51]	
		Squat + hip Lat. Rotation		-0.09 [-0.67, 0.49]	
		SLR + Lat. Rotation		0.44 [-0.15, 1.02]	
13	Coqueiro et al. 2005	Squat + Hip adduction	VMO	0.21 [-0.67, 1.09]	*P*≥0.05
			VLL	-0.05 [-0.92, 0.83]	
14	de Almeida Britto et al. 2021	Running	VL excitation onset-time	0.24 [-0.48, 0.96]	*P*=0.563
			VMO excitation end-time	0.16 [-0.56, 0.88]	*P*=0.646
			VL excitation end-time	-0.17 [-0.89, 0.54]	*P*=0.584
			VL excitation total-time	0.12 [-0.59, 0.84]	*P*=0.762
			VL excitation amplitude at onset-time	0.05 [-0.67, 0.76]	*P*=0.836
			VL excitation amplitude at end-time	0.65 [-0.09, 1.38]	*P*=0.073
			VL excitation amplitude during total-time	0.61 [-0.13, 1.34]	*P*=0.127

Table 8: Variables investigated within isolated tasks

	Authors	Task	Variable	SMD (CI %95)	*P*-value
1	Christou 2004	Flexibility test	Gastrocnemius flexibility	0.30 [-0.33, 0.92]	*P*≥0.05
2	Giles et al. 2015	Supine lying (ultrasound)	CSA VM	-0.17 [-0.64, 0.30]	*P*=0.474
			CSA VL	-0.37 [-0.84, 0.10]	*P*=0.122
			CSA VI	0.17 [-0.30, 0.64]	*P*=0.466
			CSA RF	0.15 [-0.32, 0.62]	*P*=0.508
			CSA VMO/VL	0.00 [-0.47, 0.47]	*P*=0.930
			CSA VM/VL	0.08 [-0.39, 0.55]	*P*=0.677
			CSA sum of all quadriceps	-0.14 [-0.61, 0.33]	*P*=0.554
			Extension peak torque deficit %	-0.04 [-0.35, 0.26]	*P*≥0.05
3	Duffey et al. 2000	Knee extension (OKC)	Extension average power	-0.26 [-0.56, 0.05]	*P*≥0.05
			Extension work ratio %	-0.04 [-0.34, 0.27]	*P*≥0.05
			Extension work 1st 6 reps (240°/s)	-3.60 [-4.09,-3.10]	
			Flexion peak torque deficit %	-0.06 [-0.37, 0.24]	
		Knee flexion (OKC)	Flexion average power	-0.40 [-0.71, -0.09]	*P*≥0.05
			Flexion work ratio %	0.28 [-0.03, 0.59]	*P*≥0.05
			Flexion/extension peak torque ratio at 60°/s	1.09 [0.76, 1.41]	
		OKC torque ratio	VL-VMO EMG activity onset ratio	0.35 [-0.31, 1.00]	*P*=0.261
4	Patil et al. 2011	Knee extension (OKC)	VMO EMG onset	-0.38 [-1.19, 0.43]	*P*≥0.05
5	Bevilaqua-Grossi 2008	Knee jerk reflex	VLL EMG onset	-0.17 [-0.98, 0.63]	*P*≥0.05
			VLO EMG onset	-0.38 [-1.19, 0.43]	*P*≥0.05
			VM EMG onset	0.32 [-0.53, 1.17]	
6	Peng et al. 2020	Seated isometric extension (sub-maximal at 25%, 50% and 75% MVC)	VMO EMG onset	-0.39 [-1.24, 0.45]	*P*≥0.05
			VL EMG onset	-0.22 [-1.06, 0.62]	
			RF EMG onset	-0.21 [-1.05, 0.63]	
			VM EMG amplitude	0.30 [-0.55, 1.14]	
			VMO EMG amplitude	0.56 [-0.30, 1.42]	
			VL EMG amplitude	0.49 [-0.36, 1.35]	
			RF EMG amplitude	0.57 [-0.29, 1.43]	

Table 9: Variables reported without Means and SDs (functional tasks):

	Authors	Task	Variable	*P*-value
1	Mostamand et al. 2011	Single-leg squat	VMO mean EMG amplitude	*P*>0.05
			VL mean EMG amplitude	
			VMO/VL mean EMG amplitude ratio	
2	Christou 2004	Leg press	VL mean EMG amplitude	*P*>0.05

3	Thomee et al. 1996	Isometric leg press (standing position)	RF mean EMG amplitude	$P \geq 0.05$
4	Rathleff et al. 2013	Stair descent	VM EMG sample entropy	$P=0.11$
5	Santos et al. 2008	Sit-to-stand without support	VMO mean EMG amplitude	No differences reported
		Single-leg jump	VMO mean EMG amplitude: starting from a doorstop (24cm) and landing on the ground;	
		Heel elevation	VMO mean EMG amplitude	
		Maintaining position of heel elevation	VMO mean EMG amplitude	
		Sit-to-stand without support	VLL mean EMG amplitude	
		Single-leg jump	VLL mean EMG amplitude: starting from a doorstop (24cm) and landing on the ground;	
		Heel elevation	VLL mean EMG amplitude	
		Maintaining position of heel elevation	VLL mean EMG amplitude	
		Sit-to-stand without support	VLO mean EMG amplitude	
		Single-leg jump	VLO mean EMG amplitude: starting from a doorstop (24cm) and landing on the ground;	
		Heel elevation	VLO mean EMG amplitude	
		Maintaining position of heel elevation	VLO mean EMG amplitude	
6	Stensdotter et al. 2007 (were not extracted from graph due to differing methods (Peak amplitudes))	Closed Kinetic Chain	VMO/VML peak amp ratio (CKC)	no differences reported
			VMO/VL peak amp ratio (CKC)	
			VML/VL peak amp ratio (CKC)	
			VMO/RF peak amp ratio (CKC)	
			VML/RF peak amp ratio (CKC)	
			VL/RF peak amp ratio (CKC)	
7	MacIntyre et al. 1992	Running at 80% maximum	VL grand ensemble average pattern during gait cycle	No significant differences reported
			RF grand ensemble average pattern during gait cycle	
			VM grand ensemble average pattern during gait cycle	
		Running at 12km/h	VL grand ensemble average pattern during gait cycle	
			RF grand ensemble average pattern during gait cycle	
			VM grand ensemble average pattern during gait cycle	

Table 10: Variables reported without Means and SDs (isolated tasks):

	Authors	Task	Variable	*P*-value
1	Thomee et al. 1996 (LQ study)	isometric knee extension	VM mean EMG amplitude	$P \geq 0.05$
			RF mean EMG amplitude	
2	Voight et al. 1992 (SDs cannot be extracted from graphs)	knee jerk reflex	VMO onset	$P \geq 0.05$
3	Stensdotter et al. 2007 (were not extracted from graph due to differing methods (Peak amplitudes))	Open Kinetic Chain	VMO/VML peak amp ratio (OKC)	no differences reported
			VMO/VL peak amp ratio (OKC)	
			VML/VL peak amp ratio (OKC)	
			VMO/RF peak amp ratio (OKC)	
			VML/RF peak amp ratio (OKC)	
			VL/RF peak amp ratio (OKC)	
4	Cesarelli et al. 1999	Knee extension	VL grand ensemble average pattern during knee extension	No significant differences clearly reported, and data presented in graphs + unique EMG variables
			RF grand ensemble average pattern during knee extension	
			VM grand ensemble average pattern during knee extension	
			Timing of peak phases of EMG of VL	
			Timing of peak phases of EMG of RF	
			Timing of peak phases of EMG of VM	
5	Cesarelli et al. 2000	Knee extension	VL grand ensemble average pattern during knee extension	No significant differences clearly reported, and data presented in graphs
			RF grand ensemble average pattern during knee extension	
			VM grand ensemble average pattern during knee extension	

			Timing of peak phases of EMG of VL	
			Timing of peak phases of EMG of RF	
			Timing of peak phases of EMG of VM	

3.2.3 Combined results of functional and isolated tasks

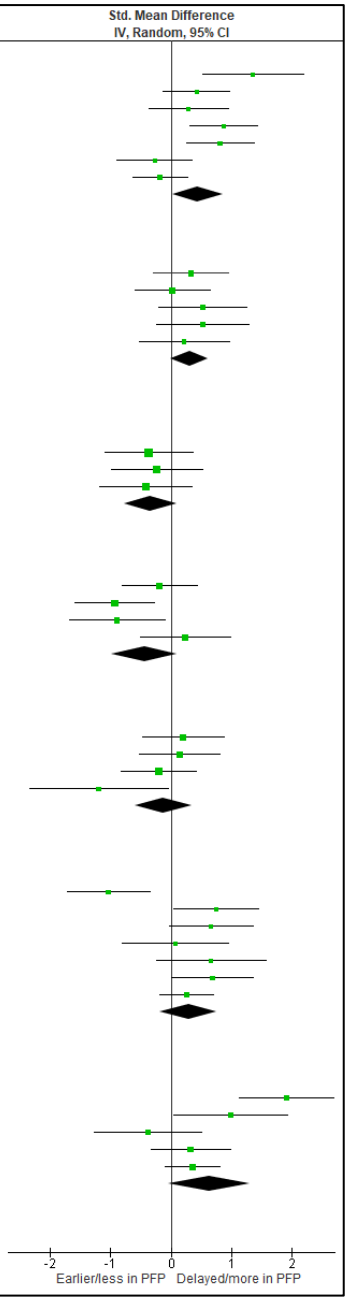
Table 11: Variables reported without Means and SDs (mixed tasks):

	Authors	Task	Variable	*P*-value
1	Stensdotter et al. 2007	Mixed CKC/OKC	CKC/OKC ratio of VML mean amplitude	*P*=0.04 (significantly higher in CKC in PFP)
			CKC/OKC ratio of VL mean amplitude	*P*=0.03 (significantly higher in CKC in PFP)
2	Santos et al. 2008	overall results of 11 tasks (functional and isolated)	overall VMO/VLO mean amp ratio	*P*=0.04 (significantly less VMO activity vs VLO in PFP)
			overall VMO/VLL mean amp ratio	*P*≥0.05
			overall VMO-VLO onset ratio	*P*=0.0023 (significantly delayed VMO vs VLO in PFP)
			overall VMO-VLL onset ratio	*P*≥0.05

3.3 Other details of included plots:

3.3.1 EMG investigations of stepping and stair negotiations

Study or Subgroup	PFP Mean	PFP SD	PFP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
1. VM onset-VL onset after specific time-point								
HQ Briani 2016; VM-VL; stair-up (highly-active)	4.06	13.1	17	-14.4	13.4	12	11.2%	1.36 [0.53, 2.19]
HQ Briani 2016; VM-VL; stair-up (mod-active)	-2.48	18.8	26	-9.89	15.3	26	15.0%	0.43 [-0.12, 0.98]
MQ Bolgla 2011; VM-VL; stair-down	3.83	9	18	1.28	8	18	13.5%	0.29 [-0.36, 0.95]
MQ Crossley 2004; VM-VL; stair-down	19.0709	25.492	47	-0.37	5.7	18	14.8%	0.87 [0.31, 1.44]
MQ Crossley 2004; VM-VL; stair-up	16.6572	26.6397	47	-2.06	1.55	18	14.9%	0.81 [0.25, 1.37]
MQ McClinton 2007; VM-VL; step-up	-9.6	24.9	20	-3.324	20.8	20	14.0%	-0.27 [-0.89, 0.35]
MQ Rathleff 2013; VM-VL; stair-down	7.42	46.732	56	15.431	40.509	29	16.5%	-0.18 [-0.63, 0.27]
Subtotal (95% CI)			**231**			**141**	**100.0%**	**0.44 [0.03, 0.85]**
Heterogeneity: Tau² = 0.22; Chi² = 20.70, df = 6 (P = 0.002); I² = 71%								
Test for overall effect: Z = 2.08 (P = 0.04)								
2. VM onset relative to time-point								
HQ Aminaka 2011; VM-onset; stair-down	-32.57	133.17	20	-75.19	117.33	20	24.3%	0.33 [-0.29, 0.96]
HQ Aminaka 2011; VM-onset; stair-up	27.5	75.37	20	25.83	67.89	20	24.7%	0.02 [-0.60, 0.64]
HQ Earl 2005 VM-onset;step-down	280	270	15	100	390	15	17.8%	0.52 [-0.21, 1.25]
MQ Brindle 2003 VM-onset;stair-down	-289.5	177.7	16	-366.9	69.2	12	16.3%	0.53 [-0.24, 1.29]
MQ Brindle 2003 VM-onset;stair-up	-167.9	136.8	16	-204.8	193	12	16.8%	0.22 [-0.53, 0.97]
Subtotal (95% CI)			**87**			**79**	**100.0%**	**0.30 [-0.01, 0.61]**
Heterogeneity: Tau² = 0.00; Chi² = 1.52, df = 4 (P = 0.82); I² = 0%								
Test for overall effect: Z = 1.93 (P = 0.05)								
3. VL onset relative to time-point								
HQ Earl 2005 VL-onset;step-down	-230	260	15	-120	320	15	35.3%	-0.37 [-1.09, 0.36]
MQ Brindle 2003 VL-onset;stair-down	349.7	234.1	16	394.8	81.8	12	32.6%	-0.24 [-0.99, 0.52]
MQ Brindle 2003 VL-onset;stair-up	150.4	116.9	16	191.1	52	12	32.1%	-0.42 [-1.17, 0.34]
Subtotal (95% CI)			**47**			**39**	**100.0%**	**-0.34 [-0.77, 0.09]**
Heterogeneity: Tau² = 0.00; Chi² = 0.12, df = 2 (P = 0.94); I² = 0%								
Test for overall effect: Z = 1.55 (P = 0.12)								
4. VM excitation duration								
HQ Aminaka 2011; stair-down	754.91	319.34	20	810.88	239.6	20	27.5%	-0.19 [-0.82, 0.43]
HQ Aminaka 2011; stair-up	634.72	168.26	20	899.07	357.35	20	26.4%	-0.93 [-1.58, -0.27]
MQ Brindle 2003; stair-down	777.1	143.5	16	913.6	154.2	12	22.5%	-0.89 [-1.68, -0.10]
MQ Brindle 2003; stair-up	757.7	139.2	16	724.2	131.7	12	23.6%	0.24 [-0.51, 0.99]
Subtotal (95% CI)			**72**			**64**	**100.0%**	**-0.44 [-0.98, 0.10]**
Heterogeneity: Tau² = 0.18; Chi² = 7.13, df = 3 (P = 0.07); I² = 58%								
Test for overall effect: Z = 1.61 (P = 0.11)								
5. VM:VL mean amplitude ratio								
HQ Keet 2007; step-down	1.4	0.541	15	1.3	0.427	20	28.0%	0.20 [-0.47, 0.88]
HQ Keet 2007; step-up	1.5	0.812	15	1.4	0.534	20	28.1%	0.15 [-0.52, 0.82]
MQ McClinton 2007; step-up (5 heights)	0.854	0.36	20	0.932	0.38	20	30.5%	-0.21 [-0.83, 0.42]
MQ Miller 1997; Step-up-down	0.802	0.25	6	2.18	1.37	9	13.4%	-1.19 [-2.34, -0.05]
Subtotal (95% CI)			**56**			**69**	**100.0%**	**-0.12 [-0.60, 0.35]**
Heterogeneity: Tau² = 0.09; Chi² = 4.91, df = 3 (P = 0.18); I² = 39%								
Test for overall effect: Z = 0.52 (P = 0.60)								
6. VM mean amplitude								
HQ Briani 2018; stair-up	50.73	3.1	19	53.49	2	19	14.6%	-1.04 [-1.72, -0.35]
HQ Keet 2007; step-down	85	27.98	15	66	22.43	20	14.4%	0.74 [0.05, 1.44]
HQ Keet 2007; step-up	77	27.08	15	60	23.5	20	14.5%	0.66 [-0.03, 1.35]
HQ Santos 2008; step-down	373.4	155.54	10	362.675	142.46	10	12.2%	0.07 [-0.81, 0.95]
HQ Santos 2008; step-up	530.385	210.23	10	396.48	171.44	10	11.8%	0.67 [-0.24, 1.58]
MQ Bolgla 2011; stair-down	52	38	18	30.6667	20	18	14.7%	0.69 [0.01, 1.36]
MQ Rathleff 2013; stair-down	29.21	11.72	29	25.4	15.97	57	17.7%	0.26 [-0.19, 0.71]
Subtotal (95% CI)			**116**			**154**	**100.0%**	**0.29 [-0.18, 0.75]**
Heterogeneity: Tau² = 0.27; Chi² = 19.54, df = 6 (P = 0.003); I² = 69%								
Test for overall effect: Z = 1.20 (P = 0.23)								
7. VL mean amplitude								
HQ Briani 2018; stair-up	59.19	3.3	19	53.88	1.96	19	19.5%	1.92 [1.13, 2.70]
HQ Santos 2008; step-down	407.22	142.43	10	267.295	126.77	10	17.5%	0.99 [0.05, 1.94]
HQ Santos 2008; step-up	246.715	101.13	10	297.4825	147.29	10	18.2%	-0.38 [-1.27, 0.50]
MQ Bolgla 2011; stair-down	37	16	18	31.33	18	18	21.1%	0.33 [-0.33, 0.98]
MQ Rathleff 2013; stair-down	26.18	8.21	29	21.66	14.41	57	23.7%	0.35 [-0.10, 0.80]
Subtotal (95% CI)			**86**			**114**	**100.0%**	**0.63 [-0.04, 1.31]**
Heterogeneity: Tau² = 0.45; Chi² = 18.02, df = 4 (P = 0.001); I² = 78%								
Test for overall effect: Z = 1.83 (P = 0.07)								
Test for subgroup differences: Chi² = 15.96, df = 6 (P = 0.01), I² = 62.4%								



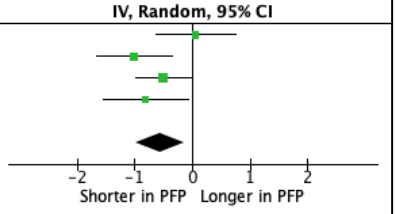
Crossley et al. (2004) had 2 PFP groups (delay and no delay) and data were combined to represent the whole PFP sample and avoid bias of including only the delayed group. Briani et al. (2016) compared between 2 PFP and 2 Healthy control groups; the difference is activity levels (highly active and moderately active). PFP groups were not combined because they were different in an individual characteristic, in contrast to Crossley et al. (2004), where separation was based on the results of the investigations. McClinton et al. (2007) repeated same exercise (stepping-up) on 5 different step heights, and data set presented after combining all 5 sets using Revman Calculator. Bolgla et al. (2011) presented data of 3 phases within stair descent task (pre-swing, loading response and single leg stance); data presented is the combination of these phases to avoid

using 3 data sets and over-inflating the pooled effect size. Negative = onset before foot contact.

3.3.2 Hamstrings flexibility investigations:

Study or Subgroup	PFP Mean	PFP SD	PFP Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
HQ Earl 2005	-6.9	8.7	16	-7.3	6.4	16	22.5%	0.05 [-0.64, 0.74]
MQ Christou 2004	66.7	9.7	15	73.9	5.15	30	24.0%	-1.02 [-1.67, -0.36]
MQ Patil 2010	-31	14.76	34	-23.5	14.76	34	32.7%	-0.50 [-0.99, -0.02]
MQ White 2009	145.6	8.7	11	153.7	10.1	25	20.9%	-0.82 [-1.55, -0.08]
Total (95% CI)			**76**			**105**	**100.0%**	**-0.57 [-0.99, -0.14]**

Heterogeneity: $Tau^2 = 0.08$; $Chi^2 = 5.35$, df = 3 (P = 0.15); $I^2 = 44\%$
Test for overall effect: Z = 2.63 (P = 0.009)



Earl et al. (2005) and Patil et al. (2010) measured it as degrees from 0°=full extension. Christou et al. (2004) considered 0° to 90°= flexed knee to full extension and found it shorter in the PFP group. White et al. (2009) considered 180°=full extension. Modifications on White et al. (2009) and Christou et al. (2004) data in the study were made to present the data as degrees needed to reach full extension of 0°. Here, original data presented by each study is used.

3.4 Gap map with citations

The gap map shows the work done within EMG, muscle performance, flexibility and cross-sectional area to detect deficits related to PFP. **BOLD** are HQ, *Italic* are MQ, and Underlined are LQ studies. Green = moderate evidence, yellow = limited evidence, orange = very limited evidence, and black = no evidence available that examined this domain within the corresponding task.

Tasks	EMG Domain							
	quadriceps		hamstrings		Gastrocnemii		TFL	
Functional tasks	Timing	Amplitude	Timing	Amplitude	Timing	Amplitude	Timing	Amplitude
Stepping and stair negotiation	**Earl et al. 2005 Santos et al. 2008, Briani et al. 2016** *McClinton et al. 2007, Aminaka et al. 2011, Crossley et al. 2004, Brindle et al. 2003, Bolgla et al. 2011* Kim and Song 2012	**Briani et al. 2018, Santos et al. 2008, Keet et al. 2007** *McClinton et al. 2007, Rathleff et al. 2013, Bolgla et al. 2011* Kim and Song 2012, Sacco et al. 2006, Miller et al. 1997					**Earl et al. 2005**	
Squatting and leg presses	**Santos et al. 2008, Stensdotter et al. 2007** *Orozco-Chavez and Mendez-Rebolledo 2018, Mostamand et al. 2011* Bevilaqua-Grossi et al. 2009	**Santos et al. 2008, Stensdotter et al. 2007, Felicio et al. 2011** *Song et al. 2015, Liebensteiner et al. 2008, Christou et al. 2004, Coqueiro et al. 2005, Mostamand et al. 2011, Gawda et al. 2019, Miller et al. 1997* Dionisio et al. 2011, Thomee et al. 1996	*Orozco-Chavez and Mendez-Rebolledo 2018*	*Liebensteiner et al. 2008* Dionisio et al. 2011		*Liebensteiner et al. 2008* Dionisio et al. 2011		
Jumping tasks	**Santos et al. 2008** *Kalytczak et al. 2018*	**Kalytczak et al. 2016, Santos et al. 2008** *Kalytczak et al. 2018, Bley et al. 2014, Baellow et al. 2020*	*Kalytczak et al. 2018*	**Kalytczak et al. 2016** *Kalytczak et al. 2018, Bley et al. 2014, Baellow et al. 2020*				
balance during standing	**Santos et al. 2008** *Stensdotter et al. 2008*	**Goto et al. 2018, Santos et al. 2008** *Stensdotter et al. 2008*						
Gait (walking)	*Pal et al. 2011, Freddolini et al. 2017*	*Santos et al. 2017*						
Gait (running)	*Pal et al. 2011, de Almeida Britto et al. 2021*	*MacIntyre and Robertson 1992, de Almeida Britto et al. 2021*						

Isolated tasks	Timing	Amplitude	Timing	Amplitude	Timing	Amplitude
Isometric	**Santos et al. 2008, Stensdotter et al. 2007** *Mellor et al. 2005, Patil et al. 2011, Peng et al. 2020* Bevilaqua-Grossi et al. 2009	**Felicio et al. 2011**, **Santos et al. 2008, Stensdotter et al. 2007, Briani et al. 2018** *Gallina et al. 2019, Peng et al. 2020* Laprade et al. 1998, Boucher et al. 1992, Thomee et al. 1996	*Patil et al. 2011*			
Concentric OKC	**Santos et al. 2008** *Cesarelli et al. 2000, Cesarelli et al. 1999* Thomee et al. 1995	**Keet et al. 2007**, **Santos et al. 2008**, *Cesarelli et al. 2000, Cesarelli et al. 1999* Thomee et al. 1995				
Eccentric OKC	Thomee et al. 1995	**Keet et al. 2007** Thomee et al. 1995				
Knee Jerk Reflex	*Voight et al. 1991, Bevilaqua-Grossi et al. 2008* Witvrouw et al. 1996	**Pazzinatto et al. 2018**				
H-Reflex		**Pazzinatto et al. 2018** *De Oliveira Silva et al. 2016*				
Electromechanical Delay	*Chen et al. 2012*	**NA**		**NA**		**NA**

Tasks	Extensors	Flexors
Isometric	**Ferreira et al. 2019a, Ferreira et al. 2019b, Briani et al. 2021, Keet et al. 2007**, **Bolgla et al. 2015, Briani et al. 2018, Stensdotter et al. 2007, Nunes et al. 2020, de Albuqurque et al. 2021** *De Oliveira Silva et al. 2018, Rathleff et al. 2013, Bolgla et al. 2011, Carvalho et al. 2016, Gallina et al. 2019, Baellow et al. 2020* Thomee et al. 1995, Thomee et al. 1996, Boucher et al. 1992	**Briani et al. 2021** *Baellow et al. 2020*
Concentric	**Ferreira et al. 2019b, Keet et al. 2007, Nunes et al. 2020, Briani et al. 2021** *De Oliveira Silva et al. 2018, Hazneci et al. 2005, Duffey et al. 2000, Cesarelli et al. 2000* Thomee et al. 1995	**Briani et al. 2021** *Hazneci et al. 2005, Duffey et al. 2000*
Eccentric	**Ferreira et al. 2019b, Keet et al. 2007, Nunes et al. 2020, Briani et al. 2021** *De Oliveira Silva et al. 2018* Thomee et al. 1995	**Briani et al. 2021**

Muscle group	Flexibility	CSA
Hamstrings	**Earl et al. 2005** *Patil et al. 2010, White et al. 2009, Christou et al. 2004*	
Quadriceps		**Giles et al. 2015** *El Sawy et al. 2021*
Gastrocnemius	*Christou et al. 2004*	
Iliotibial Band	**Earl et al. 2005**	

4 Appendix of Chapter 4

4.1 All data that formed the meta-analyses

All data that formed the meta-analyses												
outcome measure	study	intervention	task	After Rx Mean	After Rx Std-Dev	After Rx Sample size	Before Rx Mean	Before Rx Std-Dev	Before Rx Sample size	Hedges' s g	Std Err	Variance
VM mean exc. amp.	Araujo et al. 2016	McConnel taping	ant-post sway on rectangular board	27.00	19.00	20	29.00	22.00	20	-0.10	0.31	0.10
			Bosu balance ball	31.00	20.00	20	32.00	19.00	20	-0.05	0.31	0.10
			Mediolat. Sway	27.00	19.00	20	28.00	21.00	20	-0.05	0.31	0.10
			minitrampoline	28.00	15.00	20	28.00	21.00	20	0.00	0.31	0.10
			swing apparatus	29.00	21.00	20	30.00	21.00	20	-0.05	0.31	0.10
		placebo tape	ant-post sway on rectangular board	31.00	11.00	20	31.00	13.00	20	0.00	0.31	0.10
			Bosu balance ball	34.00	12.00	20	33.00	11.00	20	0.09	0.31	0.10
			Mediolat. Sway	30.00	10.00	20	30.00	15.00	20	0.00	0.31	0.10
			minitrampoline	29.00	14.00	20	28.00	14.00	20	0.07	0.31	0.10
			swing apparatus	34.00	12.00	20	34.00	16.00	20	0.00	0.31	0.10
	Cabral et al. 2008	CKC quads strengthening	isometric 90d	44.56	20.30	10	43.05	16.42	10	0.08	0.43	0.18
		OKC quads strengthening	isometric 90d	66.25	49.50	10	51.96	32.46	10	0.33	0.43	0.19
	Gulling et al. 1996	patellar brace	max conc. contraction (0 to 90d) but EMG gathered from 10 to 35d on IKD	823.44	314.18	16	874.88	354.77	16	-0.15	0.35	0.12
			max eccentric contraction (90 to 0d) but EMG gathered from 35 to 10d on IKD	539.56	279.12	16	660.12	409.86	16	-0.34	0.35	0.12
	Hickey et al. 2016	Mulligan taping	SLS (eccentric phase)	194.20	144.81	20	174.62	104.45	20	0.15	0.31	0.10
	Keet et al. 2007	medial glide taping	concentric peak torque 120d/s (J)	141.00	72.23	15	138.00	48.75	15	0.05	0.36	0.13
			eccentric peak torque 120d/s (J)	136.00	86.67	15	122.00	37.92	15	0.20	0.36	0.13
			isometric extension at 60d of flexion	93.00	27.08	15	100.00	0.00	15	-0.36	0.36	0.13
			Step-down	72.00	21.66	15	85.00	27.08	15	-0.52	0.36	0.13
			step-up	64.00	19.86	15	77.00	27.08	15	-0.53	0.36	0.13
		placebo taping	concentric peak torque 120d/s (J)	129.00	30.70	15	138.00	48.75	15	-0.21	0.36	0.13
			eccentric peak torque 120d/s (J)	118.00	39.73	15	122.00	37.92	15	-0.10	0.36	0.13
			isometric extension at 60d of flexion	107.00	36.11	15	100.00	0.00	15	0.27	0.36	0.13
			Step-down	81.00	23.47	15	85.00	27.08	15	-0.15	0.36	0.13
			step-up	77.00	27.08	15	77.00	27.08	15	0.00	0.36	0.13
	Lack et al. 2014	prefab. Foot orthosis	step-up	0.24	0.15	20	0.24	0.14	20	-0.01	0.31	0.10
	Lee et al. 2016	foot taping	Step-down	50.07	22.48	18	48.49	23.09	18	0.07	0.33	0.11
		short foot contraction	Step-down	49.11	18.15	18	48.49	23.09	18	0.03	0.33	0.11
	Lima et al. 2021	hip abduction exc	free squatting	0.49	0.14	11	0.44	0.16	11	0.34	0.41	0.17
			squatting with iso hip abd	0.55	0.18	11	0.45	0.22	11	0.46	0.42	0.17
	McCrory et al. 2004	brace (resistence off)	step-up (to side)	101.20	58.40	21	113.60	72.30	21	-0.19	0.30	0.09
			walking	3.50	4.30	21	4.20	4.50	21	-0.16	0.30	0.09
		brace (resistence on)	step-up (to side)	99.90	55.00	21	113.60	72.30	21	-0.21	0.30	0.09
			walking	4.40	5.50	21	4.20	4.50	21	0.04	0.30	0.09
	Moteallah et al. 2016	lumbopelvic manip.	rock task	92.30	14.30	14	74.30	19.70	14	1.02	0.39	0.15
		sham lbp manip.	rock task	67.40	26.70	14	71.00	25.10	14	-0.13	0.37	0.13
	Rathleff et al. 2016	education	stair descent	0.32	0.15	23	0.35	0.18	23	-0.15	0.29	0.08
		education and exc	stair descent	0.24	0.11	24	0.31	0.26	24	-0.35	0.29	0.08
VM exc. onset	Hickey et al. 2016	Mulligan taping	SLS (eccentric phase)	125.50	77.00	20	136.60	81.00	20	-0.14	0.31	0.10
	Lack et al. 2014	prefab. Foot orthosis	step-up	-258.75	30.94	20	-267.70	45.10	20	0.23	0.31	0.10
	Moteallah et al. 2016	lumbopelvic manip.	rock task	-7.90	43.50	14	50.10	54.60	14	-1.14	0.40	0.16
		sham lbp manip.	rock task	36.90	56.50	14	31.40	34.80	14	0.11	0.37	0.13
	Witvrouw et al. 2003	Quadriceps CKC strengthening	KJR	16.40	2.17	30	17.36	2.04	30	-0.45	0.26	0.07
			KJR (3 mths fl.up)	16.71	2.17	30	17.36	2.04	30	-0.30	0.26	0.07
		Quadriceps OKC strengthening	KJR	15.71	2.53	30	16.18	1.54	30	-0.22	0.26	0.07
			KJR (3 mths fl.up)	15.78	1.97	30	16.18	1.54	30	-0.22	0.26	0.07
VM exc. duration	Lima et al. 2021	hip abduction exc	free squatting	6.07	0.80	11	5.10	1.21	11	0.90	0.43	0.19
			squatting with iso hip abd	6.04	0.50	11	5.33	0.86	11	0.97	0.44	0.19
	McCrory et al. 2004	brace (resistence off)	step-up (to side)	40.50	13.30	21	42.80	12.40	21	-0.18	0.30	0.09
			walking	21.60	11.20	21	21.70	9.00	21	-0.01	0.30	0.09
		brace (resistence on)	step-up (to side)	42.20	12.80	21	42.80	12.40	21	-0.05	0.30	0.09
			walking	22.30	10.70	21	21.70	9.00	21	0.06	0.30	0.09
VL mean exc. amp.	Araujo et al. 2016	McConnel taping	ant-post sway on rectangular board	19.00	14.00	20	21.00	12.00	20	-0.15	0.31	0.10
			Bosu balance ball	25.00	17.00	20	24.00	12.00	20	0.07	0.31	0.10
			Mediolat. Sway	20.00	14.00	20	20.00	13.00	20	0.00	0.31	0.10

			minitrampoline	18.00	12.00	20	19.00	11.00	20	-0.09	0.31	0.10
			swing apparatus	22.00	17.00	20	22.00	14.00	20	0.00	0.31	0.10
		placebo tape	ant-post sway on rectangular board	19.00	9.00	20	23.00	11.00	20	-0.39	0.31	0.10
			Bosu balance ball	25.00	13.00	20	28.00	16.00	20	-0.20	0.31	0.10
			Mediolat. Sway	17.00	9.00	20	23.00	11.00	20	-0.59	0.32	0.10
			minitrampoline	19.00	9.00	20	23.00	12.00	20	-0.37	0.31	0.10
			swing apparatus	20.00	10.00	20	27.00	13.00	20	-0.59	0.32	0.10
	Cabral et al. 2008	Quadriceps CKC strengthening	isometric 90d	40.98	12.06	10	44.95	15.04	10	-0.28	0.43	0.19
		Quadriceps OKC strengthening	isometric 90d	63.71	24.75	10	29.23	26.07	10	1.30	0.48	0.23
	dos Santos et al. 2019	10% step-rate inc	running (stance phase) 0-45% of cycle	1.70	2.00	6	1.81	0.12	6	-0.07	0.53	0.28
			swing (1st half) 80-90% of cycle	0.58	0.38	6	0.43	0.32	6	0.39	0.54	0.29
			swing (2nd half) 90-100% of cycle	1.32	0.86	6	0.91	0.38	6	0.57	0.55	0.30
		for. Trunk lean	swing (1st half) 80-90% of cycle	0.41	0.28	6	0.42	0.23	6	-0.04	0.53	0.28
			swing (2nd half) 90-100% of cycle	1.26	0.74	6	1.00	0.19	6	0.44	0.54	0.29
			running (stance phase) 0-45% of cycle	1.64	0.22	6	1.83	0.15	6	-0.93	0.57	0.32
		forefoot landing	running (stance phase) 0-45% of cycle	1.81	0.11	6	1.80	0.22	6	0.05	0.53	0.28
			swing (1st half) 80-90% of cycle	0.44	0.19	6	0.30	0.16	6	0.74	0.55	0.31
			swing (2nd half) 90-100% of cycle	1.23	0.31	6	0.83	0.32	6	1.17	0.58	0.34
	Gulling et al. 1996	patellar brace	max conc. contraction (0 to 90d) but EMG gathered from 10 to 35d on IKD	577.31	205.00	16	574.75	228.97	16	0.01	0.34	0.12
			max eccentric contraction (90 to 0d) but EMG gathered from 35 to 10d on IKD	372.00	144.36	16	397.75	147.15	16	-0.17	0.35	0.12
	Hickey et al. 2016	Mulligan taping	SLS (eccentric phase)	147.25	44.41	20	147.72	56.84	20	-0.01	0.31	0.10
	Lack et al. 2014	prefab. Foot orthosis	step-up	0.17	0.11	20	0.16	0.10	20	0.03	0.31	0.10
	Lee et al. 2016	foot taping	Step-down	49.81	25.38	18	54.20	26.39	18	-0.17	0.33	0.11
		short foot contraction	Step-down	47.44	19.38	18	54.20	26.39	18	-0.29	0.33	0.11
	Lima et al. 2021	hip abduction exc	free squatting	0.48	0.20	11	0.49	0.14	11	-0.11	0.41	0.17
			squatting with iso hip abd	0.51	0.19	11	0.46	0.17	11	0.28	0.41	0.17
	McCrory et al. 2004	brace (resistence off)	step-up (to side)	101.20	58.30	21	108.60	56.90	21	-0.13	0.30	0.09
			walking	4.20	4.10	21	4.60	2.70	21	-0.11	0.30	0.09
		brace (resistence on)	step-up (to side)	99.90	48.70	21	108.60	56.90	21	-0.16	0.30	0.09
			walking	4.90	4.90	21	4.60	2.70	21	0.07	0.30	0.09
	Moteallah et al. 2016	lumbopelvic manip.	rock task	82.60	22.70	14	78.60	23.20	14	0.17	0.37	0.14
		sham lbp manip.	rock task	51.40	25.80	14	56.60	28.60	14	-0.19	0.37	0.14
	Rathleff et al. 2016	education	stair descent	0.27	0.08	23	0.29	0.08	23	-0.25	0.29	0.08
		education and exc	stair descent	0.23	0.11	24	0.27	0.18	24	-0.25	0.29	0.08
VL exc. onset	Hickey et al. 2016	Mulligan taping	SLS (eccentric phase)	122.50	80.80	20	135.40	87.90	20	-0.15	0.31	0.10
	Lack et al. 2014	prefab. Foot orthosis	step-up	-258.05	34.19	20	-255.25	34.11	20	-0.08	0.31	0.10
	Moteallah et al. 2016	lumbopelvic manip.	rock task	-16.00	56.20	14	13.70	63.20	14	-0.48	0.37	0.14
		sham lbp manip.	rock task	2.50	39.00	14	12.70	20.40	14	-0.32	0.37	0.14
	Witvrouw et al. 2003	Quadriceps CKC strengthening	KJR	16.72	2.19	30	16.91	2.07	30	-0.09	0.25	0.07
			KJR (3 mths fl.up)	16.96	1.95	30	16.91	2.07	30	0.02	0.25	0.06
		Quadriceps OKC strengthening	KJR	15.96	2.31	30	16.12	1.92	30	-0.07	0.25	0.06
			KJR (3 mths fl.up)	16.12	1.87	30	16.12	1.92	30	0.00	0.25	0.06
VL exc. duration	Lima et al. 2021	hip abduction exc	free squatting	6.05	0.90	11	5.22	1.21	11	0.75	0.43	0.18
			squatting with iso hip abd	5.89	0.60	11	5.71	0.86	11	0.23	0.41	0.17
	McCrory et al. 2004	brace (resistence off)	step-up (to side)	46.00	14.40	21	48.70	14.20	21	-0.19	0.30	0.09
			walking	26.70	14.00	21	22.40	8.10	21	0.37	0.31	0.09
		brace (resistence on)	step-up (to side)	48.00	15.20	21	48.70	14.20	21	-0.05	0.30	0.09
			walking	26.90	15.30	21	22.40	8.10	21	0.36	0.31	0.09
VM/VL mean exc. amp	Araujo et al. 2016	McConnel taping	ant-post sway on rectangular board	167.00	106.00	20	136.00	62.00	20	0.35	0.31	0.10
			Bosu balance ball	136.00	65.00	20	123.00	48.00	20	0.22	0.31	0.10
			Mediolat. Sway	160.00	47.00	20	139.00	62.00	20	0.37	0.31	0.10
			minitrampoline	147.00	73.00	20	144.00	59.00	20	0.04	0.31	0.10
			swing apparatus	151.00	84.00	20	139.00	64.00	20	0.16	0.31	0.10
		placebo tape	ant-post sway on rectangular board	166.00	91.00	20	143.00	86.00	20	0.25	0.31	0.10
			Bosu balance ball	134.00	52.00	20	120.00	57.00	20	0.25	0.31	0.10
			Mediolat. Sway	180.00	115.00	20	150.00	121.00	20	0.25	0.31	0.10
			minitrampoline	175.00	104.00	20	141.00	113.00	20	0.31	0.31	0.10
			swing apparatus	157.00	85.00	20	129.00	77.00	20	0.34	0.31	0.10
	Keet et al. 2007	medial glide taping	Step-down	1.20	0.36	15	1.40	0.54	15	-0.42	0.36	0.13
			step-up	1.30	0.54	15	1.50	0.72	15	-0.31	0.36	0.13
		placebo taping	Step-down	1.40	0.54	15	1.40	0.54	15	0.00	0.36	0.13
			step-up	1.50	0.72	15	1.50	0.72	15	0.00	0.36	0.13
			free squatting	0.77	0.04	11	0.75	0.04	11	0.36	0.41	0.17

	Lima et al. 2021	hip abduction exc	squatting with iso hip abd	0.75	0.06	11	0.70	0.13	11	0.43	0.42	0.17
	Ma et al. 2021	Dry needling & stretching	max con. Ext. at 60d/s	0.91	0.04	25	0.79	0.02	25	3.74	0.47	0.22
VM-VL exc. onset	Lima et al. 2021	hip abduction exc	free squatting	214.29	494.51	11	123.63	302.20	11	0.21	0.41	0.17
			squatting with iso hip abd	241.98	364.02	11	125.98	346.02	11	0.31	0.41	0.17
	Mostamand et al. 2011	patellar taping	SLS (eccentric phase)	-3.22	3.45	18	2.54	4.35	18	-1.43	0.37	0.13
		patellar taping (apprx. 6 wks of Rx)	SLS (eccentric phase)	-6.00	3.40	18	2.54	4.35	18	-2.14	0.41	0.17
	Moteallah et al. 2016	lumbopelvic manip.	rock task	-16.00	56.20	14	13.70	63.20	14	-0.48	0.37	0.14
		sham lbp manip.	rock task	2.50	39.00	14	12.70	20.40	14	-0.32	0.37	0.14
	Witvrouw et al. 2003	Closed KC quads stren.	KJR	16.72	2.19	30	16.91	2.07	30	-0.09	0.25	0.07
			KJR (3 mths fl.up)	16.96	1.95	30	16.91	2.07	30	0.02	0.25	0.06
		Open KC quads stren.	KJR	15.96	2.31	30	16.12	1.92	30	-0.07	0.25	0.06
			KJR (3 mths fl.up)	16.12	1.87	30	16.12	1.92	30	0.00	0.25	0.06
RF mean exc. amp	dos Santos et al. 2019	10% step-rate inc	running (stance phase) 0-45% of cycle	1.12	0.29	6	1.18	0.33	6	-0.18	0.53	0.29
			swing (1st half) 80-90% of cycle	0.35	0.16	6	0.29	0.12	6	0.39	0.54	0.29
			swing (2nd half) 90-100% of cycle	0.48	0.14	6	0.50	0.16	6	-0.12	0.53	0.28
		forefoot landing	running (stance phase) 0-45% of cycle	1.48	0.11	6	1.35	0.18	6	0.80	0.56	0.31
			swing (1st half) 80-90% of cycle	0.58	0.19	6	0.46	0.16	6	0.63	0.55	0.30
			swing (2nd half) 90-100% of cycle	1.00	0.34	6	0.60	0.18	6	1.36	0.60	0.36
		forward Trunk lean	running (stance phase) 0-45% of cycle	1.16	0.19	6	1.35	0.37	6	-0.60	0.55	0.30
			swing (1st half) 80-90% of cycle	0.44	0.20	6	0.44	0.21	6	0.00	0.53	0.28
			swing (2nd half) 90-100% of cycle	0.64	0.09	6	0.68	0.14	6	-0.31	0.54	0.29
	McCrory et al. 2004	brace (resistence off)	step-up (to side)	44.40	27.00	21	40.50	26.20	21	0.14	0.30	0.09
			walking	8.10	15.20	21	8.80	15.50	21	-0.04	0.30	0.09
		brace (resistence on)	step-up (to side)	44.00	28.60	21	40.50	26.20	21	0.13	0.30	0.09
			walking	8.00	13.60	21	8.80	15.50	21	-0.05	0.30	0.09
	Song et al. 2015	femoral rotational taping	SLS (eccentric phase)	69.02	15.82	16	68.95	15.61	16	0.00	0.34	0.12
		placebo taping	SLS (eccentric phase)	69.33	15.25	16	68.95	15.61	16	0.02	0.34	0.12
BF mean exc. amp	dos Santos et al. 2019	10% step-rate inc	running (stance phase) 0-45% of cycle	0.89	0.17	6	1.04	0.21	6	-0.72	0.55	0.31
			swing (1st half) 80-90% of cycle	2.19	0.30	6	1.98	0.54	6	0.44	0.54	0.29
			swing (2nd half) 90-100% of cycle	2.37	0.96	6	2.09	0.65	6	0.32	0.54	0.29
		forefoot landing	running (stance phase) 0-45% of cycle	1.04	0.37	6	1.08	0.32	6	-0.11	0.53	0.28
			swing (1st half) 80-90% of cycle	2.52	0.42	6	2.14	0.63	6	0.66	0.55	0.30
			swing (2nd half) 90-100% of cycle	1.72	0.48	6	1.69	0.41	6	0.06	0.53	0.28
		forward Trunk lean	running (stance phase) 0-45% of cycle	1.10	0.13	6	0.96	0.11	6	1.07	0.58	0.33
			swing (1st half) 80-90% of cycle	1.97	0.70	6	2.31	0.59	6	-0.48	0.54	0.29
			swing (2nd half) 90-100% of cycle	2.38	0.46	6	2.94	1.75	6	-0.40	0.54	0.29
	McCrory et al. 2004	brace (resistence off)	step-up (to side)	11.30	10.00	21	11.80	11.40	21	-0.05	0.30	0.09
			walking	3.40	3.10	21	3.50	2.90	21	-0.03	0.30	0.09
		brace (resistence on)	step-up (to side)	9.10	9.20	21	11.80	11.40	21	-0.26	0.30	0.09
			walking	4.30	6.10	21	3.50	2.90	21	0.16	0.30	0.09
isometric ext. pk.t	Bily et al. 2008	EMS + PT training	isometric 30d of flexion	128.00	49.00	18	108.70	29.00	19	0.47	0.33	0.11
			isometric 60d of flexion	199.00	77.00	18	188.00	77.00	19	0.14	0.32	0.10
		PT training	isometric 30d of flexion	89.70	20.80	18	94.70	23.00	19	-0.22	0.32	0.10
			isometric 60d of flexion	149.00	33.00	18	152.00	45.00	19	-0.07	0.32	0.10
	Ferber et al. 2015	HIP: balance, core and hip strengthening exc.	isometric 90d (nm/kg)	4.19	1.50	111	3.88	1.59	111	0.20	0.13	0.02
		knee targeted strengthening exercises	isometric 90d (nm/kg)	4.18	1.60	88	3.93	1.47	88	0.16	0.15	0.02
	Glaviano et al. 2019	PENS+Exc	isometric 90d (n/kg)	5.50	3.60	11	4.30	1.30	11	0.43	0.42	0.17
		Sham pens+Exc	isometric 90d (n/kg)	4.30	1.90	10	3.70	1.70	10	0.32	0.43	0.19
	Grindstaff et al. 2012	lumbopelvic manip.	isometric 90d (N)	353.40	225.80	13	380.90	201.10	16	-0.13	0.36	0.13
		passive lumbar flex/ext in side-lying 1 min	isometric 90d (N)	383.10	183.10	15	421.30	170.80	16	-0.21	0.35	0.12
		prone ext on elbows 3 min	isometric 90d (N)	334.60	246.10	13	382.00	253.90	16	-0.18	0.36	0.13
	Hott et al. 2019	free physical activity	isometric 60d of flexion (N; after Rx)	322.00	138.19	33	337.00	144.82	36	-0.10	0.24	0.06
			isometric 60d of flexion (N; follow-up 3 mths)	319.00	138.19	33	337.00	144.82	36	-0.13	0.24	0.06
		hip targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	345.00	101.97	37	321.00	114.14	39	0.22	0.23	0.05
			isometric 60d of flexion (N; follow-up 3 mths)	342.00	101.97	37	321.00	114.14	39	0.19	0.23	0.05
		knee targeted strengthening exercises	isometric 60d of flexion (N; after Rx)	326.00	120.37	34	317.00	134.97	37	0.07	0.24	0.06
			isometric 60d of flexion (N; follow-up 3 mths)	313.00	126.10	34	317.00	134.97	37	-0.03	0.23	0.06
	Keet et al. 2007	medial glide taping	isometric 60d of flexion (N)	376.00	103.90	15	362.00	88.30	15	0.14	0.36	0.13
		placebo taping	isometric 60d of flexion (N)	348.00	74.03	15	362.00	88.30	15	-0.17	0.36	0.13
	Rabelo et al. 2017	motor control + strengthening exc	isometric 60d of flexion (Nm/kg)	47.00	11.10	17	39.40	14.10	17	0.58	0.34	0.12

		strengthening exc	isometric 60d of flexion (Nm/kg)	47.50	7.30	17	38.10	11.20	17	0.97	0.35	0.13
	Rathleff et al. 2016	education	isometric 60d of flexion (Nm/kg)	2.17	0.49	23	2.26	0.44	29	-0.19	0.28	0.08
		education and exc	isometric 60d of flexion (Nm/kg)	2.54	0.64	24	2.27	0.50	28	0.47	0.28	0.08
	Rathleff et al. 2018	strength., stretch., taping and education	isometric 60d of flexion (Nm/kg)	0.84	0.23	18	0.82	0.21	20	0.09	0.32	0.10
	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	35.23	7.28	10	30.38	10.69	10	0.51	0.44	0.19
		none (control)	isometric (N/kg) angle: NA	36.76	10.44	10	39.71	9.54	10	-0.28	0.43	0.19
		quadriceps exc	isometric (N/kg) angle: NA	25.26	11.16	10	20.86	9.17	10	0.41	0.43	0.19
		stretching exc	isometric (N/kg) angle: NA	31.85	15.26	10	32.07	13.56	10	-0.01	0.43	0.18
	Singer et al. 2006	Exercise +butox	isometric 30d of flexion (Nm/kg)	24.30	5.00	8	22.70	7.70	8	0.23	0.47	0.23
concentric ext. pk.t	Aytar et al. 2011	Kinesio tape	concentric torque 180/s	77.95	28.78	12	70.04	31.21	12	0.25	0.40	0.16
			concentric torque 60/s	106.64	24.39	12	100.43	26.20	12	0.24	0.40	0.16
		placebo KT tape	concentric torque 180/s	50.30	22.41	10	45.69	15.83	10	0.23	0.43	0.18
			concentric torque 60/s	79.85	25.55	10	74.97	24.67	10	0.19	0.43	0.18
	Corum et al. 2018	stren. & stretch.	concentric peak torque 240d/s (Nm/kg)	79.10	17.10	16	71.30	14.50	16	0.48	0.35	0.12
			concentric peak torque 60d/s (Nm/kg)	176.80	25.90	16	153.10	31.00	16	0.81	0.36	0.13
		whole body vibratio + exc	concentric peak torque 240d/s (Nm/kg)	75.20	14.00	18	60.30	14.70	18	1.01	0.35	0.12
			concentric peak torque 60d/s (Nm/kg)	160.20	28.70	18	132.30	36.50	18	0.83	0.34	0.12
	Hazneci et al. 2005	OKC quads strengthening	concentric peak torque 60d/s (Nm)	146.00	51.00	24	126.00	49.00	24	0.39	0.29	0.08
	Kurt et al. 2016	Kinesio tape	peak torque 180d/s	64.20	18.90	55	61.80	20.10	55	0.12	0.19	0.04
			peak torque 60d/s	76.20	28.10	55	72.80	23.90	55	0.13	0.19	0.04
		placebo kinesio tape	peak torque 180d/s	71.40	17.10	51	70.30	18.30	51	0.06	0.20	0.04
			peak torque 60d/s	84.90	18.40	51	82.90	21.70	51	0.10	0.20	0.04
	Orscelik et al. 2015	single PRP+exc	concentric peak torque 240d/s (Nm/kg)	137.90	41.90	20	111.10	42.50	20	0.62	0.32	0.10
			concentric peak torque 60d/s (Nm/kg)	216.60	86.20	20	167.70	72.70	20	0.60	0.32	0.10
		triple PRP+exc	concentric peak torque 240d/s (Nm/kg)	132.80	39.30	10	105.70	34.60	10	0.70	0.44	0.20
			concentric peak torque 60d/s (Nm/kg)	220.90	63.10	10	166.90	53.10	10	0.89	0.45	0.20
	Osorio et al. 2013	McConnel tape	peak torque 60d/s (Nm/kg)	2.10	0.60	20	1.80	0.50	20	0.53	0.32	0.10
			total work 240d/s (j/kg)	42.90	13.80	20	35.60	14.00	20	0.51	0.32	0.10
		Spider tape	peak torque 60d/s (Nm/kg)	2.10	0.50	20	1.80	0.50	20	0.59	0.32	0.10
			total work 240d/s (j/kg)	42.50	11.00	20	35.60	14.00	20	0.54	0.32	0.10
	Paoloni et al. 2012	stren., stret. & balance+tape	concentric peak torque 60d/s (Nm) (after Rx)	195.90	51.70	44	146.20	36.50	44	1.10	0.23	0.05
			concentric peak torque 60d/s (Nm) (follow-up 12 mths)	193.80	44.20	44	146.20	36.50	44	1.16	0.23	0.05
	Witvrouw et al. 2004	Closed KC quads stren.	Concentric peak torque 180d/s (fl-up 3 mths)	167.50	44.90	30	152.30	43.50	30	0.34	0.26	0.07
			Concentric peak torque 180d/s (fl-up 5 yrs)	146.70	48.50	30	152.30	43.50	30	-0.12	0.26	0.07
			Concentric peak torque 300d/s (fl-up 3 mths)	110.90	32.50	30	101.90	38.70	30	0.25	0.26	0.07
			Concentric peak torque 300d/s (fl-up 5 yrs)	101.20	28.10	30	101.90	38.70	30	-0.02	0.25	0.06
			Concentric peak torque 60d/s (fl-up 3 mths)	241.90	58.10	30	228.90	57.30	30	0.22	0.26	0.07
			Concentric peak torque 60d/s (fl-up 5 yrs)	263.40	59.30	30	228.90	57.30	30	0.58	0.26	0.07
		Open KC quads stren.	Concentric peak torque 180d/s (fl-up 3 mths)	175.90	44.40	30	151.50	43.50	30	0.55	0.26	0.07
			Concentric peak torque 180d/s (fl-up 5 yrs)	173.10	49.50	30	151.50	43.50	30	0.46	0.26	0.07
			Concentric peak torque 300d/s (fl-up 3 mths)	120.70	32.90	30	100.70	38.20	30	0.55	0.26	0.07
			Concentric peak torque 300d/s (fl-up 5 yrs)	118.30	28.20	30	100.70	38.20	30	0.52	0.26	0.07
			Concentric peak torque 60d/s (fl-up 3 mths)	233.70	58.50	30	219.50	57.30	30	0.24	0.26	0.07
			Concentric peak torque 60d/s (fl-up 5 yrs)	252.80	59.80	30	219.50	57.30	30	0.56	0.26	0.07
mean ext. moment/ average torque	Drover et al. 2004	active release technique (quads and patellar tendon)	mean extensor moment (Nm)	159.00	51.00	9	165.00	65.00	9	-0.10	0.45	0.20
			mean extensor moment (Nm) 20 min after Rx	156.00	55.00	9	165.00	65.00	9	-0.14	0.45	0.20
	Thomee 1997	only ecc. Exc prog	Average torque (12 mo. "follow-up")	116.40	21.91	20	100.80	29.09	20	0.59	0.32	0.10
			Average torque (3 mo. "post")	112.40	35.42	20	100.80	29.09	20	0.35	0.31	0.10
		only isom. Exc prog	Average torque (12 mo. "follow-up")	147.90	29.52	20	133.20	36.68	20	0.43	0.31	0.10
			Average torque (3 mo. "post")	144.50	44.27	20	133.20	36.68	20	0.27	0.31	0.10
isometric flex. pk.t	Glaviano et al. 2019	PENS+Exc	isometric 90d (n/kg)	2.50	0.70	11	2.50	0.60	11	0.00	0.41	0.17
		Sham pens+Exc	isometric 90d (n/kg)	2.40	0.60	10	1.70	0.40	10	1.31	0.48	0.23
	Rathleff et al. 2018	stren., stretch. +tape + edu	isometric 60d of flexion (Nm/kg)	0.33	0.07	18	0.33	0.07	20	0.00	0.32	0.10
	Saad et al. 2018	hip exc	isometric (N/kg) angle: NA	14.07	3.02	10	12.76	4.09	10	0.35	0.43	0.19
		none (control)	isometric (N/kg) angle: NA	11.39	2.98	10	12.53	3.46	10	-0.34	0.43	0.19
		quadriceps exc	isometric (N/kg) angle: NA	13.46	11.02	10	8.95	4.02	10	0.52	0.44	0.19
		stretching exc	isometric (N/kg) angle: NA	13.71	5.07	10	14.15	7.08	10	-0.07	0.43	0.18
concentric flex. pk.t	Corum et al. 2018	stren. & stretch.	concentric peak torque 240d/s (Nm/kg)	65.20	16.60	16	55.80	15.00	16	0.58	0.35	0.12
			concentric peak torque 60d/s (Nm/kg)	121.00	15.20	16	96.70	16.60	16	1.49	0.39	0.15

		whole body vibratio + exc	concentric peak torque 240d/s (Nm/kg)	64.20	11.90	18	49.70	16.80	18	0.97	0.35	0.12
			concentric peak torque 60d/s (Nm/kg)	106.60	15.80	18	85.60	21.10	18	1.10	0.35	0.12
	Hazneci et al. 2005	OKC quads strengthening	concentric peak torque 60d/s (Nm)	83.00	30.00	24	70.00	27.00	24	0.45	0.29	0.08
	Kurt et al. 2016	Kinesio tape	peak torque 180d/s	38.70	19.10	55	37.70	18.90	55	0.05	0.19	0.04
			peak torque 60d/s	46.20	24.50	55	44.40	23.90	55	0.07	0.19	0.04
		placebo kinesio tape	peak torque 180d/s	41.40	17.70	51	40.10	18.70	51	0.07	0.20	0.04
			peak torque 60d/s	51.30	22.00	51	49.90	22.70	51	0.06	0.20	0.04
	Orscelik et al. 2015	single PRP+exc	concentric peak torque 240d/s (Nm/kg)	84.70	32.40	20	67.00	24.00	20	0.61	0.32	0.10
			concentric peak torque 60d/s (Nm/kg)	122.00	45.30	20	89.70	39.60	20	0.74	0.32	0.10
		triple PRP+exc	concentric peak torque 240d/s (Nm/kg)	75.60	19.00	10	65.60	14.00	10	0.57	0.44	0.19
			concentric peak torque 60d/s (Nm/kg)	112.70	37.30	10	84.90	32.80	10	0.76	0.44	0.20
	Witvrouw et al. 2004	Closed KC quads stren.	Concentric peak torque 180d/s (fl-up 3 mths)	105.50	28.30	30	90.80	19.80	30	0.59	0.26	0.07
			Concentric peak torque 180d/s (fl-up 5 yrs)	81.10	31.20	30	90.80	19.80	30	-0.37	0.26	0.07
			Concentric peak torque 300d/s (fl-up 3 mths)	72.00	25.30	30	63.10	22.20	30	0.37	0.26	0.07
			Concentric peak torque 300d/s (fl-up 5 yrs)	52.50	24.30	30	63.10	22.20	30	-0.45	0.26	0.07
			Concentric peak torque 60d/s (fl-up 3 mths)	142.40	39.20	30	127.00	31.20	30	0.43	0.26	0.07
			Concentric peak torque 60d/s (fl-up 5 yrs)	122.40	33.70	30	127.00	31.20	30	-0.14	0.26	0.07
		Open KC quads stren.	Concentric peak torque 180d/s (fl-up 3 mths)	102.40	28.90	30	88.70	19.30	30	0.55	0.26	0.07
			Concentric peak torque 180d/s (fl-up 5 yrs)	93.00	31.10	30	88.70	19.30	30	0.16	0.26	0.07
			Concentric peak torque 300d/s (fl-up 3 mths)	71.30	25.30	30	63.40	22.70	30	0.32	0.26	0.07
			Concentric peak torque 300d/s (fl-up 5 yrs)	69.70	24.30	30	63.40	22.70	30	0.26	0.26	0.07
			Concentric peak torque 60d/s (fl-up 3 mths)	136.60	39.40	30	122.30	30.70	30	0.40	0.26	0.07
			Concentric peak torque 60d/s (fl-up 5 yrs)	127.50	34.40	30	122.30	30.70	30	0.16	0.26	0.07
ext. total work	Corum et al. 2018	stren. & stretch.	total work (J/kg) 240d/s	969.80	226.40	16	965.30	244.10	16	0.02	0.34	0.12
		whole body vibratio + exc	total work (J/kg) 240d/s	965.20	225.80	18	818.70	246.20	18	0.61	0.33	0.11
	Hazneci et al. 2005	OKC quads strengthening	total work 180d/s (Nm)	113.00	42.00	24	94.00	28.00	24	0.52	0.29	0.08
	Orscelik et al. 2015	single PRP+exc	total work 240d/s (j)	1115.60	467.80	20	770.50	332.40	20	0.83	0.32	0.10
			total work 60d/s (j)	798.00	508.10	20	505.90	245.70	20	0.72	0.32	0.10
		triple PRP+exc	total work 240d/s (j)	1141.10	595.40	10	869.00	548.10	10	0.46	0.43	0.19
			total work 60d/s (j)	697.20	298.00	10	520.80	244.30	10	0.62	0.44	0.19
	Osorio et al. 2013	McConnel tape	total work 240d/s (j/kg)	42.90	13.80	20	35.60	14.00	20	0.51	0.32	0.10
		Spider tape	total work 240d/s (j/kg)	42.50	11.00	20	35.60	14.00	20	0.54	0.32	0.10
flex. Total work	Corum et al. 2018	stren. & stretch.	total work (J/kg) 240d/s	925.80	358.10	16	829.70	342.00	16	0.27	0.35	0.12
		whole body vibratio + exc	total work (J/kg) 240d/s	954.60	246.00	18	771.50	288.90	18	0.67	0.34	0.11
	Hazneci et al. 2005	OKC quads strengthening	total work 180d/s (Nm)	72.00	29.00	24	57.00	20.00	24	0.59	0.29	0.08
	Orscelik et al. 2015	single PRP+exc	total work 240d/s (j)	672.00	316.20	20	468.60	245.50	20	0.70	0.32	0.10
			total work 60d/s (j)	492.90	283.10	20	306.90	170.60	20	0.78	0.32	0.10
		triple PRP+exc	total work 240d/s (j)	555.40	237.30	10	470.40	228.70	10	0.35	0.43	0.19
			total work 60d/s (j)	397.50	180.80	10	296.50	153.00	10	0.58	0.44	0.19
Concentric flex/ext pk.t ratio	Corum et al. 2018	stren. & stretch.	peak torque ratio 240d/s	82.30	12.10	16	76.00	12.10	16	0.51	0.35	0.12
			peak torque ratio 60d/s	68.90	8.50	16	64.30	8.60	16	0.52	0.35	0.12
		whole body vibratio + exc	peak torque ratio 240d/s	85.70	15.00	18	82.30	19.00	18	0.19	0.33	0.11
			peak torque ratio 60d/s	67.00	8.20	18	66.00	16.20	18	0.08	0.33	0.11
	Kurt et al. 2016	Kinesio tape	peak torque ratio 180d/s	64.60	10.10	55	63.80	10.60	55	0.08	0.19	0.04
			peak torque ratio 60d/s	53.30	12.80	55	52.90	13.10	55	0.03	0.19	0.04
		placebo kinesio tape	peak torque ratio 180d/s	69.70	8.80	51	69.50	9.90	51	0.02	0.20	0.04
			peak torque ratio 60d/s	57.80	11.80	51	59.10	12.10	51	-0.11	0.20	0.04
mean muscle inhibition	Drover et al. 2004	active release technique (quads and patellar tendon)	mean extensor moment (Nm)	17.40	6.80	9	18.30	9.60	9	-0.10	0.45	0.20
			mean extensor moment (Nm) 20 min after Rx	16.80	6.60	9	18.30	9.60	9	-0.17	0.45	0.20
	Grindstaff et al. 2012	lumbopelvic manip.	central activation ratio; iso. 90d	0.77	0.14	13	0.81	0.16	16	-0.20	0.36	0.13
		passive lumbar flex/ext in side-lying 1 min	central activation ratio; iso. 90d	0.61	0.29	15	0.67	0.31	16	-0.18	0.35	0.12
		prone ext on elbows 3 min	central activation ratio; iso. 90d	0.64	0.20	13	0.68	0.25	16	-0.20	0.36	0.13
Hams flexibility	Cabral et al. 2008	Quadriceps CKC strengthening	flexibility test	-42.90	13.92	10	-54.10	10.21	10	0.88	0.45	0.20
		Quadriceps OKC strengthening	flexibility test	-46.90	11.27	10	-57.00	11.01	10	0.87	0.45	0.20
	Glaviano et al. 2019	PENS+Exc	flexibility test	97.70	13.60	11	81.60	29.70	11	0.67	0.42	0.18
		Sham pens+Exc	flexibility test	91.80	13.30	10	83.90	14.80	10	0.54	0.44	0.19
			flexibility test (3 mths fl-up)	94.90	16.47	30	89.80	14.58	30	0.32	0.26	0.07

	Witvrouw et al. 2000	Closed KC quads stren.	flexibility test after Rx	95.60	19.70	30	89.80	14.60	30	0.33	0.26	0.07
		Open KC quads stren.	flexibility test (3 mths fl-up)	93.70	17.12	30	87.80	15.29	30	0.36	0.26	0.07
			flexibility test after Rx	92.30	18.70	30	87.80	15.30	30	0.26	0.26	0.07
Quads flexibility	Glaviano et al. 2019	PENS+Exc	flexibility test	141.20	3.60	11	134.90	8.60	11	0.92	0.43	0.19
		Sham pens+Exc	flexibility test	136.50	8.90	10	135.00	7.80	10	0.17	0.43	0.18
	Witvrouw et al. 2000	Closed KC quads stren.	flexibility test (3 mths fl-up)	137.50	14.59	30	116.20	13.52	30	1.49	0.29	0.08
			flexibility test after Rx	129.10	14.60	30	116.20	13.50	30	0.91	0.27	0.07
		Open KC quads stren.	flexibility test (3 mths fl-up)	135.80	16.44	30	119.70	18.66	30	0.90	0.27	0.07
			flexibility test after Rx	126.90	12.10	30	119.70	18.70	30	0.45	0.26	0.07
ITB flexibility	Glaviano et al. 2019	PENS+Exc	flexibility test	32.40	9.60	11	31.40	10.20	11	0.10	0.41	0.17
		Sham pens+Exc	flexibility test	35.90	4.40	10	23.00	15.20	10	1.10	0.46	0.21
	Malarvizhi et al. 2017	hip stren. & itb stretching	flexibility test	-6.85	2.50	20	-11.00	2.53	20	1.62	0.36	0.13
Gast. flexibility	Glaviano et al. 2019	PENS+Exc	flexibility test	15.40	4.60	11	14.00	5.80	11	0.26	0.41	0.17
		Sham pens+Exc	flexibility test	20.00	4.30	10	14.10	7.90	10	0.89	0.45	0.20
	Witvrouw et al. 2000	Closed KC quads stren.	flexibility test (3 mths fl-up)	39.70	4.93	30	33.60	6.97	30	1.00	0.27	0.07
			flexibility test after Rx	35.00	5.20	30	33.60	7.00	30	0.22	0.26	0.07
		Open KC quads stren.	flexibility test (3 mths fl-up)	38.00	7.08	30	32.00	4.90	30	0.97	0.27	0.07
			flexibility test after Rx	34.80	4.30	30	32.00	4.90	30	0.60	0.26	0.07

4.2 Data that were not pooled with reasons

Data that were not pooled with reasons				after Rx			before Rx			Reasons
outcome	**study name**	**groups**	**tasks**	**mean**	**SD**	**n**	**mean**	**SD**	**n**	
VM mean amplitude	**Araujo et al. 2016**	McConnel taping	swing apparatus	29	21	20	30	21	20	methodological heterogeneity (tasks)
			ant-post sway on rectangular board	27	19	20	29	22	20	
			Mediolat. Sway	27	19	20	28	21	20	
			minitrampoline	28	15	20	28	21	20	
			Bosu balance ball	31	20	20	32	19	20	
		placebo tape	swing apparatus	34	12	20	34	16	20	
			ant-post sway on rectangular board	31	11	20	31	13	20	
			Mediolat. Sway	30	10	20	30	15	20	
			minitrampoline	29	14	20	28	14	20	
			Bosu balance ball	34	12	20	33	11	20	
	Moteallah et al. 2016	lumbopelvic manip.	rock task	92.3	14.3	14	74.3	19.7	14	
		sham lbp manip.	rock task	67.4	26.7	14	71	25.1	14	
	McCrory et al. 2004	brace (resistence on)	walking	4.4	5.5	21	4.2	4.5	21	
		brace (resistence off)	walking	3.5	4.3	21	4.2	4.5	21	
VM excitation onset	**Hickey et al. 2016**	Mulligan taping	SLS (eccentric phase)	125.5	77	20	136.6	81	20	methodological heterogeneity (tasks)
	Lack et al. 2014	prefab. Foot orthosis	step-up	-258.75	30.93	20	-267.7	45.10	20	
	Moteallah et al. 2016	lumbopelvic manip.	rock task	-7.9	43.5	14	50.1	54.6	14	
		sham lbp manip.	rock task	36.9	56.5	14	31.4	34.8	14	
	Witvrouw et al. 2003	Quadriceps OKC strengthening	KJR	15.71	2.53	30	16.18	1.54	30	
		Quadriceps CKC strengthening	KJR	16.40	2.17	30	17.36	2.04	30	
		Quadriceps OKC strengthening	KJR (3 mths fl.up)	15.78	1.97	30	16.18	1.54	30	different time point (not immediate effect after intervention, and no similar investigation from another study was found)
		Quadriceps CKC strengthening	KJR (3 mths fl.up)	16.71	2.17	30	17.36	2.04	30	
VM excitation duration	**McCrory et al. 2004**	brace (resistence on)	walking	22.3	10.7	21	21.7	9	21	methodological heterogeneity (tasks)
			step-up (to side)	42.2	12.8	21	42.8	12.4	21	
		brace (resistence off)	walking	21.6	11.2	21	21.7	9	21	
			step-up (to side)	40.5	13.3	21	42.8	12.4	21	
	Lima et al. 2021	hip abduction exc	free squatting	6.069	0.802	11	5.104	1.21	11	
			squatting with iso hip abd	6.037	0.503	11	5.333	0.855	11	
VL mean amplitude	**Araujo et al. 2016**	McConnel taping	swing apparatus	22	17	20	22	14	20	methodological heterogeneity (tasks)
			ant-post sway on rectangular board	19	14	20	21	12	20	
			Mediolat. Sway	20	14	20	20	13	20	
			minitrampoline	18	12	20	19	11	20	
			Bosu balance ball	25	17	20	24	12	20	
		placebo tape	swing apparatus	20	10	20	27	13	20	
			ant-post sway on rectangular board	19	9	20	23	11	20	
			Mediolat. Sway	17	9	20	23	11	20	

			minitrampoline	19	9	20	23	12	20	
			Bosu balance ball	25	13	20	28	16	20	
	Moteallah et al. 2016	lumbopelvic manip.	rock task	82.6	22.7	14	78.6	23.2	14	
		sham lbp manip.	rock task	51.4	25.8	14	56.6	28.6	14	
VL excitation onset	**Hickey et al. 2016**	Mulligan taping	SLS (eccentric phase)	122.5	80.8	20	135.4	87.9	20	methodological heterogeneity (tasks)
	Lack et al. 2014	prefab. Foot orthosis	step-up	-258.05	34.19	20	-255.25	34.109	20	
	Moteallah et al. 2016	lumbopelvic manip.	rock task	-16	56.2	14	13.7	63.2	14	
		sham lbp manip.	rock task	2.5	39	14	12.7	20.4	14	
	Witvrouw et al. 2003	Quadriceps OKC strengthening	KJR	15.96	2.31	30	16.12	1.92	30	
		Quadriceps CKC strengthening	KJR	16.72	2.19	30	16.91	2.07	30	
		Quadriceps OKC strengthening	KJR (3 mths fl.up)	16.12	1.87	30	16.12	1.92	30	different time point (not immediate effect after intervention, and no similar investigation from another study was found)
		Quadriceps CKC strengthening	KJR (3 mths fl.up)	16.96	1.95	30	16.91	2.07	30	
VL excitation duration	**McCrory et al. 2004**	brace (resistence on)	walking	26.9	15.3	21	22.4	8.1	21	methodological heterogeneity (tasks)
			step-up (to side)	48	15.2	21	48.7	14.2	21	
		brace (resistence off)	walking	26.7	14	21	22.4	8.1	21	
			step-up (to side)	46	14.4	21	48.7	14.2	21	
	Lima et al. 2021	hip abduction exc	free squatting	6.053	0.899	11	5.218	1.211	11	
			squatting with iso hip abd	5.886	0.604	11	5.71	0.864	11	
VM/VL mean excitation amplitude (ratio)	**Araujo et al. 2016**	McConnel taping	swing apparatus	151	84	20	139	64	20	methodological heterogeneity (tasks)
			ant-post sway on rectangular board	167	106	20	136	62	20	
			Mediolat. Sway	160	47	20	139	62	20	
			minitrampoline	147	73	20	144	59	20	
			Bosu balance ball	136	65	20	123	48	20	
		placebo tape	swing apparatus	157	85	20	129	77	20	
			ant-post sway on rectangular board	166	91	20	143	86	20	
			Mediolat. Sway	180	115	20	150	121	20	
			minitrampoline	175	104	20	141	113	20	
			Bosu balance ball	134	52	20	120	57	20	
	Keet et al. 2007	medial glide taping	step-up	1.3	0.541	15	1.5	0.722	15	
			Step-down	1.2	0.36	15	1.4	0.541	15	
		placebo taping	step-up	1.5	0.72	15	1.5	0.72	15	
			Step-down	1.4	0.54	15	1.4	0.54	15	
	Lima et al. 2021	hip abduction exc	free squatting	0.767	0.04	11	0.752	0.04	11	
			squatting with iso hip abd	0.748	0.064	11	0.703	0.126	11	
	Ma et al. 2021	Dry needling & stretching	max con. Ext. at 60d/s	0.91	0.04	25	0.79	0.02	25	
VM-VL excitation onset	**Mostamand et al. 2011**	patellar taping	SLS (eccentric phase)	-3.22	3.45	18	2.54	4.35	18	methodological heterogeneity (tasks)
		patellar taping	SLS (eccentric phase)	-6	3.4	18	2.54	4.35	18	
	Moteallah et al. 2016	lumbopelvic manip.	rock task	-16	56.2	14	13.7	63.2	14	
		sham lbp manip.	rock task	2.5	39	14	12.7	20.4	14	
	Lima et al. 2021	hip abduction exc	free squatting	214.28	494.5	11	123.62	302.19	11	
		hip abduction exc	squatting with iso hip abd	241.98	364	11	125.97	346	11	
	Witvrouw et al. 2003	Open KC quads stren.	KJR	15.96	2.31	30	16.12	1.92	30	
		Closed KC quads stren.	KJR	16.72	2.19	30	16.91	2.07	30	
		Open KC quads stren.	KJR (3 mths fl.up)	16.12	1.87	30	16.12	1.92	30	different time point (not immediate effect after intervention, and no similar investigation from another study was found)
		Closed KC quads stren.	KJR (3 mths fl.up)	16.96	1.95	30	16.91	2.07	30	
RF mean amplitude	**McCrory et al. 2004**	brace (resistence on)	step-up (to side)	44	28.6	21	40.5	26.2	21	methodological heterogeneity (taks), different than reported meta-analysis
		brace (resistence off)	step-up (to side)	44.4	27	21	40.5	26.2	21	
	Song et al. 2015	femoral rotational taping	SLS (eccentric phase)	69.02	15.82	16	68.95	15.61	16	
		placebo taping	SLS (eccentric phase)	69.33	15.25	16	68.95	15.61	16	
BF excitation duration	**McCrory et al. 2004**	brace (resistence on)	walking	24.8	16.5	21	21.4	12.1	21	heterogenous outcome measure (no other study reported the same investigation)
	McCrory et al. 2004	brace (resistence on)	side step-up	17.2	14.2	21	26.6	20.3	21	
	McCrory et al. 2004	brace (resistence off)	walking	24.5	14	21	21.4	12.1	21	
	McCrory et al. 2004	brace (resistence off)	side step-up	20.1	16.4	21	26.6	20.3	21	
Gastrocnemius medialis mean excitation amplitude	**dos Santos et al. 2019**	forefoot landing	running stance phase	1.64	0.35	6	1.96	0.45	6	heterogenous outcome measure (no other study reported the same investigation)
			1st half og late swing	0.94	0.34	6	0.23	0.25	6	

			2nd half of late swing	2.1	0.68	6	0.72	0.63	6	
		10% step-rate inc	running stance phase	1.96	0.17	6	1.98	0.08	6	
			1st half og late swing	0.44	0.67	6	0.18	0.07	6	
			2nd half of late swing	1.19	0.91	6	0.76	0.43	6	
		Forward Trunk lean	running stance phase	1.83	0.27	6	2.1	0.11	6	
			1st half og late swing	0.16	0.06	6	0.11	0.03	6	
			2nd half of late swing	0.88	0.63	6	0.42	0.31	6	
mean extension moment	**Drover et al. 2004**	active release technique (quads and patellar tendon)	mean extensor moment (Nm)	159	51	9	165	65	9	methodological heterogeneity (tasks are not clear)
			mean extensor moment (Nm) 20 min after Rx	156	55	9	165	65	9	
	Thomee 1997	only ecc. Exc prog	Average torque (after Rx)	112.4	35.41	20	100.8	29.1	20	
		only isom. Exc prog	Average torque (after Rx)	144.5	44.27	20	133.2	36.68	20	
		only ecc. Exc prog	Average torque (12 mo. "follow-up")	116.4	21.91	20	100.8	29.1	20	different time point (not immediate effect after intervention, and no similar investigation from another study was found)
		only isom. Exc prog	Average torque (12 mo. "follow-up")	147.9	29.51	20	133.2	36.68	20	
Concentric extension peak torque	**Witvrouw et al. 2004**	Open KC quads stren.	Concentric peak torque 60d/s (fl-up 3 mths)	233.7	58.5	30	219.5	57.3	30	different time point (not immediate effect after intervention, and not similar investigation from another study was found)
			Concentric peak torque 60d/s (fl-up 5 yrs)	252.8	59.8	30	219.5	57.3	30	
			Concentric peak torque 180d/s (fl-up 3 mths)	175.9	44.4	30	151.5	43.5	30	
			Concentric peak torque 180d/s (fl-up 5 yrs)	173.1	49.5	30	151.5	43.5	30	
			Concentric peak torque 300d/s (fl-up 3 mths)	120.7	32.9	30	100.7	38.2	30	
			Concentric peak torque 300d/s (fl-up 5 yrs)	118.3	28.2	30	100.7	38.2	30	
		Closed KC quads stren.	Concentric peak torque 60d/s (fl-up 3 mths)	241.9	58.1	30	228.9	57.3	30	
			Concentric peak torque 60d/s (fl-up 5 yrs)	263.4	59.3	30	228.9	57.3	30	
			Concentric peak torque 180d/s (fl-up 3 mths)	167.5	44.9	30	152.3	43.5	30	
			Concentric peak torque 180d/s (fl-up 5 yrs)	146.7	48.5	30	152.3	43.5	30	
			Concentric peak torque 300d/s (fl-up 3 mths)	110.9	32.5	30	101.9	38.7	30	
			Concentric peak torque 300d/s (fl-up 5 yrs)	101.2	28.1	30	101.9	38.7	30	
	Orscelik et al. 2015	single PRP+exc	concentric peak torque 240d/s (Nm/kg)	137.90	41.90	20	111.10	42.50	20	Different intervention type
			concentric peak torque 60d/s (Nm/kg)	216.60	86.20	20	167.70	72.70	20	
		triple PRP+exc	concentric peak torque 240d/s (Nm/kg)	132.80	39.30	10	105.70	34.60	10	
			concentric peak torque 60d/s (Nm/kg)	220.90	63.10	10	166.90	53.10	10	
	Paoloni et al. 2012	stren., stret. & balance+tape	concentric peak torque 60d/s (Nm) (after Rx)	195.90	51.70	44	146.20	36.50	44	
			concentric peak torque 60d/s (Nm) (follow-up 12 mths)	193.80	44.20	44	146.20	36.50	44	
Concentric flexion peak torque	**Witvrouw et al. 2004**	Open KC quads stren.	Concentric peak torque 60d/s (fl-up 3 mths)	136.6	39.4	30	122.3	30.7	30	different time point (not immediate effect after intervention, and not similar investigation from another study was found)
			Concentric peak torque 60d/s (fl-up 5 yrs)	127.5	34.4	30	122.3	30.7	30	
			Concentric peak torque 180d/s (fl-up 3 mths)	102.4	28.9	30	88.7	19.3	30	
			Concentric peak torque 180d/s (fl-up 5 yrs)	93.0	31.1	30	88.7	19.3	30	
			Concentric peak torque 300d/s (fl-up 3 mths)	71.3	25.3	30	63.4	22.7	30	
			Concentric peak torque 300d/s (fl-up 5 yrs)	69.7	24.3	30	63.4	22.7	30	
		Closed KC quads stren.	Concentric peak torque 60d/s (fl-up 3 mths)	142.4	39.2	30	127.0	31.2	30	
			Concentric peak torque 60d/s (fl-up 5 yrs)	122.4	33.7	30	127.0	31.2	30	
			Concentric peak torque 180d/s (fl-up 3 mths)	105.5	28.3	30	90.8	19.8	30	
			Concentric peak torque 180d/s (fl-up 5 yrs)	81.1	31.2	30	90.8	19.8	30	
			Concentric peak torque 300d/s (fl-up 3 mths)	72.0	25.3	30	63.1	22.2	30	
			Concentric peak torque 300d/s (fl-up 5 yrs)	52.5	24.3	30	63.1	22.2	30	
Concentric peak torque ratio	**Corum et al. 2018**	whole body vibratio + exc	peak torque ratio 60d/s	67	8.2	18	66	16.2	18	outcomes differ in how they were being calculated (extension/flexion and flexion/extension) check notes in tasks' cells
			peak torque ratio 240d/s	85.7	15	18	82.3	19	18	
		stren. & stretch.	peak torque ratio 60d/s	68.9	8.5	16	64.3	8.6	16	
			peak torque ratio 240d/s	82.3	12.1	16	76	12.1	16	
	Kurt et al. 2016	Kinesio tape	peak torque ratio 60d/s	53.3	12.8	55	52.9	13.1	55	
			peak torque ratio 180d/s	64.6	10.1	55	63.8	10.6	55	
		placebo kinesio tape	peak torque ratio 60d/s	57.8	11.8	51	59.1	12.1	51	
			peak torque ratio 180d/s	69.7	8.8	51	69.5	9.9	51	
mean muscle inhibition	**Grindstaff et al. 2012**	lumbopelvic manip.	central activation ratio; iso. 90d	0.774	0.138	13	0.805	0.155	16	outcomes differ in how they were being calculated (extension/flexion and flexion/extension) check notes in tasks' cells
		passive lumbar flex/ext in side-lying 1 min	central activation ratio; iso. 90d	0.613	0.289	15	0.669	0.310	16	
		prone ext on elbows 3 min	central activation ratio; iso. 90d	0.636	0.204	13	0.683	0.246	16	
	Drover et al. 2004	active release technique (quads and patellar tendon)	mean extensor moment (Nm)	17.4	6.8	9	18.3	9.6	9	
			mean extensor moment (Nm) 20 min after Rx	16.8	6.6	9	18.3	9.6	9	
		functional stabilisation ex	90-20d 60d/s, extensors	3.4	0.4	16	2.9	0.4	16	

eccentric extension peak torque	**Baldon et al. 2014**	standard ex	90-20d 60d/s, extensors	3.1	0.6	15	2.8	0.7	15	heterogenous outcome measure (no other study reported the same investigation)
eccentric flexion peak torque		functional stabilisation ex	90-20d 60d/s, extensors	1.5	0.1	16	1.3	0.2	16	heterogenous outcome measure (no other study reported the same investigation)
		standard ex	90-20d 60d/s, extensors	1.3	0.2	15	1.3	0.2	15	
Concentric extension peak torque ratio	**Kurt et al. 2016**	Kinesio tape	between 60-180d/s	363.2	165.3	55	359.2	195.6	55	heterogenous outcome measure (no other study reported the same investigation)
		placebo kinesio tape	between 60-180d/s	399.3	225.2	51	402.6	216.4	51	
Concentric flexion peak torque ratio	**Kurt et al. 2016**	Kinesio tape	between 60-180d/s	165.9	91.3	55	162.6	98.6	55	heterogenous outcome measure (no other study reported the same investigation)
		placebo kinesio tape	between 60-180d/s	269.6	112.3	51	274.3	101.9	51	
Isometric peak torque	**Singer et al. 2006**	Exercise +butox	isometric 30d of flexion (Nm/kg)	24.30	5.00	8	22.70	7.70	8	Different intervention type

Studies included and excluded from meta-analysis

	Pooled		Not Pooled	notes
1	Aytar	1	Araujo	Different tasks
2	Bily	2	Baldon	eccentric 90-20 60d/s, the only study reporting eccentric peak torque
3	Cabral	3	Christou	Christou's data is unretrievable; had amp of VMO and VL, hamstrings flexibility (baseline only), leg-press torque data (functional & SEM no SD); Hamstrings data works for SR1 only
4	Corum	4	Clark	no data retrievable
5	Dos Santos	5	Constantinou	Author was contacted as one data set was not correct (mean out of CI), reponse was promised after a week from my email, but never repsonded
6	Ferber	6	Drover	Different tasks
7	Galviano 19	7	Glaviano 20	data unretreivable
8	Grindstaff	8	Hamstra-Wright	follow-up of 1 year, no similar time point for similar outcome/task to be pooled with
9	Gulling	9	Ma	Author contacted, no reponse
10	Hazneci	10	Mills	data provided by author, but it doesn't have baseline (pre) data
11	Hickey	11	Mostamand	Different tasks, some data is non-parametric (no means SD)
12	Hott	12	Motealleh	Different tasks
13	Keet	13	Riel	hip and knee data mixed (isometric pk.t)
14	Kurt	14	Song	RF mean exc amp in SLS, Different tasks so wasn't pooled with the rest
15	Lack	15	Thomee	Different tasks
16	Lee	16	Witvrouw 04	follow-ups, no similar time point for similar outcome/task to be pooled with
17	Lima	17	Witvrouw 03	Different tasks
18	Malarvizhi	18	Yosmaoglu	data is non-parametric (no means SD)
19	Mccrory	19	Orscelik	Pooled then removed as they used different intervention type to other studies pooled in extension concentric peak torque plot (0.673 [0.166,1.180]).
20	Osorio	20	Paoloni	Pooled then removed as they used different intervention type to other studies pooled in extension concentric peak torque plot (1.132 [0.686,1.579]).
21	Rabelo	21	Singer	Pooled then removed as they used different intervention type to other studies pooled in extension isometric peak torque plot (0.233 [-0.697,1.163]). Other data were unretrievable (Quadriceps Cross-sectional area).
22	Rathlef 16			
23	Rathlef 18			
24	Saad			
25	Witvrouw 2000			

5 Appendix of Chapter 5: MATLAB scripts and functions

5.1 VM-VL timing function

```
function [output] = VMVL_processing(filename, startSD, endSD,
startTime, endTime, stepTime);

%% Import data
data =load(filename); % to load the task file (step-up)

VM = data.EMG.Channel19.value; % single muscle
VL = data.EMG.Channel21.value; % single muscle

Fs =data.EMG.Channel19.Rate; % Sampling freq

FP1=data.Force.F1.value; %data_from_ForcePlate1
%% set parameters for filters
% Bandpass
order = 4;
HP = 20;
if Fs == 500   % some data collection samples were collected at 500Hz
Fs, so this part is written here for this purpose
    Upper = 250;
else
    Upper = 500;
end

% Linear envelope
fco=50; %cut off frequncy 50Hz

%% Set up time variable
lVM=length(VM); % data points      %ADDED
time=(0:lVM-1)/Fs; % freq into time   %ADDED



%% Band Pass Filter (BP): 4th order butterworth filter (band-pass) of
20-500 Hz, (SENIAM recommendations)
% sampling similar to what equipment collect (2000 Hz)
BPfreq=[HP Upper];
[b,a]= butter(order/2,(BPfreq/Fs)); % (a & b with band pass fillter
formula)
filtered_Data_VM=filtfilt(b,a,VM);  % filtered data
filtered_Data_VL=filtfilt(b,a,VL);  %
filtered_Data_BF=filtfilt(b,a,BF);

%% Rectification
emg_rec_VM=abs(filtered_Data_VM);
emg_rec_VL=abs(filtered_Data_VL);

%% Low-pass filter
[b,a]=butter(order/2,fco/Fs,'low'); %low Pass Butterworth filter 4th
order

emg_le_VM= filtfilt(b,a,emg_rec_VM);
emg_le_VL= filtfilt(b,a,emg_rec_VL);

%% Force data
% plot of force plate 1 (a box was on this force plate, and a
participant steps up and down repeatedly)
```

```
% fx_fp1=FP1(:,1);
% fy_fp1=FP1(:,2);
fz_fp1=FP1(:,3); % vertical force

% plot of force plate 2 (used to take SD of 200ms resting period
before ground reaction force disturbed)
FP2=data.Force.F2.value; %data_from_ForcePlate2

% fx_fp2=FP2(:,1);
% fy_fp2=FP2(:,2);
fz_fp2=FP2(:,3); % vertical force


ax1 = subplot (2,1,1);
plot(fz_fp2,'k');
hold on
plot(fz_fp1,'r')
hold off;
ax2 = subplot (2,1,2);
plot(emg_le_VM,'r');
hold on
plot(emg_le_VL,'b');
hold off

%% step identification (finding onset of FP1 (step start time))
no_reps = inputdlg("how many reps");
% this is to pick the times the participant steps on the box

[x_step, ~] = ginput(str2num(no_reps{1}));
% this is the mouse click function to choose each step
% (the times the RED graph goes up and down)
x_step = round(x_step);

threshold_step = zeros(length(x_step),1);  % DEFINING INITIAL VECTOR
BEFORE FOR LOOPS FASTENS THE CODE

for i = 1:length(x_step)
    threshold_step(i) = find(fz_fp1(1:x_step(i)) <= 10, 1, 'last') +
1;
    % so that the code chooses each step whenever the force passes 10
newtons
end

for i = 1:length(threshold_step)
    xline(ax1, threshold_step(i));
    xline(ax2, threshold_step(i));
end


%% setting the muscle activity onset thresholds
[x,~] = ginput(1);
x = round(x);

% for VL muscle
BL(1) = mean(emg_le_VL(x-(0.2*Fs):x));
SD(1) = std(emg_le_VL(x-(0.2*Fs):x));           % finding the SD of
that 200 ms period (0.2 x 2000 = 400 frames of 2000f/s = 200 ms)

% for VM muscle
```

```
BL(2) = mean(emg_le_VM(x-(0.2*Fs):x));
SD(2) = std(emg_le_VM(x-(0.2*Fs):x));           % finding the SD of
that 200 ms period


%% here, we set 2 thresholds to identify muscle onset:
% if it stays 25 milliseconds above # SD



output = array2table(zeros(0,7));
output.Properties.VariableNames =
{'currentSD';'currentTime';'Step';'Step_Onset';'VM_Nearest_Act';'VL_Ne
arest_Act';'VM_VL_Delay'};


for currentSD = startSD:endSD

    for TimeWindow = startTime:stepTime:endTime
        %% Select areas that meet dbl threshold
        %disp(currentSD)
        minAcceptableLength = TimeWindow*Fs;

        % onset of VL
        threshold = currentSD*SD(1)+BL(1); % change this from 3 to 15
        above_threshold = (emg_le_VL > threshold);
        % Find spans that are long enough.
        isLongEnoughVL = bwareafilt(above_threshold,
[minAcceptableLength, inf]);       % Count the number of spans
(bursts) that are long enough.

        %onset of VM
        threshold = currentSD*SD(2)+BL(2); % using relevent SD from
range
        above_threshold = (emg_le_VM > threshold);
        % Find spans that are long enough.
        isLongEnoughVM = bwareafilt(above_threshold,
[minAcceptableLength, inf]);       % Count the number of spans
(bursts) that are long enough.

    clear minAcceptableLength threshold

        %% plot of thresholds

        ax1 = subplot (4,1,1);
        plot(time,fz_fp2,'k'); xlabel('Time (s)'); ylabel('vGRF');
title ('Force data black=plate1 blue=plate2');
        hold on
        plot(time,fz_fp1,'r');
        hold off

        ax2 = subplot (4,1,2);
        plot(time,emg_le_VM,'r'); xlabel('Time (s)');
ylabel('Amplitude'); title ('EMG activity (VM=red, VL=blue)');
%CHANGED
        hold on
        plot(time,emg_le_VL,'b');  %CHANGED
        hold off

        ax3 = subplot (4,1,3);
```

```
        plot(time,bwlabel(isLongEnoughVM),'r'); xlabel('Time (s)');
ylabel('Amplitude'); title ('VM onsets');  % CHANGED

        ax4 = subplot (4,1,4);
        plot(time,bwlabel(isLongEnoughVL),'b'); xlabel('Time (s)');
ylabel('Amplitude'); title ('VL onsets');  % CHANGED


        threshold_step_time = (threshold_step-1)/Fs;  %CHANGED
        %
        for i = 1:length(threshold_step_time)  %CHANGED
            xline(ax1, threshold_step_time(i))  %CHANGED
            xline(ax2, threshold_step_time(i))  %CHANGED
            xline(ax3, threshold_step_time(i))  %CHANGED
            xline(ax4, threshold_step_time(i))
        end


        %% time points of step start, vm onset and vl onset

        step_onset = threshold_step;
        t_act_VM = zeros(length(threshold_step),1);
        t_act_VL = zeros(length(threshold_step),1);


        for i = 1:length(step_onset)

            if bwlabel(isLongEnoughVM(step_onset(i))) == 0     % if
the VM signal is not activated yet
                t_act_VM(i) = find( bwlabel(isLongEnoughVM(
step_onset(i):end )>0), 1, "first" ) + step_onset(i) -1;   % scans
forward to catch the trigger point (safety factor is already included
in FP1_onset)

            else     % if it is already activated
                t_act_VM(i) = find( bwlabel(isLongEnoughVM(
1:step_onset(i) )<1), 1, "last" ) + 1;         % scans backwardsto
catch the trigger point
            end

            %
            if bwlabel(isLongEnoughVL(step_onset(i))) == 0
                t_act_VL(i) = find( bwlabel(isLongEnoughVL(
step_onset(i):end )>0), 1, "first") + step_onset(i) -1;
            else
                t_act_VL(i) = find( bwlabel(isLongEnoughVL(
1:step_onset(i) )<1), 1, "last") + 1;
            end
        end
        %%
        % sample point to time (ms)
        time_onset = round(1000*(step_onset)/Fs);
        time_act_VM = round(1000*(t_act_VM)/Fs);
        time_act_VL = round(1000*(t_act_VL)/Fs);

        VMVL_delay = time_act_VM - time_act_VL;

        % shown in the table
        step_num = [1:length(threshold_step)]';
```

```
        % T = table(step_num, step_onset, t_act_VM,
t_act_VL,'VariableNames',{'Step';'Step_Onset';'VM_Nearest_Act';'VL_Nea
rest_Act'});

        currentSDrow(1:length(threshold_step)) = currentSD;
        currentSDrow = currentSDrow';

        currentTIMErow(1:length(threshold_step)) = TimeWindow;
        currentTIMErow = currentTIMErow';

        T_msec = table(currentSDrow, currentTIMErow, step_num,
time_onset, time_act_VM, time_act_VL, VMVL_delay,...

'VariableNames',{'currentSD';'currentTime';'Step';'Step_Onset';'VM_Nea
rest_Act';'VL_Nearest_Act';'VM_VL_Delay'});

        % you can copy to Excell
        % C = table2array (T(:,2:end));
        % C_msec = table2array (T_msec(:,2:end));
        % C_sec = C_msec/1000;

        output = [output;T_msec];

clear time_onset time_act_VM time_act_VL VMVL_delay step_num
currentSDrow currentTIMErow T_msec isLongEnoughVL isLongEnoughVM
    end
end
```

5.2 VM-VL timing script

```
%% Don't forget to change numbers on line 32 and 34

%% set-up
clc; clear all; close all;
%% raw data
filename=uigetfile();



%% set parameters for conditions
startSD = 1;
endSD = 15;
startTime = 0.025;
endTime = 0.1;
stepTime = 0.025;

%% run processing
% what conditions - dbl threshold / filtering
[output] = VMVL_processing(filename, startSD, endSD, startTime,
endTime, stepTime);


%% participant and session
name_split = strsplit(filename, "_");

output.participant = repmat(name_split{1},size(output,1),1);
output.session = repmat(name_split{2}, size(output,1),1);

output = movevars(output,{'participant','session'},'Before',1);
```

```
%% save matlab data file
% particpant name and session
PH11_S1 = output; % change numbers for P (participant) and S (Session)

save('destination_from_ones_PC.mat','P?_S?','-append') % change
numbers for P and S
```

5.3 Biceps Femoris excitation amplitude in during triple-hop

```
clc; clear all; close all;
%% Getting data
data =load('filename'); % to load the file
% must check that channels used during session are the same here:

BF= data.EMG.Channel22.value;
Fs =data.EMG.Channel22.Rate; % to compensate for any Fs problems in
initial sessions in healthy participants
%figure (1);
%subplot (3,1,1),
% plot(BF,'g'); title ('EMG signal'); xlabel ('time (s)'); ylabel
('Amplitude (mV)');

%% raw data (Force):
FP1=data.Force.F1.value; % data_from_ForcePlate1
FP2=data.Force.F2.value; % data_from_ForcePlate1
N1=length(FP1);
N2=length(FP2);
T=1/Fs;

%fx_fp1=FP1(:,1);
%fy_fp1=FP1(:,2);
fz_fp1=FP1(:,3);

%fx_fp2=FP2(:,1);
%fy_fp2=FP2(:,2);
fz_fp2=FP2(:,3);

%% filter (Force):
% As I am using force only for timing, I will use raw data (10n to
avoid noise)
%% raw data (EMG)

L1=length(BF); % data points
t=(0:L1-1)/Fs; % freq into time

%% New filter (since we have higher freq (2000, and Bley had 1000,
band-pass chosen is higher than Bley's)
% Bandpass
order = 4;
HP = 20;
if Fs == 500   % some data collection samples were collected at 500Hz
Fs, so this part is written here for this purpose
    Upper = 250;
else
    Upper = 500;
end
% Linear envelope
fco=50; %cut off frequncy 50Hz
BPfreq=[HP Upper];
[b,a]= butter(order/2,(BPfreq/Fs)); % (a & b with band pass fillter
formula)
```

```
filtered_Data_BF=filtfilt(b,a,BF);  % filtered data

% Rectification
emg_rec_BF=abs(filtered_Data_BF);

%% Find window of stance
bodymass = ? ; %enter bodyweight
BW = bodymass * 9.81;

% Plot force data and select just after take-off
figure (9);
subplot (3,1,1); plot(fz_fp1,'b');
title('Force Plate_1'); xlabel('Time (s)'); ylabel('fz (N)');
subplot (3,1,2); plot(fz_fp2,'b');
title('Force Plate_2'); xlabel('Time (s)'); ylabel('fz (N)');
subplot (3,1,3)
plot(emg_rec_BF,'r'); xlabel('Time (s)'); ylabel('Amplitude'); title
('Low pas Filter'); % Plot against row number NOT time

% Find take-off
threshold = 10; % value which is defined as being off (10 to 0 N
recommened by Tirosh et al. 2003) I used 10 to also avoid noise at the
end of the recording

% if FORCE PLATE 1 was used:
passing_BW_time=find(fz_fp1 >= BW, 1, 'first' ); % find first time grf
crosses BW
landing=find(fz_fp1 (1:passing_BW_time)<= threshold, 1, 'last' ) + 1;
% find "first" point 10 n happened (touchdown), I used + 1 to take the
next sample as I am using <=
take_off=find(fz_fp1 (passing_BW_time:end)<= threshold, 1, 'first' ) +
passing_BW_time - 1 ; % find first point after BW that reaches 10 n

% if FORCE PLATE 2 was used:
% passing_BW_time=find(fz_fp2 >= BW, 1, 'first' ); % find first time
grf crosses BW
% landing=find(fz_fp2 (1:passing_BW_time)<= threshold, 1, 'last' ) +
1; % find "first" point 10 n happened (touchdown), I used + 1 to take
the next sample as I am using <=
% take_off=find(fz_fp2 (passing_BW_time:end)<= threshold, 1, 'first' )
+ passing_BW_time - 1 ; % find first point after BW that reaches 10 n

%% find mean BF excitation amplitude in stance
zRMS_BF = sqrt(mean(emg_rec_BF(landing:take_off).^2));
zmax_BF = max(emg_rec_BF(landing:take_off));
p_to_t_duration = (take_off - landing)*(1/Fs);
```

5.4 Biceps Femoris (MVC)

```
clc; clear all; close all;
%% raw data
data =load('filename'); % to load the file
% must check that channels used during session are the same here:

BF= data.EMG.Channel22.value;
Fs =data.EMG.Channel22.Rate; % to compensate for any Fs problems in
initial sessions in healthy participants
l1=length(BF); % data points
t=(0:l1-1)/Fs; % freq into time

figure (1);
```

```
%subplot (3,1,1),
plot(BF,'g'); title ('EMG signal'); xlabel ('time (s)'); ylabel
('Amplitute (mV)');

%% filtering
%% New filter (since we have higher freq (2000, and Bley had 1000,
band-pass chosen is higher than Bley's)
% Bandpass
order = 4;
HP = 20;
if Fs == 500   % some data collection samples were collected at 500Hz
Fs, so this part is written here for this purpose
    Upper = 250;
else
    Upper = 500;
end
% Linear envelope
fco=50; %cut off frequncy 50Hz
BPfreq=[HP Upper];
[b,a]= butter(order/2,(BPfreq/Fs)); % (a & b with band pass fillter
formula)
filtered_Data_BF=filtfilt(b,a,BF);  % filtered data

%% Rectification
emg_rec_BF=abs(filtered_Data_BF);
% select region for MVC
plot(emg_rec_BF); title('Select before and after the MVC')
[MVC, ~] = ginput(2);

peak_BF = max(movmean(emg_rec_BF(MVC(1):MVC(2)),300));
```

5.5 Torque and rate of torque development function

```
function [BIODEX, filename] = importbiodex(filename, startRow, endRow)
%IMPORTFILE Import numeric data from a text file as a matrix.
[file, pathname] = uigetfile('*.*', 'Pick your BIODEX file');
[~,filename,extension] = fileparts(file);

%% Initialize variables.
delimiter = '\t';
if nargin<=2
    startRow = 2;
    endRow = inf;
end

%% Format for each line of text:
formatSpec = '%f%f%f%f%[^\n\r]';

%% Open the text file.
fileID = fopen([pathname,'/',filename,extension],'r');

%% Read columns of data according to the format.
% This call is based on the structure of the file used to generate
this code. If an error occurs for a different file, try regenerating
the code
% from the Import Tool.
dataArray = textscan(fileID, formatSpec, endRow(1)-startRow(1)+1,
'Delimiter', delimiter, 'TextType', 'string', 'EmptyValue', NaN,
'HeaderLines', startRow(1)-1, 'ReturnOnError', false, 'EndOfLine',
'\r\n');
for block=2:length(startRow)
    frewind(fileID);
```

```
    dataArrayBlock = textscan(fileID, formatSpec, endRow(block)-
startRow(block)+1, 'Delimiter', delimiter, 'TextType', 'string',
'EmptyValue', NaN, 'HeaderLines', startRow(block)-1, 'ReturnOnError',
false, 'EndOfLine', '\r\n');
    for col=1:length(dataArray)
        dataArray{col} = [dataArray{col};dataArrayBlock{col}];
    end
end

%% Close the text file.
fclose(fileID);

%% Create output variable
BIODEX = [dataArray{1:end-1}];
BIODEX = resample(BIODEX,2000,2000);
%% Filter (Based on residual analysis at QMUL labs)
fs = 2000;
order = 4;
LPfreq = 14;
[bl,al] = butter(order/2,LPfreq/fs,'low');

for i=2:4
    BIODEX(:,i) = filtfilt(bl,al,BIODEX(:,i));
end
%% Convert
BIODEX(:,2) = ((BIODEX(:,2)*1000)/9.8)*1.356;
BIODEX(:,3) = ((BIODEX(:,3)*1000)/9.8);
BIODEX(:,4) = ((BIODEX(:,4)*1000)/29.2);
```

5.6 Torque and rate of torque development script

```
clear; close all; clc;

%% Openening file
BIODEX= importbiodex();

Fs = 2000; % sample frequency you used during data collection
Force = BIODEX(:,2);
if abs(max(Force)) < abs(min(Force)) % check direction of contraction
    Force = Force*(-1);
end

%% Define time
time = [0:(length(Force)-1)]/Fs; % define and convert time from
milliseconds to seconds

%% Plot Time x Torque
figure('color','w');
plot(Force); title('Select where zero is and after end of
contraction')
xlabel('Time (frames)');
ylabel('Torque (Nm)');
[Tclicks, ~] = ginput(2);

x0=Tclicks(1); % start of baseline
x1=Tclicks(2); % end of contraction - just needs to be after the peak

BL_mean = mean(Force(x0:x0+0.01*Fs)); % change window if needed from
200ms
% BL_SD = std(Force(x0:x0+0.2*Fs));
Torque = Force-BL_mean;
```

```
PeakT = max(Torque(x0:x1));
PeakT_time = find(Torque == max(Torque));

%% Calculate time points
Onset_twopercent = find(Torque(1:PeakT_time) < 0.02*PeakT,1,'last')+1;


%% Calculate RTD to percetanges of peak
for i = 1:3 % using 30, 60 and 90% of peak
    Torque_BL = Torque(Onset_twopercent);
    Torque_time(i) = find(Torque > PeakT*(i*0.3),1,'first'); % 0.3x1=
30% etc...
    RTD_percentage(i) = (Torque(Torque_time(i))-
Torque_BL)/((Torque_time(i) - Onset_twopercent)/Fs);
    clear Torque_BL
end

%% second method based on fixed time windows (Absolute RTD)

% Window times
RTD_window = [0.025, 0.05, 0.075, 0.10, 0.125, 0.15, 0.175, 0.2];
no_SD = 5;
% Onset_abs = find(Torque(1:PeakT_time) < (no_SD * BL_SD),1,'last')+1;
Onset_abs = find(Torque(1:PeakT_time) < 7.5, 1,'last')+1;
for i=1:length(RTD_window)
    window_end = Onset_abs+RTD_window(i)*Fs;
    RTD_time(i) = (Torque(window_end)-
Torque(Onset_abs))/RTD_window(i);
end

%% Single variable for copying
alldata_output = [RTD_percentage, RTD_time, PeakT, PeakT_time,
Onset_twopercent, Onset_abs];

%% Plot output
figure('color','w');
plot(time,Torque); title('points show 2% of peak (onset), 30%, 60%,
and 90% (black circles) of peak (red)')
xlabel('Time (s)');
ylabel('Torque (Nm)'); hold on

plot(time(Torque_time(1)),Torque(Torque_time(1)),'ok'); % plot peak
torque, 'ok' means circle it with black
plot(time(Torque_time(2)),Torque(Torque_time(2)),'ok');
plot(time(Torque_time(3)),Torque(Torque_time(3)),'ok');

plot(time(Onset_twopercent),Torque(Onset_twopercent),'or');
plot(time(PeakT_time), Torque(PeakT_time), 'or');

plot(time(Onset_abs(1)),Torque(Onset_abs(1)),'ob'); % plot abs onset
```

6 Appendix of Chapter 6

6.1 VM-VL excitation onset data

Individuals' data tables cannot be added to the appendix as they are too large, but available in attached excel sheet.

6.1.1 Within-session (VM-VL timing)

A		within session reliability (PFP n=14) (n=13 from SD8)										Reliability scoring (ICC-Two-way mixed, absolute agreement, single measures, power 95%)					
thresholds		Rep 1		Rep 2		Rep 3		Rep 4		Rep 5							
SD	ime-windov	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
SD1	25ms	-31.57	110.19	-29.07	162.48	-180.21	303.49	-300.36	529.13	-8.86	130.38	-0.061	-0.144	0.139	315.09	-193.25	873.38
SD1	50ms	-23.50	107.64	-24.29	165.58	-180.21	303.49	-300.36	529.13	-8.86	130.38	-0.054	-0.139	0.150	314.90	-202.08	872.87
SD1	75ms	-23.50	107.64	-18.29	167.96	-180.71	303.31	-305.93	525.97	-8.86	130.38	-0.052	-0.137	0.151	314.89	-216.11	872.82
SD1	100ms	-15.79	104.00	-18.29	167.96	-187.36	299.48	-305.93	525.97	-8.86	130.38	-0.049	-0.134	0.155	314.27	-213.09	871.11
SD2	25ms	-105.43	168.98	-35.64	181.86	-121.64	195.63	-99.93	157.38	-20.86	154.72	0.424	0.194	0.700	130.71	-572.76	362.30
SD2	50ms	-90.14	171.19	-37.86	181.34	-119.79	196.31	-105.43	154.06	-17.93	154.12	0.430	0.200	0.705	129.69	-567.52	359.47
SD2	75ms	-90.14	171.19	-31.86	180.80	-124.64	192.65	-105.43	154.06	-17.93	154.12	0.432	0.202	0.706	129.21	-546.42	358.14
SD2	100ms	-90.14	171.19	-39.50	176.23	-124.64	192.65	-105.43	154.06	-17.93	154.12	0.431	0.201	0.705	128.37	-599.84	355.83
SD3	25ms	-43.79	165.65	-24.50	74.81	-57.79	127.34	-69.79	138.33	-23.86	140.97	0.312	0.090	0.615	108.02	163.98	299.43
SD3	50ms	-38.14	166.26	-30.79	76.71	-61.71	124.79	-72.14	134.28	-23.86	140.97	0.306	0.086	0.610	107.78	58.44	298.76
SD3	75ms	-38.14	166.26	-24.86	74.72	-61.71	124.79	-72.14	134.28	-23.86	140.97	0.313	0.092	0.616	107.19	66.37	297.10
SD3	100ms	-30.14	168.94	-43.14	79.45	-61.71	124.79	-72.14	134.28	-23.86	140.97	0.293	0.075	0.599	109.58	44.81	303.73
SD4	25ms	-52.21	150.39	-9.57	88.46	-39.21	52.24	-78.79	167.75	-45.57	106.46	0.173	-0.012	0.480	108.33	-67.73	300.28
SD4	50ms	-52.21	150.39	-15.86	91.19	-44.50	53.28	-84.29	163.49	-45.57	106.46	0.156	-0.024	0.463	108.77	-110.27	301.50
SD4	75ms	-52.21	150.39	-18.57	98.62	-38.36	52.96	-84.29	163.49	-51.71	108.15	0.162	-0.020	0.469	109.58	-89.14	303.74
SD4	100ms	-44.36	153.97	-18.57	98.62	-38.36	52.96	-84.29	163.49	-51.71	108.15	0.146	-0.032	0.452	111.41	-93.92	308.81
SD5	25ms	-52.50	149.48	-9.29	62.90	-41.50	52.62	-43.71	123.51	-37.00	66.37	0.497	0.260	0.753	68.76	-16.88	190.59
SD5	50ms	-52.50	149.48	-15.64	66.91	-43.71	54.79	-49.21	119.47	-42.36	70.08	0.472	0.234	0.737	70.47	-58.82	195.34
SD5	75ms	-52.50	149.48	-13.07	64.21	-37.50	54.31	-49.21	119.47	-42.36	70.08	0.497	0.260	0.753	68.59	-54.56	190.13
SD5	100ms	-44.64	152.98	-13.07	64.21	-37.50	54.31	-49.21	119.47	-42.36	70.08	0.462	0.224	0.730	71.57	-59.12	198.37
SD6	25ms	-75.36	152.56	-8.21	59.68	-7.71	115.62	-45.29	115.43	-42.64	84.75	0.194	0.006	0.500	98.75	81.49	273.71
SD6	50ms	-71.86	156.92	-22.64	70.22	-9.71	117.27	-50.79	111.01	-47.86	87.31	0.206	0.012	0.514	99.25	-34.19	275.10
SD6	75ms	-71.86	156.92	-12.00	61.14	-3.50	115.14	-50.79	111.01	-47.86	87.31	0.204	0.013	0.510	98.80	-37.92	273.86
SD6	100ms	-64.00	158.95	0.93	95.17	2.86	128.14	-50.79	111.01	-39.00	85.59	0.224	0.029	0.531	104.28	27.55	289.05
SD7	25ms	-57.29	98.95	-13.29	63.49	-12.93	107.43	-48.14	121.45	-43.43	77.22	0.180	-0.007	0.488	86.03	-58.54	238.46
SD7	50ms	-57.57	105.68	-16.64	64.54	-14.93	109.16	-53.57	117.20	-43.43	77.22	0.219	0.021	0.528	84.66	-46.49	234.67
SD7	75ms	-57.57	105.68	-8.43	60.88	-2.43	116.41	-53.57	117.20	-43.43	77.22	0.243	0.043	0.548	85.29	-65.62	236.41
SD7	100ms	-49.79	107.34	4.43	94.26	-2.43	116.41	-53.57	117.20	-41.93	91.80	0.190	0.004	0.496	95.19	-32.28	263.86
SD8	25ms	-52.00	107.78	-17.62	55.72	-2.38	108.65	-33.69	107.10	-22.38	87.68	0.247	0.034	0.570	81.61	67.73	226.22
SD8	50ms	-52.31	114.54	-11.62	57.59	-11.77	111.40	-39.54	102.71	-22.38	87.68	0.291	0.067	0.610	80.28	80.55	222.52
SD8	75ms	-56.92	113.82	-11.62	57.59	1.54	118.31	-39.54	102.71	-22.38	87.68	0.300	0.078	0.616	81.66	56.27	226.34
SD8	100ms	-48.54	115.34	2.15	80.53	1.54	118.31	-39.54	102.71	-30.38	104.93	0.231	0.025	0.554	91.25	54.52	252.93
SD9	25ms	-15.69	97.36	-37.08	54.25	-6.46	107.94	-37.92	105.39	-23.85	58.23	0.332	0.099	0.645	70.23	47.22	194.66
SD9	50ms	-16.00	104.95	-30.92	54.31	-13.54	108.93	-40.77	101.21	-23.85	58.23	0.371	0.131	0.676	68.69	62.08	190.40
SD9	75ms	-20.62	105.94	-30.92	54.31	-4.85	108.24	-40.77	101.21	-23.85	58.23	0.382	0.142	0.684	68.33	38.20	189.39
SD9	100ms	-20.62	105.94	-17.23	81.43	-4.85	108.24	-25.62	110.57	-21.15	58.58	0.453	0.204	0.736	68.31	34.21	189.34
SD10	25ms	-11.92	75.26	-2.38	106.86	-29.62	49.77	-48.46	109.00	-16.62	47.66	0.193	-0.004	0.516	72.87	81.97	201.98
SD10	50ms	-16.69	86.30	1.31	105.69	-32.92	48.62	-44.69	111.48	-16.62	47.66	0.211	0.009	0.535	74.00	73.18	205.13
SD10	75ms	-16.69	86.30	1.31	105.69	-24.23	50.76	-39.23	121.17	-17.85	47.60	0.227	0.018	0.553	75.25	50.98	208.58
SD10	100ms	-16.69	86.30	14.85	117.64	-24.23	50.76	-48.08	106.87	-17.85	47.60	0.260	0.049	0.579	74.26	49.28	205.83
SD11	25ms	-6.38	91.49	0.00	107.57	-38.00	40.11	-48.77	109.22	-39.31	91.23	0.058	-0.092	0.359	88.02	-133.77	243.97
SD11	50ms	-9.62	100.98	15.77	117.50	-38.00	40.11	-45.00	111.68	-44.92	92.90	0.142	-0.034	0.458	89.52	-145.88	248.14
SD11	75ms	-9.62	100.98	15.77	117.50	-24.69	50.78	-39.62	121.21	-46.85	92.17	0.188	-0.005	0.509	89.40	-168.64	247.79
SD11	100ms	-9.62	100.98	15.77	117.50	-24.69	50.78	-48.46	106.97	-46.85	92.17	0.153	-0.027	0.470	88.81	-167.83	246.17
SD12	25ms	-4.77	49.15	2.46	103.01	-40.15	42.43	-57.92	98.92	-33.00	86.95	-0.017	-0.131	0.243	81.59	-11.79	226.15
SD12	50ms	-0.85	64.00	21.00	111.73	-36.54	59.91	-54.08	102.03	-36.15	89.61	0.106	-0.052	0.409	84.56	-43.36	234.38
SD12	75ms	4.08	60.70	21.00	111.73	-29.54	58.57	-54.08	106.40	-29.92	91.03	0.169	-0.011	0.483	81.94	-22.10	227.12
SD12	100ms	4.08	60.70	21.00	111.73	-29.54	58.57	-54.08	106.40	-29.92	91.03	0.169	-0.011	0.483	81.94	-22.10	227.12
SD13	25ms	-9.62	54.74	-5.46	82.79	-43.62	48.97	-57.92	98.74	-10.31	34.86	0.128	-0.038	0.435	64.78	740.27	179.56
SD13	50ms	-1.92	63.52	13.08	91.29	-37.31	60.74	-46.23	106.74	-2.08	63.67	0.329	0.107	0.636	65.71	701.07	182.14
SD13	75ms	2.92	60.39	8.69	95.23	-30.31	59.52	-51.62	106.58	-7.46	42.14	0.279	0.069	0.593	65.89	733.17	182.64
SD13	100ms	2.92	60.39	8.69	95.23	-30.31	59.52	-51.62	106.58	-7.46	42.14	0.279	0.069	0.593	65.89	733.17	182.64
SD14	25ms	-13.38	49.92	-9.77	69.95	-42.62	49.82	-33.77	70.48	-12.46	34.49	0.327	0.102	0.638	46.28	50.28	128.28
SD14	50ms	-5.62	57.15	8.85	80.71	-36.38	61.13	-29.92	79.10	-4.31	63.91	0.490	0.249	0.756	49.30	10.97	136.66
SD14	75ms	-11.31	70.68	4.31	85.10	-29.31	59.85	-34.46	74.65	-9.69	42.20	0.465	0.223	0.741	49.32	48.71	136.70
SD14	100ms	-21.62	78.97	-8.38	71.48	-35.69	49.05	-34.46	74.65	-9.69	42.20	0.398	0.159	0.694	49.65	60.60	137.63
SD15	25ms	-13.77	49.84	1.62	83.92	-37.69	49.79	-23.23	30.23	-12.92	34.92	0.384	0.151	0.682	41.69	56.69	115.56
SD15	50ms	-6.00	57.07	-8.38	71.77	-31.46	60.57	-16.62	41.59	-7.85	65.85	0.442	0.198	0.726	44.14	73.24	122.36
SD15	75ms	-11.54	70.83	-8.38	71.77	-30.92	48.13	-21.23	34.21	-13.23	44.23	0.435	0.190	0.722	41.13	111.15	114.01
SD15	100ms	-22.00	79.18	-14.69	73.60	-30.92	48.13	-21.23	34.21	-13.23	44.23	0.394	0.150	0.693	44.39	37.83	123.05

B		within session reliability (Uninjured n=11)										Reliability scoring (ICC-Two-way mixed, absolute agreement, single measures, power 95%)					
thresholds		Rep 1		Rep 2		Rep 3		Rep 4		Rep 5							
SD	ime-windov	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
SD1	25ms	-87.55	410.64	-45.00	164.44	-63.36	293.90	-108.09	187.06	-62.45	230.87	0.482	0.210	0.778	189.16	-123.16	524.32
SD1	50ms	-91.64	409.42	-45.00	164.44	-63.36	293.90	-105.27	188.06	-62.45	230.87	0.482	0.210	0.779	188.98	103.71	523.84
SD1	75ms	-91.64	409.42	-45.00	164.44	-63.36	293.90	-105.27	188.06	-62.45	230.87	0.482	0.210	0.779	188.98	103.71	523.84
SD1	100ms	-91.64	409.42	-45.00	164.44	-63.36	293.90	-105.27	188.06	-70.45	227.39	0.481	0.209	0.778	188.73	3.67	523.12
SD2	25ms	-42.82	163.04	-13.64	103.11	-58.91	154.54	-71.64	221.46	-110.00	220.31	0.493	0.228	0.783	124.19	-85.64	344.23
SD2	50ms	-42.82	163.04	-13.64	103.11	-58.91	154.54	-76.00	231.12	-114.27	217.76	0.486	0.222	0.778	126.51	-46.44	350.66
SD2	75ms	-42.82	163.04	-13.64	103.11	-58.91	154.54	-76.00	231.12	-114.27	217.76	0.486	0.222	0.778	126.51	-46.44	350.66
SD2	100ms	-42.82	163.04	-13.64	103.11	-58.91	154.54	-76.00	231.12	-114.27	217.76	0.486	0.222	0.778	126.51	-46.44	350.66
SD3	25ms	-52.09	166.90	10.73	70.05	-23.00	71.09	-65.45	167.82	-85.36	172.05	0.354	0.107	0.689	110.36	-59.75	305.91
SD3	50ms	-51.82	167.07	10.73	70.05	-23.00	71.09	-65.45	167.82	-89.18	174.66	0.350	0.105	0.686	111.42	-63.21	308.85
SD3	75ms	-51.82	167.07	10.73	70.05	-23.00	71.09	-65.45	167.82	-89.18	174.66	0.350	0.105	0.686	111.42	-63.21	308.85
SD3	100ms	-51.82	167.07	10.73	70.05	-23.00	71.09	-65.45	167.82	-89.18	174.66	0.350	0.105	0.686	111.42	-63.21	308.85
SD4	25ms	-15.36	47.37	28.91	91.58	-24.82	69.19	-16.55	81.50	-63.36	74.33	0.243	0.036	0.587	67.32	-86.75	186.60
SD4	50ms	-11.55	50.25	28.91	91.58	-24.82	69.19	-16.55	81.50	-67.36	81.59	0.232	0.029	0.576	69.74	-85.83	193.31
SD4	75ms	-11.55	50.25	28.91	91.58	-24.82	69.19	-16.55	81.50	-67.36	81.59	0.232	0.029	0.576	69.74	-85.83	193.31
SD4	100ms	-11.55	50.25	28.91	91.58	-24.82	69.19	-16.55	81.50	-67.36	81.59	0.232	0.029	0.576	69.74	-85.83	193.31
SD5	25ms	-24.82	49.06	-2.00	32.28	-15.64	60.59	-19.09	63.57	-57.00	78.39	0.218	0.010	0.569	52.65	-174.51	145.93
SD5	50ms	-24.82	49.06	-2.00	32.28	-15.64	60.59	-19.09	63.57	-57.00	78.39	0.218	0.010	0.569	52.65	-174.51	145.93
SD5	75ms	-24.82	49.06	-2.00	32.28	-15.64	60.59	-25.91	58.53	-57.00	78.39	0.225	0.015	0.576	51.52	-138.36	142.81
SD5	100ms	-24.82	49.06	-2.00	32.28	-15.64	60.59	-25.91	58.53	-57.00	78.39	0.225	0.015	0.576	51.52	-138.36	142.81
SD6	25ms	-28.27	47.88	-7.00	34.31	-12.55	61.83	-8.36	24.08	-27.82	42.56	0.309	0.068	0.656	36.07	148.58	99.97
SD6	50ms	-28.27	47.88	-7.00	34.31	-20.82	62.44	-17.27	22.30	-27.82	42.56	0.314	0.069	0.661	35.67	174.97	98.87
SD6	75ms	-28.27	47.88	-7.00	34.31	-20.82	62.44	-17.27	22.30	-22.36	44.90	0.346	0.093	0.686	35.07	-45.27	97.21
SD6	100ms	-28.27	47.88	-7.00	34.31	-20.82	62.44	-17.27	22.30	-29.82	53.24	0.352	0.100	0.690	36.46	-48.14	101.05
SD7	25ms	-29.00	47.76	-12.91	34.49	-6.09	75.76	-9.09	23.93	-18.18	35.91	0.301	0.058	0.651	38.47	-64.43	106.62
SD7	50ms	-31.82	44.05	-12.91	34.49	-14.36	76.81	-17.91	22.45	-18.18	35.91	0.304	0.058	0.654	37.77	-33.05	104.70
SD7	75ms	-37.45	47.62	-12.91	34.49	-14.36	76.81	-22.73	29.79	-19.64	36.92	0.339	0.089	0.680	38.37	-33.67	106.37
SD7	100ms	-37.45	47.62	-12.91	34.49	-14.36	76.81	-22.73	29.79	-19.64	36.92	0.339	0.089	0.680	38.37	-33.67	106.37
SD8	25ms	-28.82	35.74	-12.91	34.56	-9.91	65.80	-16.82	31.08	-21.18	35.34	0.421	0.158	0.739	31.51	-60.51	87.34
SD8	50ms	-28.82	35.74	-15.82	38.39	-18.09	66.21	-26.55	32.64	-26.18	44.29	0.428	0.161	0.745	33.04	-36.27	91.59
SD8	75ms	-34.55	40.50	-15.82	38.39	-18.09	66.21	-26.55	32.64	-20.18	34.24	0.441	0.176	0.752	32.15	-33.96	89.13
SD8	100ms	-34.55	40.50	-15.82	38.39	-18.09	66.21	-26.55	32.64	-20.18	34.24	0.441	0.176	0.752	32.15	-33.96	89.13
SD9	25ms	-21.73	28.27	-16.55	38.29	-7.73	46.12	-15.82	30.55	-22.73	33.95	0.581	0.319	0.832	22.69	-49.62	62.89
SD9	50ms	-27.45	35.20	-16.55	38.29	-15.82	46.83	-25.64	28.69	-27.55	42.84	0.586	0.324	0.835	24.31	-24.74	67.39
SD9	75ms	-27.45	35.20	-16.55	38.29	-15.82	46.83	-25.64	28.69	-15.45	36.67	0.496	0.228	0.786	25.95	-29.32	71.94
SD9	100ms	-27.45	35.20	-16.55	38.29	-15.82	46.83	-25.64	28.69	-15.45	36.67	0.496	0.228	0.786	25.95	-29.32	71.94
SD10	25ms	-21.09	28.97	-21.55	37.29	-9.55	48.00	-21.18	25.74	-18.45	31.19	0.568	0.303	0.826	22.42	-35.57	62.15
SD10	50ms	-27.00	35.87	-21.55	37.29	-17.64	47.99	-26.55	28.49	-27.55	35.74	0.621	0.362	0.853	22.40	-20.32	62.10
SD10	75ms	-27.00	35.87	-21.55	37.29	-17.64	47.99	-26.55	28.49	-21.45	31.98	0.573	0.306	0.829	23.33	-22.70	64.67
SD10	100ms	-27.00	35.87	-21.55	37.29	-17.64	47.99	-26.55	28.49	-21.45	31.98	0.573	0.306	0.829	23.33	-22.70	64.67
SD11	25ms	-22.36	28.33	-18.91	33.16	-22.27	37.20	-21.82	25.27	-18.45	32.44	0.585	0.317	0.835	19.59	166.60	54.30
SD11	50ms	-28.27	34.94	-18.91	33.16	-22.27	37.20	-27.18	28.14	-27.64	37.25	0.675	0.431	0.878	18.94	171.80	52.49
SD11	75ms	-28.27	34.94	-18.91	33.16	-22.27	37.20	-27.18	28.14	-21.64	33.25	0.626	0.368	0.855	19.82	169.69	54.93
SD11	100ms	-28.27	34.94	-18.91	33.16	-22.27	37.20	-27.18	28.14	-21.64	33.25	0.626	0.368	0.855	19.82	169.69	54.93
SD12	25ms	-18.82	29.66	-16.64	35.53	-17.73	30.73	-23.18	24.02	-21.82	33.80	0.615	0.354	0.850	18.57	-68.31	51.49
SD12	50ms	-24.73	30.68	-16.64	35.53	-21.64	37.28	-28.55	26.95	-26.64	37.98	0.666	0.420	0.874	19.03	-63.06	52.76
SD12	75ms	-24.73	30.68	-16.64	35.53	-21.64	37.28	-28.55	26.95	-20.73	33.85	0.634	0.380	0.859	19.40	-64.65	53.77
SD12	100ms	-24.73	30.68	-16.64	35.53	-21.64	37.28	-28.55	26.95	-20.73	33.85	0.634	0.380	0.859	19.40	-64.65	53.77
SD13	25ms	-13.45	27.48	-15.91	34.45	-18.18	27.75	-28.64	26.80	-20.55	34.53	0.557	0.294	0.819	19.79	-71.07	54.84
SD13	50ms	-19.45	29.46	-15.91	34.45	-22.27	35.22	-28.64	26.80	-25.73	38.93	0.632	0.379	0.858	19.60	-67.03	54.34
SD13	75ms	-19.45	29.46	-15.91	34.45	-27.91	44.12	-28.64	26.80	-20.00	34.53	0.575	0.312	0.829	21.82	-69.95	60.49
SD13	100ms	-19.45	29.46	-15.91	34.45	-27.91	44.12	-28.64	26.80	-20.00	34.53	0.575	0.312	0.829	21.82	-69.95	60.49
SD14	25ms	-12.73	27.47	-16.00	34.66	-18.55	27.51	-29.27	26.69	-18.55	34.98	0.538	0.275	0.808	20.30	-74.14	56.28
SD14	50ms	-18.64	29.49	-16.00	34.66	-22.64	35.11	-29.27	26.69	-20.73	34.80	0.607	0.349	0.846	19.71	-68.68	54.63
SD14	75ms	-18.64	29.49	-16.00	34.66	-28.36	44.03	-29.27	26.69	-20.73	34.80	0.585	0.324	0.834	21.63	-70.61	59.95
SD14	100ms	-18.64	29.49	-16.00	34.66	-28.36	44.03	-29.27	26.69	-20.73	34.80	0.585	0.324	0.834	21.63	-70.61	59.95
SD15	25ms	-10.82	29.95	-16.55	34.13	-25.64	34.40	-29.00	26.91	-18.00	35.28	0.529	0.267	0.803	21.80	-81.35	60.43
SD15	50ms	-12.82	37.94	-16.55	34.13	-25.64	34.40	-29.00	26.91	-20.45	35.07	0.602	0.345	0.842	20.91	-77.24	57.95
SD15	75ms	-7.27	32.67	-16.55	34.13	-31.55	43.10	-29.00	26.91	-20.45	35.07	0.568	0.310	0.824	22.75	-80.94	63.05
SD15	100ms	-7.27	32.67	-16.55	34.13	-31.55	43.10	-29.00	26.91	-20.45	35.07	0.568	0.310	0.824	22.75	-80.94	63.05

6.1.2 Test-retest (VM-VL timing)

A	test-retest reliability (PFP n=11) (n=10 from SD8)					Reliability scoring (ICC-Two-way mixed, absolute agreement, single measures, power 95%)					
thresholds		Session 1		Session 2							
SD	window	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
SD1	25ms	-82.65	109.58	-53.62	164.64	0.235	-0.439	0.721	120.07	49.51	332.83
SD1	50ms	-79.38	111.83	-57.18	166.90	0.208	-0.478	0.709	123.79	34.22	343.13
SD1	75ms	-79.40	111.82	-57.42	169.50	0.207	-0.480	0.709	125.18	34.88	346.99
SD1	100ms	-79.13	112.51	-57.42	169.50	0.215	-0.472	0.713	124.77	38.15	345.85
SD2	25ms	-60.20	138.51	-18.18	149.84	-0.013	-0.634	0.580	143.36	-35.33	397.38
SD2	50ms	-56.27	138.28	-16.80	150.04	-0.011	-0.638	0.582	143.02	-29.25	396.44
SD2	75ms	-55.98	137.99	-19.69	150.31	-0.029	-0.658	0.573	144.07	-31.82	399.34
SD2	100ms	-57.93	137.11	-19.69	150.31	-0.033	-0.657	0.569	144.07	11.25	399.34
SD3	25ms	-34.62	98.02	-67.73	117.71	-0.276	-0.809	0.392	120.93	-63.39	335.20
SD3	50ms	-36.53	96.98	-68.69	117.51	-0.312	-0.833	0.361	121.90	-56.77	337.89
SD3	75ms	-35.02	97.38	-63.36	129.13	-0.258	-0.813	0.411	126.23	-62.51	349.89
SD3	100ms	-37.64	96.63	-63.07	132.34	-0.263	-0.821	0.410	127.92	-48.94	354.57
SD4	25ms	-41.67	76.21	-43.89	74.34	-0.417	-0.927	0.286	87.46	-126.93	242.43
SD4	50ms	-46.20	74.19	-45.07	76.73	-0.464	-0.950	0.240	89.12	-58.76	247.02
SD4	75ms	-45.33	76.46	-41.85	86.81	-0.422	-0.929	0.281	95.22	-77.10	263.93
SD4	100ms	-43.33	75.32	-41.85	86.81	-0.440	-0.939	0.263	95.18	-75.65	263.82
SD5	25ms	-31.87	84.15	-22.89	59.47	0.000	-0.663	0.597	71.26	-90.91	197.52
SD5	50ms	-36.42	83.04	-18.05	73.87	0.151	-0.512	0.677	71.20	-78.42	197.36
SD5	75ms	-34.18	84.21	-20.76	71.00	0.093	-0.579	0.649	72.69	-86.10	201.47
SD5	100ms	-32.18	82.70	-20.76	71.00	0.072	-0.601	0.638	72.67	-84.54	201.44
SD6	25ms	-31.18	71.76	-24.71	53.75	-0.051	-0.703	0.566	63.52	-168.42	176.07
SD6	50ms	-36.85	74.54	-21.35	68.31	0.199	-0.472	0.702	62.85	-161.03	174.20
SD6	75ms	-32.56	73.36	-24.18	60.70	0.082	-0.597	0.645	63.09	-166.82	174.88
SD6	100ms	-25.65	79.65	-27.69	52.12	0.133	-0.564	0.674	61.17	-167.55	169.55
SD7	25ms	-30.13	60.27	-20.91	54.34	0.129	-0.551	0.669	52.44	-26.07	145.37
SD7	50ms	-32.96	62.77	-15.58	67.96	0.297	-0.354	0.748	54.05	-24.11	149.81
SD7	75ms	-27.69	65.57	-18.47	60.47	0.212	-0.476	0.712	54.80	-33.04	151.89
SD7	100ms	-24.29	65.80	-21.98	52.30	0.172	-0.528	0.694	52.79	-34.24	146.32
SD8	25ms	-23.02	63.26	-13.98	47.12	0.011	-0.691	0.630	54.19	-278.41	150.20
SD8	50ms	-23.74	65.26	-10.70	50.43	0.090	-0.613	0.669	54.52	-285.73	151.13
SD8	75ms	-21.48	67.53	-17.86	39.00	-0.147	-0.813	0.538	57.52	-286.47	159.43
SD8	100ms	-17.80	66.99	-17.86	39.00	-0.140	-0.812	0.543	56.96	-284.36	157.88
SD9	25ms	-19.48	60.60	-8.54	50.15	0.134	-0.582	0.693	50.65	393.10	140.40
SD9	50ms	-19.48	62.18	-7.40	52.55	0.194	-0.524	0.721	50.61	391.17	140.28
SD9	75ms	-18.42	63.06	-15.92	46.41	-0.091	-0.779	0.573	56.30	391.47	156.06
SD9	100ms	-10.22	72.33	-15.92	46.41	-0.012	-0.720	0.619	59.58	395.26	165.14
SD10	25ms	-17.68	48.74	-5.70	53.53	0.315	-0.389	0.775	41.55	-7.69	115.18
SD10	50ms	-16.80	49.99	-6.40	57.61	0.293	-0.428	0.767	44.37	9.08	122.99
SD10	75ms	-13.44	52.91	-13.40	51.11	-0.010	-0.724	0.621	50.89	0.07	141.05
SD10	100ms	-12.22	55.37	-15.50	51.08	0.024	-0.697	0.640	51.25	11.41	142.05
SD11	25ms	-23.74	44.66	2.16	67.33	0.243	-0.374	0.731	49.75	-74.60	137.89
SD11	50ms	-19.10	52.83	2.22	77.39	0.339	-0.327	0.781	53.18	-58.60	147.41
SD11	75ms	-14.74	58.87	-3.14	64.86	0.152	-0.569	0.702	55.78	-70.20	154.62
SD11	100ms	-17.04	53.51	-63.04	195.58	0.037	-0.623	0.635	138.89	-76.44	384.99
SD12	25ms	-24.86	31.53	-14.54	56.30	0.323	-0.383	0.779	36.80	-134.60	102.00
SD12	50ms	-15.28	42.81	-15.64	71.11	0.379	-0.362	0.805	45.02	-107.58	124.78
SD12	75ms	-9.16	48.06	-20.92	60.88	0.104	-0.604	0.677	50.85	-117.12	140.95
SD12	100ms	-9.16	48.06	-78.54	193.53	0.019	-0.566	0.609	140.43	-125.11	389.25
SD13	25ms	-21.40	31.44	-11.98	56.58	0.237	-0.483	0.742	39.14	-238.42	108.49
SD13	50ms	-6.86	52.05	-16.52	69.80	0.369	-0.351	0.800	47.77	-185.85	132.40
SD13	75ms	-6.32	45.55	-22.54	67.30	0.107	-0.579	0.675	53.44	-184.43	148.12
SD13	100ms	-6.32	45.55	-76.78	191.90	0.067	-0.519	0.635	135.69	-192.79	376.10
SD14	25ms	-18.08	34.17	-10.34	64.82	0.236	-0.499	0.743	44.22	-716.03	122.57
SD14	50ms	-4.16	51.18	-16.36	67.37	0.331	-0.382	0.783	47.90	-700.30	132.78
SD14	75ms	-6.30	45.64	-76.30	192.30	0.039	-0.546	0.619	137.92	-711.55	382.29
SD14	100ms	-13.94	39.69	-76.30	192.30	0.077	-0.536	0.646	133.42	-703.76	369.83
SD15	25ms	-9.84	31.40	-13.84	57.39	0.550	-0.120	0.868	30.24	-100.63	83.81
SD15	50ms	-3.34	37.08	-16.60	69.86	0.368	-0.327	0.797	43.61	-86.15	120.89
SD15	75ms	-5.96	27.36	-75.44	192.58	0.037	-0.545	0.617	135.95	-696.65	376.83
SD15	100ms	-8.68	30.24	-134.44	373.10	0.068	-0.532	0.639	256.39	-696.52	710.68

B		test-retest reliability (Uninjured n=10)				Reliability scoring (ICC-Two-way mixed, absolute agreement, single measures, power 95%)					
thresholds		Session 1		Session 2							
SD	window	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
SD1	25ms	-23.16	127.25	-120.04	319.68	0.243	-0.400	0.734	210.53	723.58	583.55
SD1	50ms	-23.44	127.13	-120.04	319.68	0.234	-0.410	0.730	211.72	579.56	586.86
SD1	75ms	-23.44	127.13	-121.14	319.79	0.229	-0.413	0.728	212.57	776.80	589.22
SD1	100ms	-25.20	126.76	-123.08	318.93	0.225	-0.416	0.726	212.59	766.88	589.26
SD2	25ms	-24.76	78.79	-93.22	156.45	0.214	-0.359	0.709	111.33	394.93	308.58
SD2	50ms	-26.66	81.34	-95.02	157.71	0.198	-0.378	0.701	113.79	-227.61	315.41
SD2	75ms	-26.66	81.34	-93.74	158.90	0.198	-0.384	0.703	114.26	-239.41	316.71
SD2	100ms	-26.66	81.34	-97.90	159.95	0.220	-0.349	0.711	113.75	-204.89	315.30
SD3	25ms	-21.18	67.20	-68.74	156.55	-0.205	-0.772	0.473	131.47	88.78	364.41
SD3	50ms	-21.96	67.96	-67.54	157.43	-0.208	-0.781	0.474	132.23	-87.27	366.52
SD3	75ms	-21.96	67.96	-67.86	156.47	-0.212	-0.782	0.470	131.83	-3610.82	365.42
SD3	100ms	-21.96	67.96	-72.66	154.12	-0.188	-0.750	0.482	129.50	-154.59	358.95
SD4	25ms	-12.78	46.97	-67.58	136.09	-0.014	-0.573	0.583	103.72	-81.63	287.48
SD4	50ms	-12.82	47.77	-68.34	137.42	-0.017	-0.575	0.581	104.98	174.46	291.00
SD4	75ms	-12.82	47.77	-65.48	136.51	-0.012	-0.582	0.587	103.76	175.38	287.60
SD4	100ms	-12.82	47.77	-65.28	134.86	0.019	-0.555	0.605	101.11	175.76	280.26
SD5	25ms	-18.68	34.11	-51.30	111.13	-0.064	-0.673	0.569	84.32	456.41	233.71
SD5	50ms	-18.68	34.11	-53.26	112.30	-0.067	-0.667	0.564	85.43	458.46	236.79
SD5	75ms	-20.18	33.95	-51.90	112.50	-0.085	-0.694	0.557	85.93	456.82	238.19
SD5	100ms	-20.18	33.95	-51.68	109.84	-0.044	-0.661	0.582	82.52	458.66	228.73
SD6	25ms	-11.14	23.83	-55.50	109.77	-0.001	-0.554	0.588	80.63	104.62	223.48
SD6	50ms	-14.92	24.75	-55.50	109.77	0.022	-0.556	0.608	79.30	-150.32	219.82
SD6	75ms	-13.72	25.89	-51.76	109.46	0.050	-0.547	0.628	77.81	-161.55	215.69
SD6	100ms	-15.36	28.14	-51.50	106.96	0.078	-0.529	0.645	75.23	-161.64	208.51
SD7	25ms	-10.14	27.79	-49.52	89.48	-0.039	-0.569	0.560	68.88	62.18	190.92
SD7	50ms	-14.52	28.17	-50.16	90.38	-0.030	-0.589	0.573	68.68	-96.49	190.36
SD7	75ms	-17.14	31.28	-46.98	85.81	0.163	-0.451	0.690	59.19	-107.43	164.06
SD7	100ms	-17.14	31.28	-45.18	85.97	0.152	-0.475	0.687	59.47	-109.36	164.85
SD8	25ms	-13.02	27.67	-33.20	57.04	-0.250	-0.782	0.433	50.14	-153.17	138.97
SD8	50ms	-18.70	31.01	-31.12	53.56	-0.180	-0.792	0.503	46.78	-95.72	129.68
SD8	75ms	-18.64	30.72	-31.66	49.75	-0.025	-0.674	0.600	41.30	-88.76	114.47
SD8	100ms	-18.64	30.72	-31.66	49.75	-0.025	-0.674	0.600	41.30	-88.76	114.47
SD9	25ms	-13.56	28.50	-33.20	56.66	-0.280	-0.806	0.410	50.69	248.47	140.49
SD9	50ms	-19.82	31.87	-29.78	51.41	-0.140	-0.780	0.534	44.79	280.49	124.14
SD9	75ms	-17.16	28.49	-30.28	47.63	-0.119	-0.736	0.539	41.03	284.24	113.74
SD9	100ms	-17.16	28.49	-30.28	47.63	-0.119	-0.736	0.539	41.03	284.24	113.74
SD10	25ms	-14.72	26.89	-35.42	55.15	-0.320	-0.818	0.373	50.03	-121.04	138.66
SD10	50ms	-20.98	31.00	-31.30	48.48	-0.082	-0.735	0.570	41.56	-92.97	115.20
SD10	75ms	-19.64	29.18	-33.18	47.74	-0.118	-0.732	0.540	41.37	-88.17	114.68
SD10	100ms	-19.64	29.18	-33.18	47.74	-0.118	-0.732	0.540	41.37	-88.17	114.68
SD11	25ms	-17.36	24.05	-35.42	53.41	-0.273	-0.802	0.416	46.67	-77.98	129.37
SD11	50ms	-21.86	29.09	-32.44	49.12	-0.118	-0.757	0.547	41.94	-74.81	116.24
SD11	75ms	-20.54	27.20	-34.34	48.20	-0.137	-0.742	0.526	41.31	-69.39	114.52
SD11	100ms	-20.54	27.20	-34.34	48.20	-0.137	-0.742	0.526	41.31	-69.39	114.52
SD12	25ms	-16.66	24.81	-34.80	53.29	-0.334	-0.839	0.367	47.94	-77.16	132.90
SD12	50ms	-21.06	29.13	-31.00	46.13	-0.252	-0.843	0.454	42.40	-66.88	117.53
SD12	75ms	-19.76	27.58	-34.14	45.68	-0.191	-0.768	0.485	40.88	-62.94	113.30
SD12	100ms	-19.76	27.58	-34.14	45.68	-0.191	-0.768	0.485	40.88	-62.94	113.30
SD13	25ms	-16.36	23.50	-34.42	50.03	-0.263	-0.787	0.421	44.00	-84.44	121.97
SD13	50ms	-19.72	27.80	-33.40	47.86	-0.153	-0.754	0.515	41.59	-78.09	115.28
SD13	75ms	-19.70	27.77	-106.84	267.96	-0.078	-0.659	0.553	198.02	-69.37	548.88
SD13	100ms	-19.70	27.77	-243.36	699.05	-0.032	-0.626	0.582	502.84	-69.08	1393.80
SD14	25ms	-16.04	23.29	-31.54	50.36	-0.307	-0.836	0.395	44.59	-79.95	123.60
SD14	50ms	-18.72	26.42	-33.04	46.86	-0.178	-0.761	0.495	40.97	-67.51	113.55
SD14	75ms	-19.98	28.14	-104.54	268.85	-0.082	-0.668	0.552	198.72	-66.14	550.82
SD14	100ms	-19.98	28.14	-241.06	700.07	-0.033	-0.629	0.582	503.47	-65.84	1395.56
SD15	25ms	-17.18	25.08	-30.96	47.01	-0.366	-0.878	0.349	43.65	-83.62	120.99
SD15	50ms	-18.16	27.91	-34.68	49.79	-0.202	-0.765	0.474	44.06	-567.10	122.13
SD15	75ms	-19.46	29.61	-243.62	706.33	-0.035	-0.629	0.581	508.63	-565.39	1409.86
SD15	100ms	-19.46	29.61	-458.54	1385.81	-0.018	-0.616	0.591	989.01	-565.28	2741.41

6.2 BF mean excitation amplitude

6.2.1 Participants data

	Session1							
	mvc				mean amp			
participants	rep1	rep2	rep3	**maxMVC**	rep1	rep2	rep3	**avMeanAMP/maxMVC**
PH1	129.10	110.13	117.36	129.10	3000.52	2972.51	3244.45	2379.93
PH2	172.79	169.96	175.86	175.86	142.34	176.21	201.07	98.49
PH3	229.35	271.60	300.68	300.68	297.52	307.17	306.61	101.03
PH4	195.42	182.34	166.48	195.42	153.81	167.03	135.87	77.90
PH5	78.56	93.81	106.42	106.42	96.44	88.71	91.13	86.54
PH6	231.80	235.32	193.16	235.32	226.52	166.62	163.68	78.87
PH7	442.48	408.59	408.03	442.48	593.42	616.28	527.42	130.86
PH8	316.18	270.25	290.66	316.18	383.09	315.13	270.01	102.07
PH9	732.44	792.65	781.44	792.65	523.63	455.17	468.89	60.88
PH10	302.71	279.24	263.41	302.71	320.62	252.19	276.24	93.50
PH11	248.00	251.48	264.37	264.37	348.23	311.65	349.44	127.26
PFP6	222.61	208.20	227.40	227.40	213.92	193.91	219.03	91.89
PFP7	165.38	166.55	145.97	166.55	212.74	127.56	135.72	95.27
PFP12	241.03	190.55	213.20	241.03	268.55	272.52	343.26	122.30
PFP16	271.76	268.39	299.58	299.58	374.85	393.69	406.12	130.70
PFP24	558.48	542.97	492.64	558.48	298.27	343.02	331.02	58.03
PFP29	670.27	671.26	721.98	721.98	424.49	416.05	529.13	63.24
PFP34	836.03	847.90	623.25	847.90	498.94	818.13	589.97	74.97
PFP41	431.76	394.53	385.21	431.76	441.99	530.21	525.31	115.61
PFP42	519.49	538.42	635.73	635.73	368.87	258.53	353.22	51.42
PFP44	468.18	458.30	501.60	501.60	489.39	414.89	336.92	82.48
PFP46	296.10	279.11	280.18	296.10	248.56	285.01	263.85	89.77
PFP47	378.64	282.00	279.13	378.64	342.81	273.49	451.71	94.02
PFP49	711.22	667.80	716.00	716.00	1103.85	953.10	873.13	136.41
PFP50	237.32	208.04	218.46	237.32	172.08	161.94	130.88	65.30

	Session2							
	mvc				mean amp			
participants	rep1	rep2	rep3	**maxMVC**	rep1	rep2	rep3	**avMeanAMP/maxMVC**
PH1	212.20	167.52	169.21	212.20	141.71	174.75	190.27	79.60
PH2	267.00	175.39	201.40	267.00	207.11	236.15	215.83	82.28
PH3	373.31	514.98	362.55	514.98	327.33	330.17	374.66	66.81
PH4	133.18	158.57	150.84	158.57	172.94	193.91	173.30	113.55
PH5	73.23	75.85	70.40	75.85	68.86	92.09	82.58	107.01
PH6	308.32	230.35	197.88	308.32	138.86	247.24	223.75	65.93
PH7	708.32	695.52	595.19	708.32	758.48	596.77	646.12	94.18
PH8	221.32	198.13	175.65	221.32	286.20	368.25	355.03	152.04
PH9								
PH10	244.20	294.77	246.20	294.77	298.97	316.94	234.83	96.20
PH11	254.68	255.37	260.43	260.43	307.16	390.16	427.16	143.93
PFP6	363.65	355.04	340.10	363.65	369.41	342.47	425.67	104.27
PFP7	268.93	260.92	189.97	268.93	123.24	150.96	160.43	53.87
PFP12	264.09	201.90	180.33	264.09	198.30	255.13	242.19	87.80
PFP16	288.89	356.66	311.06	356.66	336.41	374.29	313.03	95.68
PFP24	375.18	334.88	339.35	375.18	407.57	646.02	556.55	143.05
PFP29	841.77	791.08	979.55	979.55	379.62	397.85	406.79	40.30
PFP34								
PFP41	480.65	365.45	308.75	480.65	442.85	302.82	477.13	84.80
PFP42	346.20	329.97	358.65	358.65	227.78	300.34	342.47	80.91
PFP44								
PFP46	259.08	323.22	275.64	323.22	280.63	275.17	258.29	83.95
PFP47	305.24	371.04	310.18	371.04	210.18	266.95	186.68	59.64
PFP49								
PFP50	289.24	261.35	283.81	289.24	178.15	200.58	143.31	60.16

6.2.2 Reliability results

BF mean excitation amplitude in single-leg triple-hop test (normalised, unnormalised and MVC analysed)		Rep 1 (or Session1)		Rep 2 (or Session 2)		Rep 3		Reliability scoring (ICC-Two-way mixed, absolute agreement, single measures, power 95%)					
		mean	SD	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
meanExc /MVC	within-session; 3 reps												
	Uninjured (n=11)	302.60	670.83	294.73	666.27	312.85	730.10	0.997	0.992	0.999	36.58	9.92	101.39
	PFP (n=14)	92.04	30.45	88.42	28.52	91.99	30.79	0.755	0.514	0.905	14.48	14.69	40.13
	Outlier removed (P1 from uninjured group); mean excitation amplitude												
	Uninjured (n=10)	100.45	22.91	93.96	23.41	92.82	23.85	0.775	0.502	0.931	10.83	10.42	30.01
	Test-retest												
	Uninjured (n=10)	327.65	721.32	100.15	29.65			-0.019	-0.618	0.591	515.21	28.93	1428.10
	PFP (n=11)	88.87	26.88	81.31	28.21			0.049	-0.589	0.619	26.49	25.44	73.43
	Outlier removed												
	Uninjured (n=9)	99.61	18.91	102.44	30.50			0.309	-0.49	0.796	20.50	17.45	56.82
not normalised	within-session; 3 reps												
	Uninjured (n=11)	553.29	826.19	529.88	823.61	548.62	904.05	0.996	0.989	0.999	52.18	9.92	144.65
	PFP (n=14)	389.95	230.59	388.72	238.35	392.09	196.48	0.898	0.771	0.963	69.32	14.69	192.15
	Outlier removed (P1 from uninjured group)												
	Uninjured (n=10)	308.56	162.65	285.62	156.41	279.04	140.92	0.955	0.873	0.988	31.56	10.42	87.48
	Test-retest												
	Uninjured (n=10)	550.07	896.64	285.92	162.35			-0.037	-0.647	0.583	653.38	20.01	1811.06
	PFP (n=11)	312.49	112.15	308.46	116.39			0.591	-0.012	0.873	71.34	16.77	197.75
	Outlier removed												
	Uninjured (n=9)	269.80	144.06	298.92	166.58			0.967	0.686	0.994	27.58	8.16	76.45
MVC only	within-session; 3 reps												
	Uninjured (n=11)	279.89	179.12	278.67	191.70	278.90	188.87	0.988	0.966	0.996	19.80	7.63	54.87
	PFP (n=14)	429.16	207.39	408.86	215.85	410.02	201.51	0.953	0.892	0.983	44.10	7.91	122.23
	Test-retest												
	Uninjured (n=10)	246.85	100.45	302.18	182.51			0.671	0.164	0.904	83.84	21.87	232.38
	PFP (n=11)	381.32	184.09	402.81	200.62			0.731	0.262	0.92	110.57	18.39	306.49

6.3 Muscle performance

6.3.1 Rate of torque development data and isometric peak torque

6.3.1.1 Session 1

Uninjured group RTD and isometric peak torque			Session 1 Normalised by bodymass											
			RTD (method 1)			RTD (method 2)								peak Iso T
part.	Bmass	reps	0.3	0.6	0.9	25ms	50ms	75ms	100ms	125ms	150ms	175ms	200ms	
PH1	63.7	1	1219.97	1311.70	237.18	987.60	1194.02	1330.73	1397.68	1379.86	1291.75	1174.62	1062.85	323.31
		2	1605.32	1733.65	323.99	1434.38	1696.34	1797.07	1775.61	1660.39	1496.25	1331.33	1188.56	311.01
		3	1399.97	1427.10	433.54	1271.27	1435.13	1500.90	1497.97	1417.51	1283.40	1145.14	1031.28	301.53
PH2	51.9	1	378.02	379.95	162.78	406.82	431.89	438.89	432.47	420.46	409.82	404.26	403.36	165.86
		2	308.73	137.56	50.49	319.34	334.12	341.64	345.21	345.21	344.41	345.03	347.74	205.41
		3	332.76	313.84	65.72	348.79	370.07	377.87	376.31	371.05	365.32	360.70	357.50	192.07
PH3	59.3	1	668.36	691.87	169.59	539.41	677.34	784.66	830.40	821.88	793.30	763.96	737.03	254.68
		2	846.52	789.06	175.22	757.44	920.09	997.92	994.15	937.77	863.15	796.51	749.49	244.96
		3	532.53	517.85	406.01	489.72	567.76	608.03	617.43	603.33	578.68	558.79	550.16	218.76
PH4	94.0	1	1153.74	1308.54	319.01	824.18	1088.35	1263.33	1338.41	1331.66	1264.39	1169.38	1072.76	280.43
		2	1621.00	1628.40	345.30	1399.10	1635.28	1719.01	1674.40	1535.93	1381.46	1265.81	1186.36	306.81
		3	1306.50	1221.12	273.64	1065.65	1291.15	1384.26	1371.81	1276.21	1145.31	1035.32	965.86	287.52
PH5	68.4	1	328.76	414.18	374.78	336.59	400.47	454.79	491.76	507.22	504.44	492.21	477.73	147.69
		2	315.87	374.16	334.50	350.87	407.44	444.57	460.21	458.97	449.98	440.25	431.03	137.38
		3	420.24	473.03	379.91	449.85	522.65	563.02	568.02	547.22	518.22	493.18	472.71	138.18
PH6	107.6	1	480.04	460.98	233.38	335.94	417.19	478.48	506.07	502.99	487.37	476.37	474.74	215.52
		2	556.88	505.15	446.88	383.23	497.80	582.76	614.01	599.10	566.83	540.81	526.85	199.56
		3	536.32	478.19	321.08	434.12	537.89	587.30	567.30	519.34	492.16	489.70	491.96	218.48
PH7	89.2	1	1123.75	892.58	178.91	775.27	996.66	1119.75	1131.93	1072.37	1001.59	956.93	937.39	425.09
		2	1295.30	697.58	147.99	861.17	1124.79	1273.40	1288.55	1210.66	1108.82	1034.26	990.17	465.70
		3	1304.13	619.37	159.96	879.04	1144.14	1284.28	1295.96	1223.39	1126.04	1045.67	985.44	470.72
PH8	65.4	1	1008.03	818.28	525.75	870.30	1026.68	1106.49	1110.29	1040.95	935.59	845.29	793.06	268.11
		2	1203.31	1001.05	92.94	1028.13	1188.62	1277.05	1279.90	1200.31	1094.88	1010.59	950.84	313.36
		3	818.68	729.93	643.20	707.81	821.97	894.06	916.12	882.03	817.39	762.33	733.18	248.58
PH9	63.7	1	709.26	529.99	199.38	626.90	723.80	762.21	755.45	717.36	665.97	620.67	592.91	283.22
		2	517.77	475.69	181.53	606.60	631.55	602.88	557.25	528.49	519.05	515.21	513.21	274.75
		3	399.73	430.40	205.58	315.19	388.57	433.17	448.03	450.42	453.73	458.77	463.00	284.32
PH10	63.8	1	624.14	525.84	184.98	538.52	612.77	655.48	673.69	670.55	651.89	626.08	600.20	261.93
		2	682.19	511.89	95.21	542.58	638.22	701.86	735.14	738.68	718.71	686.08	651.54	291.62
		3	664.86	560.15	250.13	554.53	637.89	688.99	712.46	711.26	692.21	664.27	636.07	276.22
PH11	59.8	1	938.87	1030.94	862.30	865.51	1056.44	1143.31	1131.27	1083.72	1042.99	999.95	940.48	229.29
		2	902.94	979.15	176.28	851.77	1019.77	1082.75	1067.85	1035.52	999.92	941.00	861.27	220.67
		3	981.08	1072.61	862.10	905.11	1098.88	1178.58	1165.76	1125.58	1084.12	1030.43	961.63	235.73

PFP group RTD and isometric peak torque			Session 1 Normalised by bodymass											
			RTD (method 1)			RTD (method 2)								peak Iso T
part.	Bmass	reps	0.3	0.6	0.9	25ms	50ms	75ms	100ms	125ms	150ms	175ms	200ms	
PFP6	58.5	1	675.92	620.92	506.77	671.90	778.71	823.42	796.31	725.09	663.59	634.00	622.09	190.69
		2	575.89	593.78	529.90	580.65	668.50	717.73	721.05	684.04	636.88	606.70	594.40	178.11
		3	686.37	767.81	541.57	708.95	825.01	880.52	868.14	800.86	727.13	675.51	640.61	176.31
PFP7	67.8	1	224.81	201.18	69.23	239.54	260.60	269.35	265.69	256.30	245.09	233.94	224.30	104.06
		2	175.62	173.24	30.27	195.74	216.83	229.48	235.69	238.87	236.60	227.78	216.24	103.92
		3	248.57	222.21	90.13	284.81	300.11	299.29	291.21	280.76	267.65	253.47	240.88	103.76
PFP12	53.8	1	1135.00	1176.14	239.13	1050.80	1283.30	1380.97	1327.88	1186.64	1036.61	916.40	829.19	262.51
		2	1044.57	1116.17	611.11	996.94	1188.79	1262.19	1229.16	1126.66	1009.60	912.43	839.53	242.54
		3	1119.14	1240.39	335.10	1090.09	1303.49	1376.01	1317.93	1191.81	1059.05	940.46	842.64	237.56
PFP16	80.2	1	746.39	813.50	673.63	633.18	791.56	864.45	877.07	867.69	838.46	796.83	756.82	202.55
		2	818.86	870.13	655.51	719.58	888.09	948.63	944.04	912.06	857.50	798.95	750.65	201.06
		3	835.26	886.20	627.20	727.35	899.15	965.40	963.32	928.76	870.14	808.37	759.40	206.07
PFP24	89.3	1	584.22	593.52	269.18	119.37	180.20	277.92	401.36	518.07	603.31	646.70	657.28	368.43
		2	626.62	537.16	157.92	339.59	447.02	550.56	616.47	641.63	641.89	632.13	617.09	346.22
		3	512.99	625.69	148.50	180.23	228.83	299.46	364.22	407.37	439.09	475.29	516.95	380.33
PFP29	63	1	802.65	715.36	120.28	698.77	817.79	861.48	850.96	822.05	796.07	774.29	753.17	294.77
		2	727.09	538.18	110.95	667.24	770.98	799.69	773.45	727.92	689.55	663.16	643.85	305.69
		3	784.61	554.65	138.57	711.91	826.28	852.80	819.58	773.78	739.42	714.63	690.55	299.43
PFP34	69.5	1	488.72	470.03	65.61	433.45	499.01	528.98	534.57	528.53	522.37	521.54	522.28	265.72
		2	575.74	553.58	104.22	492.73	577.54	615.56	624.15	627.85	634.78	636.04	625.04	258.06
		3	514.92	469.62	74.37	435.55	509.28	544.54	555.08	557.76	560.02	560.42	555.61	262.39
PFP41	56.6	1	473.93	498.92	61.69	462.90	529.97	561.15	562.73	554.59	548.06	539.33	523.95	179.57
		2	472.93	501.99	136.95	476.24	543.00	572.25	572.50	562.98	553.93	540.88	518.56	172.41
		3	442.55	517.38	460.41	446.96	513.87	553.40	568.49	576.25	582.22	578.18	562.31	158.22
PFP42	75.5	1	757.92	661.60	209.28	622.66	785.70	871.68	870.37	823.94	759.05	691.48	630.59	219.08
		2	640.65	586.68	288.83	537.14	643.90	693.75	699.59	685.89	663.30	639.17	615.37	228.05
		3	434.28	338.38	199.57	379.96	449.49	483.71	483.39	468.33	448.62	428.08	409.10	207.66
PFP44	65.1	1	1208.93	1379.84	199.07	891.41	1162.89	1358.29	1454.08	1451.56	1372.08	1265.89	1170.13	329.11
		2	1211.38	1324.13	195.44	963.21	1221.92	1392.96	1445.06	1376.91	1250.56	1136.31	1040.35	304.61
		3	1065.14	1068.85	295.86	826.66	1054.92	1212.81	1261.86	1206.60	1113.96	1038.40	975.48	297.40
PFP46	89.65	1	467.48	125.94	50.46	460.25	519.72	523.27	495.95	466.92	448.73	439.47	430.62	197.06
		2	540.68	409.03	78.07	485.88	560.79	582.32	571.22	547.43	519.98	495.00	473.79	192.31
		3	650.37	272.85	41.71	578.38	679.06	703.79	671.83	614.32	552.15	498.37	455.87	193.36
PFP47	117.8	1	700.16	588.15	106.15	529.59	679.48	752.60	761.21	724.36	665.24	613.76	581.40	194.75
		2	318.18	244.61	190.83	222.84	268.01	293.19	305.92	321.37	333.74	339.34	340.50	192.47
		3	721.57	565.90	52.04	556.46	705.28	765.18	756.73	707.66	646.14	598.93	570.89	198.60
PFP49	61.75	1	1552.16	1916.92	1761.54	1376.48	1786.14	2017.52	2058.47	1926.02	1686.88	1438.59	1229.74	290.11
		2	1298.61	1536.23	1021.84	1185.94	1476.72	1621.00	1621.00	1490.60	1306.53	1164.70	1077.16	259.50
		3	839.35	947.52	587.38	713.77	854.61	950.20	1002.76	1013.92	1001.59	977.33	938.08	258.32
PFP50	67.55	1	385.90	347.07	72.94	307.39	357.65	396.40	420.29	428.06	424.70	416.20	407.74	246.35
		2	396.82	418.25	181.05	353.73	401.34	435.48	458.46	470.07	470.43	463.73	454.77	183.32
		3	192.28	239.26	80.65	102.29	103.20	103.05	104.99	111.07	121.94	139.68	163.16	217.46

6.3.1.2 Session 2

Uninjured group RTD and isometric peak torque			Session 2 Normalised by bodymass											
			RTD (method 1)			RTD (method 2)								peak Iso T
part.	Bmass	reps	0.3	0.6	0.9	25ms	50ms	75ms	100ms	125ms	150ms	175ms	200ms	
PH1	63.7	1	1126.33	1164.64	254.66	897.09	1106.94	1232.69	1279.18	1259.99	1185.05	1078.03	966.52	310.24
		2	1225.19	1298.10	213.76	1012.64	1263.83	1389.74	1404.57	1349.11	1247.63	1127.19	1015.91	299.69
		3	1121.87	1036.56	291.97	915.78	1128.95	1227.82	1226.72	1174.84	1099.84	1013.43	928.24	303.95
PH2	51.9	1	364.56	361.80	96.99	391.69	427.58	446.90	450.26	439.61	422.90	406.56	393.35	158.06
		2	369.61	349.39	97.05	394.29	416.98	418.88	408.27	395.62	385.51	376.92	368.06	153.63
		3	348.02	308.89	133.16	389.27	402.67	395.31	376.60	358.79	345.75	335.70	326.59	144.94
PH3	59.3	1	372.01	296.45	42.33	334.29	383.67	419.86	441.84	449.50	443.95	430.82	415.20	220.29
		2	513.31	44.31	27.40	581.19	540.17	497.24	460.81	435.60	418.19	398.15	370.58	169.83
		3	613.24	499.34	142.26	569.21	657.06	693.23	697.10	677.24	641.45	601.99	567.88	235.43
PH4	94.0	1	1047.80	923.92	215.24	759.71	971.22	1095.48	1136.06	1115.75	1043.98	940.92	841.37	288.33
		2	1014.98	896.69	202.41	728.16	927.03	1035.99	1069.09	1058.36	1012.10	942.51	871.28	296.37
		3	1078.25	992.08	267.11	797.02	1024.79	1142.90	1161.57	1118.01	1038.27	950.78	879.00	279.84
PH5	68.4	1	294.13	339.15	243.55	344.32	384.23	406.24	410.84	398.76	375.33	349.11	327.25	104.91
		2	314.67	340.61	114.17	361.24	396.42	412.42	415.24	405.96	385.89	359.38	333.06	116.20
		3	313.98	340.59	229.89	362.58	399.32	416.10	415.78	399.87	373.51	344.37	320.23	108.82
PH6	107.6	1	621.05	527.52	242.71	455.61	573.66	643.08	656.15	632.06	597.34	568.51	550.60	218.46
		2	531.09	487.98	280.47	419.22	506.90	551.71	557.06	538.93	514.94	497.95	493.58	228.53
		3	473.46	444.75	195.84	328.17	414.12	473.67	498.27	496.72	484.53	473.84	469.35	221.95
PH7	89.2	1	1042.58	516.01	141.36	856.79	1035.58	1096.01	1073.59	1022.55	974.24	930.04	887.64	429.72
		2	1195.91	778.51	130.68	959.68	1115.41	1185.89	1195.17	1166.53	1119.98	1066.36	1011.07	420.99
		3	1288.66	787.91	202.76	922.36	1164.48	1281.19	1298.11	1258.12	1193.27	1120.28	1040.37	393.38
PH8	65.4	1	929.23	832.08	162.66	732.98	857.11	939.55	984.47	985.30	950.77	907.68	872.35	332.71
		2	988.58	785.25	131.49	817.80	971.36	1042.95	1039.08	986.40	918.49	861.54	822.55	312.39
		3	859.36	808.68	315.26	817.73	878.89	891.22	891.78	883.30	860.73	827.92	793.31	266.56
PH9	63.7	1												
		2												
		3												
PH10	63.8	1	565.94	479.98	209.91	449.55	533.24	586.87	617.73	625.79	614.60	596.24	580.31	291.32
		2	575.34	400.83	129.58	473.58	536.58	579.03	605.33	612.68	600.65	577.87	554.06	291.33
		3	654.85	497.13	182.44	541.96	627.10	677.68	697.52	689.66	663.59	633.42	608.66	297.49
PH11	59.8	1	851.62	816.99	193.68	702.59	852.18	929.16	944.44	933.48	911.77	878.85	838.20	294.39
		2	952.24	938.29	183.74	785.66	965.84	1064.45	1079.86	1049.73	1004.98	953.87	899.59	286.41
		3	970.83	976.62	555.72	828.74	1023.56	1118.05	1115.08	1070.33	1018.99	964.53	910.54	270.64

PFP group RTD and isometric peak torque			Session 2 Normalised by bodymass											
			RTD (method 1)			RTD (method 2)								peak Iso T
part.	Bmass	reps	0.3	0.6	0.9	25ms	50ms	75ms	100ms	125ms	150ms	175ms	200ms	
PFP6	58.5	1	804.91	912.04	656.66	774.20	947.22	1037.31	1029.84	951.20	864.37	803.38	762.51	205.62
		2	777.94	894.17	453.13	738.73	896.83	993.97	1009.00	948.30	865.79	804.39	763.16	208.11
		3	714.22	756.46	482.55	661.33	803.72	890.43	906.37	856.43	787.45	737.11	704.80	209.86
PFP7	67.8	1	189.28	199.12	120.35	206.63	239.55	263.46	270.21	267.17	260.92	252.38	241.47	105.71
		2	377.62	275.21	62.56	419.37	451.09	441.72	414.42	384.76	351.59	317.49	287.37	115.40
		3	285.84	225.50	108.96	316.51	348.91	350.95	332.54	311.40	290.31	269.12	251.01	111.97
PFP12	53.8	1	853.07	776.87	277.14	810.59	934.29	964.68	933.83	886.84	839.61	795.60	756.97	248.50
		2	996.99	808.48	157.58	953.98	1085.81	1087.97	1018.44	941.71	877.47	827.47	788.68	264.85
		3	926.27	805.64	220.53	872.40	1000.05	1017.22	970.89	918.01	872.79	834.75	802.39	269.92
PFP16	80.2	1	993.43	1130.55	888.84	862.46	1090.80	1192.03	1198.56	1136.59	1046.67	972.32	918.23	217.05
		2	926.40	1032.68	771.41	800.56	1004.83	1095.30	1105.30	1057.86	978.65	906.23	851.64	214.74
		3	943.00	973.42	79.11	805.54	1003.73	1079.18	1072.39	1006.65	909.20	821.32	757.41	222.28
PFP24	89.3	1	738.75	583.16	296.84	455.31	594.14	707.93	759.16	759.41	741.30	714.18	679.85	320.31
		2	180.52	279.86	206.70	119.05	113.72	99.39	87.72	87.66	98.47	111.51	117.63	359.37
		3	567.39	531.56	300.60	332.23	438.03	526.09	569.59	579.06	582.52	585.56	578.26	334.41
PFP29	63	1	473.59	387.55	129.03	388.38	481.83	527.49	523.42	510.09	510.29	513.43	509.01	326.44
		2	755.08	649.86	200.04	649.19	763.90	806.02	804.11	794.80	786.28	772.26	746.99	314.95
		3	495.08	396.42	65.49	400.38	465.79	501.93	518.42	526.96	527.09	520.31	512.19	341.09
PFP34	69.5	1												
		2												
		3												
PFP41	56.6	1	491.05	535.77	94.08	515.48	572.86	601.67	612.35	605.81	589.78	573.50	549.00	171.39
		2	416.69	469.40	51.79	404.86	472.92	513.37	532.81	540.16	539.39	533.06	523.36	188.90
		3	442.58	518.81	291.08	396.90	464.92	510.96	541.64	560.48	571.14	578.55	576.68	209.73
PFP42	75.5	1	573.56	552.03	163.06	460.84	564.01	629.41	655.20	655.49	637.70	610.94	583.32	213.54
		2	597.73	459.97	92.68	462.07	582.93	659.91	670.09	643.12	605.24	566.45	532.75	222.21
		3	494.97	496.55	150.12	301.41	391.91	482.49	541.79	571.35	583.04	582.65	574.97	258.44
PFP44	65.1	1												
		2												
		3												
PFP46	89.65	1	556.55	251.90	58.42	422.33	503.16	550.07	568.78	573.24	570.78	561.21	544.27	288.74
		2	777.81	225.26	78.55	594.31	742.57	810.28	802.79	762.01	717.27	675.16	632.15	275.48
		3	725.96	352.09	91.93	585.05	714.71	765.50	753.13	717.18	678.20	645.31	618.21	280.82
PFP47	117.8	1	744.29	702.65	348.12	532.63	668.40	751.44	786.03	781.83	754.69	725.00	702.78	234.34
		2	583.01	374.14	63.18	465.24	566.67	607.48	603.83	572.13	527.09	488.23	463.86	234.76
		3	523.35	543.22	47.51	362.83	437.51	487.66	524.01	549.38	563.17	566.79	563.39	229.32
PFP49	61.75	1												
		2												
		3												
PFP50	67.55	1	606.95	413.09	251.48	513.28	591.65	632.84	645.09	635.96	615.24	592.04	571.12	279.64
		2	476.57	425.61	125.21	378.71	448.64	493.59	515.43	520.05	513.54	503.08	493.29	278.19
		3	496.34	405.53	131.71	373.37	446.67	499.91	530.41	539.96	534.22	520.26	504.87	290.18

6.3.2 Concentric and eccentric knee extensors peak torque

Uninjured group			Peak Concentric torque		Peak Eccentric torque	
part.	Bmass	reps	Session 1	Session 2	Session 1	Session 2
PH1	**63.7**	**1**	285.63	286.47	565.55	527.84
		2	305.90	341.93	570.48	577.45
		3	302.46	311.40	573.35	628.64
PH2	**51.9**	**1**	130.68	129.41	170.16	201.98
		2	133.37	145.32	188.15	184.18
		3	118.93	150.10	180.88	186.20
PH3	**59.3**	**1**	171.34	133.86	265.25	256.32
		2	167.36	170.13	255.25	259.00
		3	185.30	189.41	251.53	252.48
PH4	**94.0**	**1**	231.69	256.08	372.87	453.25
		2	267.09	276.67	446.10	453.96
		3	248.98	239.78	448.21	305.42
PH5	**68.4**	**1**	106.14	99.70	165.59	153.12
		2	103.20	91.94	152.79	169.72
		3	107.18	100.29	164.23	173.33
PH6	**107.6**	**1**	226.06	214.93	232.29	236.08
		2	212.63	211.95	295.69	320.44
		3	225.71	224.57	358.87	324.72
PH7	**89.2**	**1**	331.72	318.59	591.05	556.19
		2	337.78	367.45	548.29	562.09
		3	369.02	366.65	590.75	589.81
PH8	**65.4**	**1**	308.99	264.32	398.51	274.93
		2	296.12	274.68	382.73	322.57
		3	265.47	263.62	392.13	319.05
PH9	**63.7**	**1**	147.87		303.88	
		2	166.99		334.64	
		3	171.28		420.47	
PH10	**63.8**	**1**	230.12	238.46	282.82	306.16
		2	231.39	209.38	291.95	325.20
		3	232.80	213.36	288.84	297.75
PH11	**59.8**	**1**	194.43	186.98	314.32	284.03
		2	208.24	208.86	291.20	298.91
		3	200.74	223.43	292.20	309.22

PFP group			Peak Concentric torque		Peak Eccentric torque	
part.	Bmass	reps	Session 1	Session 2	Session 1	Session 2
PFP6	**58.5**	**1**	167.05	177.34	221.11	264.31
		2	186.52	219.36	231.70	285.95
		3	189.38	222.54	276.01	293.30
PFP7	**67.8**	**1**	74.27	79.96	130.10	93.96
		2	75.59	79.88	144.10	97.61
		3	77.70	66.22	127.42	102.70
PFP12	**53.8**	**1**	201.29	235.37	198.42	299.50
		2	212.60	249.21	261.38	249.61
		3	215.67	250.70	297.70	303.01
PFP16	**80.2**	**1**	231.16	208.51	217.27	295.46
		2	231.17	234.22	275.54	230.83
		3	208.76	230.86	246.51	243.24
PFP24	**89.3**	**1**	300.13	256.26	402.90	417.21
		2	311.46	259.17	405.72	416.33
		3	314.05	252.84	442.53	422.63
PFP29	**63**	**1**	240.54	276.13	396.61	421.21
		2	282.26	257.54	389.35	403.02
		3	277.03	267.88	409.49	385.69
PFP34	**69.5**	**1**	187.53		382.93	
		2	199.68		386.19	
		3	197.56		417.37	
PFP41	**56.6**	**1**	147.71	163.14	253.73	250.47
		2	144.63	164.66	273.63	273.19
		3	141.86	155.77	257.00	250.83
PFP42	**75.5**	**1**	224.45	181.83	306.83	276.09
		2	226.68	197.21	302.74	337.58
		3	257.31	257.57	328.07	380.34
PFP44	**65.1**	**1**	280.11		361.60	
		2	284.67		355.89	
		3	281.99		357.63	
PFP46	**89.65**	**1**	148.91	174.51	243.86	227.95
		2	146.30	208.64	231.20	216.42
		3	144.12	206.88	278.93	303.85
PFP47	**117.8**	**1**	140.12	150.13	302.35	370.05
		2	150.82	148.22	305.69	364.76
		3	165.25	172.92	344.31	363.24
PFP49	**61.75**	**1**	292.07		356.90	
		2	270.16		360.04	
		3	285.62		335.87	
PFP50	**67.55**	**1**	107.67	114.40	367.20	371.33
		2	113.68	103.50	330.67	398.22
		3	118.72	129.11	362.75	406.65

6.3.3 All reliability analyses for muscle performance outcome measures

6.3.3.1 Within-session

Within session Reliability	Repetition 1		Repetition 2		Repetition 3		Reliability scoring (ICC3,1-Two-way mixed, absolute agreement, single measures, power 95%)					
	mean	SD	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
Uninjured (n=11)												
Isometric PKT (60d of flexion)	259.56	75.31	270.11	85.72	261.10	84.45	0.956	0.888	0.987	16.68	5.78	46.22
Concentric PKT (90d to 20d)	214.97	73.40	220.92	75.04	220.72	76.81	0.972	0.926	0.992	12.18	4.80	33.75
Eccentric PKT (20d to 90d)	332.94	141.26	341.57	134.73	360.13	142.50	0.951	0.871	0.985	30.02	6.71	83.20
RTD to 30% of Iso.PKT	784.81	320.21	895.98	476.48	790.62	398.11	0.891	0.729	0.966	130.07	13.91	360.53
RTD to 60% of Iso.PKT	760.44	341.39	803.03	503.61	713.05	363.30	0.905	0.769	0.971	122.64	15.22	339.94
RTD to 90% of Iso.PKT	313.46	212.92	215.48	127.24	363.72	226.18	0.354	0.019	0.719	158.97	35.55	440.65
RTD to 25 ms (Absolute)	646.09	231.52	775.87	390.56	674.64	315.79	0.807	0.563	0.938	138.07	15.78	382.72
RTD to 50 ms (Absolute)	784.15	298.17	917.64	467.45	801.46	378.52	0.849	0.643	0.953	147.70	15.06	409.39
RTD to 75 ms (Absolute)	867.10	337.10	983.72	497.03	863.68	404.73	0.880	0.706	0.963	141.61	13.97	392.52
RTD to 100 ms (Absolute)	890.86	347.54	981.12	485.18	867.02	401.29	0.903	0.758	0.970	126.17	12.72	349.73
RTD to 125 ms (Absolute)	868.09	335.06	931.91	439.86	829.76	372.26	0.920	0.795	0.976	106.09	11.44	294.06
RTD to 150 ms (Absolute)	822.65	307.76	867.59	383.26	777.87	328.40	0.928	0.811	0.978	89.23	10.26	247.34
RTD to 175 ms (Absolute)	775.43	275.06	809.72	333.92	731.30	285.29	0.929	0.812	0.979	77.68	9.26	215.31
RTD to 200 ms (Absolute)	735.68	242.98	763.37	295.01	695.34	250.23	0.929	0.813	0.979	68.46	8.39	189.77
PFP (n=14)												
Isometric PKT (60d of flexion)	238.91	68.74	226.31	64.56	228.35	68.70	0.962	0.902	0.987	12.85	4.26	35.63
Concentric PKT (90d to 20d)	197.59	68.11	204.08	69.48	205.54	70.93	0.978	0.946	0.992	10.07	4.02	27.91
Eccentric PKT (20d to 90d)	295.84	85.80	303.85	73.68	320.11	81.91	0.921	0.800	0.973	22.29	7.06	61.78
RTD to 30% of Iso.PKT	728.87	358.10	673.12	324.95	646.24	275.15	0.825	0.638	0.933	131.86	15.64	365.50
RTD to 60% of Iso.PKT	722.08	480.70	671.65	398.66	622.62	319.81	0.831	0.650	0.936	163.29	19.36	452.62
RTD to 90% of Iso.PKT	314.64	454.65	306.64	287.76	262.36	212.23	0.704	0.435	0.882	177.65	36.99	492.42
RTD to 25 ms (Absolute)	606.98	331.02	586.96	294.51	553.10	268.73	0.825	0.636	0.934	122.43	19.86	339.36
RTD to 50 ms (Absolute)	745.19	431.82	705.25	371.18	660.90	332.38	0.806	0.605	0.926	164.24	20.45	455.26
RTD to 75 ms (Absolute)	820.53	485.61	765.34	408.87	713.58	359.53	0.802	0.598	0.924	183.85	19.82	509.62
RTD to 100 ms (Absolute)	834.07	488.07	772.70	406.63	716.39	353.06	0.807	0.607	0.926	181.05	18.56	501.86
RTD to 125 ms (Absolute)	805.70	448.65	743.88	366.28	688.52	324.39	0.819	0.626	0.931	160.36	17.18	444.50
RTD to 150 ms (Absolute)	757.87	385.94	700.38	311.33	652.08	291.01	0.837	0.657	0.939	131.90	15.65	365.60
RTD to 175 ms (Absolute)	709.17	323.95	661.17	268.73	620.51	262.58	0.863	0.703	0.949	104.28	13.79	289.06
RTD to 200 ms (Absolute)	667.09	274.96	629.09	240.38	594.39	238.12	0.886	0.746	0.958	83.51	11.97	231.48

6.3.3.2 Test-retest

Test-Retest Reliability	Repetition 1		Repetition 2		Reliability scoring (ICC3,1-Two-way mixed, absolute agreement, single measures, power 95%)					
	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
Uninjured (n=10)										
Isometric PKT (60d of flexion)	276.78	87.92	266.28	82.85	0.905	0.681	0.975	25.68	8.33	71.18
Concentric PKT (90d to 20d)	234.40	81.26	238.70	81.54	0.976	0.911	0.994	12.28	4.07	34.03
Eccentric PKT (20d to 90d)	359.52	145.75	358.84	152.84	0.974	0.900	0.994	23.44	4.82	64.97
RTD to 30% of Iso.PKT	851.96	399.41	753.96	328.85	0.923	0.556	0.983	99.79	8.85	276.60
RTD to 60% of Iso.PKT	786.86	406.27	642.37	304.75	0.823	0.298	0.956	150.33	15.91	416.68
RTD to 90% of Iso.PKT	307.76	153.10	194.34	70.46	0.417	-0.123	0.804	99.08	29.73	274.65
RTD to 25 ms (Absolute)	717.13	310.62	631.03	226.78	0.848	0.461	0.961	104.62	10.04	290.00
RTD to 50 ms (Absolute)	859.73	380.14	749.56	297.81	0.885	0.447	0.973	114.32	10.09	316.89
RTD to 75 ms (Absolute)	935.37	411.37	809.71	334.56	0.896	0.371	0.977	119.51	10.48	331.26
RTD to 100 ms (Absolute)	945.60	409.59	820.25	340.58	0.900	0.361	0.978	117.71	10.43	326.26
RTD to 125 ms (Absolute)	907.71	381.03	799.62	329.34	0.913	0.439	0.981	103.54	9.67	287.00
RTD to 150 ms (Absolute)	850.35	338.82	761.61	308.10	0.922	0.533	0.983	88.94	8.99	246.53
RTD to 175 ms (Absolute)	796.21	297.29	717.16	281.88	0.918	0.550	0.981	81.57	8.70	226.11
RTD to 200 ms (Absolute)	752.31	262.40	675.22	255.91	0.904	0.495	0.978	79.12	8.82	219.30
PFP (n=11)										
Isometric PKT (60d of flexion)	227.18	72.22	254.52	67.80	0.862	0.280	0.967	25.92	9.36	71.85
Concentric PKT (90d to 20d)	195.28	72.29	205.92	61.27	0.903	0.694	0.972	20.44	7.67	56.65
Eccentric PKT (20d to 90d)	312.50	80.30	324.76	92.44	0.948	0.821	0.986	19.32	6.21	53.56
RTD to 30% of Iso.PKT	603.64	237.90	621.42	200.68	0.828	0.480	0.951	89.15	13.52	247.12
RTD to 60% of Iso.PKT	562.49	275.72	555.90	246.72	0.823	0.461	0.949	107.43	12.21	297.77
RTD to 90% of Iso.PKT	244.41	197.12	227.77	170.58	0.915	0.724	0.976	52.50	22.08	145.53
RTD to 25 ms (Absolute)	519.37	246.58	525.34	196.72	0.862	0.562	0.961	80.87	14.70	224.16
RTD to 50 ms (Absolute)	618.66	297.53	631.33	238.15	0.846	0.522	0.956	103.24	15.28	286.15
RTD to 75 ms (Absolute)	665.17	309.78	684.23	248.65	0.823	0.465	0.949	115.40	14.82	319.86
RTD to 100 ms (Absolute)	665.67	289.42	691.14	239.09	0.806	0.429	0.944	114.25	13.60	316.67
RTD to 125 ms (Absolute)	641.02	254.11	671.30	216.26	0.808	0.442	0.944	101.12	13.24	280.30
RTD to 150 ms (Absolute)	608.97	220.25	642.16	190.24	0.814	0.465	0.946	86.92	12.66	240.94
RTD to 175 ms (Absolute)	579.78	194.58	614.58	171.56	0.816	0.473	0.946	77.17	11.98	213.89
RTD to 200 ms (Absolute)	555.58	176.77	589.81	160.51	0.813	0.468	0.945	71.65	11.65	198.61

6.4 Hamstrings flexibility

6.4.1 Individuals' data

hamstrings flexibility	measured by iphone (mbi)		mbi-90	
	S1	S2	S1	S2
PFP6	56	59	34	31
PFP7	90	90	0	0
PFP12	77	78	13	12
PFP16	62	64	28	26
PFP24	80	80	10	10
PFP29	77	79	13	11
PFP41	70	75	20	15
PFP42	83	81	7	9
PFP46	88	85	2	5
PFP47	67	67	23	23
PFP50	55	68	35	22
PH1	68	69	22	21
PH2	59	59	31	31
PH3	73	76	17	14
PH4	62	61	28	29
PH5	55	55	35	35
PH6	78	79	12	11
PH7	70	71	20	19
PH8	66	68	24	22
PH10	90	90	0	0
PH11	85	88	5	2

6.4.2 Reliability analysis

Hamstrings flexibility	Test-retest				Reliability scoring (ICC3,1-Two-way mixed, absolute agreement, single measures, power 95%)					
	Session 1		Session 2							
	mean	SD	mean	SD	ICC	lower CI	upper CI	SEM	CV (%)	MDC
uninjured (n=10)	16.82	12.14	14.91	9.49	0.915	0.721	0.976	3.11	9.60	8.63
Reliability (PFP (n=11)	19.40	11.18	18.40	11.78	0.990	0.940	0.998	1.12	14.54	3.10

6.5 Torque data onset

With reference to Chapter 5 (Results section 5.3.2.2.2) some participants had very low baseline due to the leg weight, which caused the absolute onset point to be earlier than the initiation of the contraction (Figures 1 and 2). Therefore, changing the onset to a fixed 7.5 N was done.

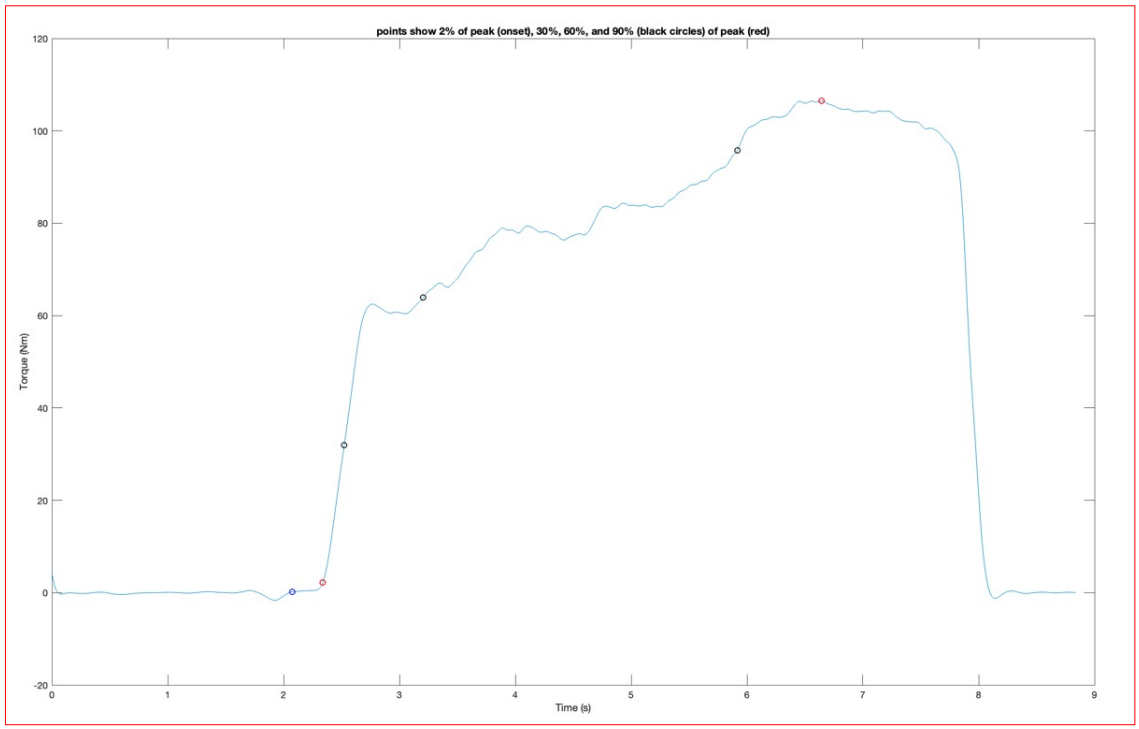


Figure 16: blue circle represents the onset when 3xSD+mean was used.

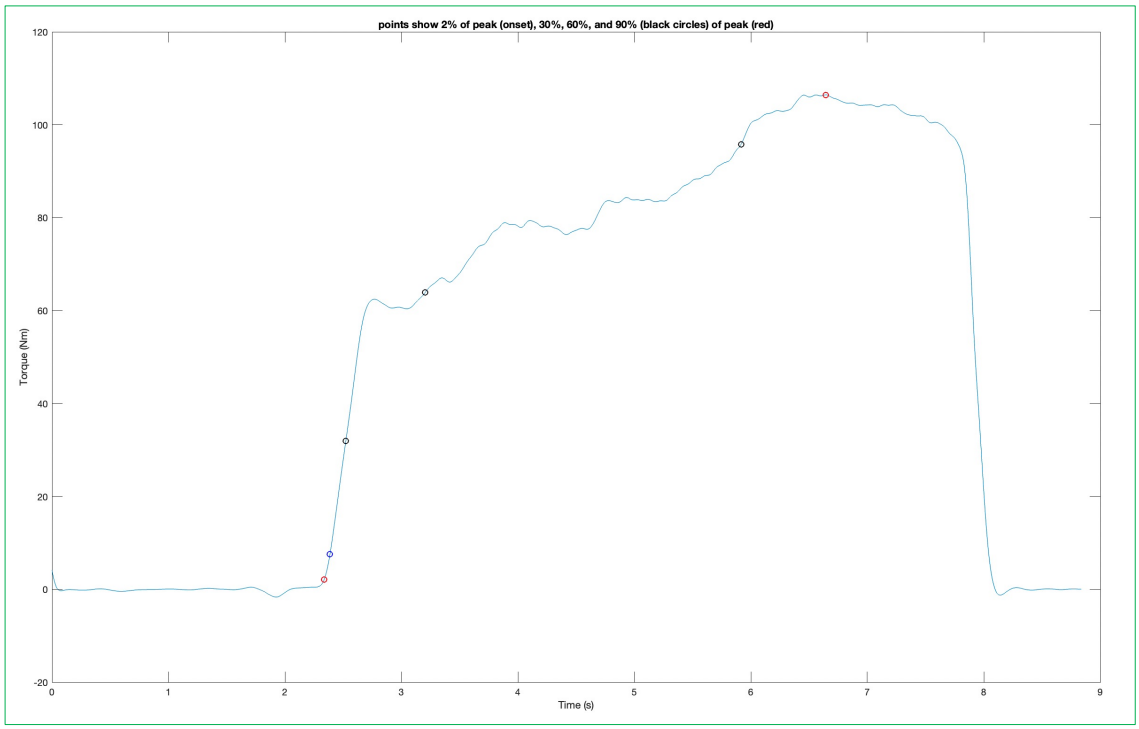


Figure 17: blue circle represents the onset when it is set at 7.5 N.

7 Appendix of Chapter 7

7.1 Screening survey

Is a lab-based muscle testing protocol applicable for patients with knee-cap pain?

We would like to thank you in advance for taking this survey.

We aim to understand how treatment work in patients with knee cap pain. in order to do that, we need to check if a specific muscle testing procedure is applicable with these patients.

Answering the next few questions will determine if your are eligible. After that, you will be asked to attend to Mile-End campus of Queen Mary's University of London to have your knee cap pain checked, and then have multiple measurements done to your thigh muscles.

in order to ask you few questions about your condition, we need to have a formal consent from you to proceed, so please, if you wish to participate, please leave your email and we will contact you very soon.

* Required

Do you have pain around and/or behind your knee-cap?

pain that you feel in the front of your knee.

1. *

Mark only one oval.

- Yes
- No

Did this pain start gradually without a trauma (e.g. without falling or a hit to your knee)?

2. *

Mark only one oval.

- Yes
- No

3. If you answered "No", when was the injury:

Mark only one oval.

- within last month
- from 1 to 6 months ago
- between 6 months to 1 year ago
- before more than 1 year

Are you between 18 and 40 years of age?

4. *

Mark only one oval.

- Yes
- No

Do you feel the pain more when climbing up stairs, sitting for long periods or when standing after sitting?

5. *

Mark only one oval.

- Yes
- No

Have you had previous surgery to the lower limb or back?

6. *

Mark only one oval.

- Yes
- No

Have you ever injured or been diagnosed with any other conditions of the knee?

like cruciate ligament injuries (ACL, PCL), meniscus, osteoarthritis...etc

7. *

Mark only one oval.

- Yes
- No

Do you have any history of heart and/or breathing/chest problems or skin allergies?

8. *

Mark only one oval.

- Yes
- No

Thank you for taking the time to answer these questions

Please click SUBMIT and we will contact you soon. Thanks a lot

7.2 Assessment conducted to exclude conditions other than PFP

Title: Biomechanical testing of local deficits associated with patellofemoral pain: a pilot feasibility and reliability study
Investigator: Saleh Alsaleh
Participant's data collection sheet

Participant code:

Date: **Time:**

Age:

Assigned sex at birth?

Female Male Intersex Prefer not to say Other

Height: **Mass:**

PFP Examination:

Dx	test	+ve/-ve
Patellar tendinopathy	localised along the patellar tendon	
Hoffa's fat pad	Palpate in flexed position, over extension causes more pain	
Quadriceps and suprapatellar fat-pad	Imaging, but palpate the area for localised pain.	
Mensci	McMurry's test (flex., exten. with lat/med force)	
ACL/PCL	Drawer test (permission, stabilise foot, pull and push tibia in knee flexed position)	
Osgood-Schlatter lesion/Sending-Larsen	Localised pain at tibial tubercle or patellar apex	
Patellar instability	Apprehension test (laterally pushing the patella, watch for apprehension signs)	
Patellar tilt test	Tilt patella, look for tightness/pain.	
Chondromalacia	Extended knee, clasp patella, contract quads	
McConnell test	Iso quads with/without medial glide	
Double/single squatting	Pain/no pain	

EMG placement:

Vastus Medialis: 80% on the line from anterior superior iliac spine (ASIS) and knee joint space in front of the medial collateral ligament (Figure 4.1; Left).

Vastus Lateralis: 2/3 on the line from ASIS and lateral border of the patella (Figure 4.1; middle).

Biceps Femoris: 50% on the line from ischial tuberosity to lateral tibial epicondyle (Figure 4.1; right).

	PFP6	PFP12	PFP16	PFP24	PFP29	PFP34	PFP41	PFP46	PFP47	PFP49	PFP50
AKPS_Pre	87	91	88	82	88	85	40	78	82	94	72
AKPS_Post	92	82	88	80	91	93	89	91	88	96	67
VAS_worstlastwk_Pre	4	3	2	6	3	3	3	5	5	5	4
VAS_worstlastwk_Post	4	2	4	2	0	3	0	2	6	3	0
VAS_beforeSession_Pre	1	1	0	0	1	0	0	0	0	0	0
VAS_beforeSession_Post	0	1	0	0	0	0	0	1	2	0	1
VAS_MVC_Pre	1	0	0	2	0	0	0	0	0	0	0
VAS_MVC_Post	0	0	0	0	0	0	0	0	1	0	1
VAS_stepup_Pre	2	0	0	1	0	0	1	1	3	0	0
VAS_stepup_Post	1	0	0	0	0	0	0	1	3	0	0
VAS_sltht_Pre	2	2	0	1	2	0	1	1	0	0	0
VAS_sltht_Post	1	0	0	0	1	0	0	2	1	0	2
VAS_Iso_Pre	3	3	0	0	1	0	1	1	2	0	0
VAS_Iso_Post	2	2	0	0	0	0	0	1	3	0	2
VAS_Con_Pre	3	2	0	1	1	0	0	1	4	0	0
VAS_Con_Post	2	1	0	0	0	0	0	1	2	0	1
VAS_Ecc_Pre	4	5	2	5	1	0	3	2	4	0	3
VAS_Ecc_Post	2	1	0	1	1	0	0	4	3	0	3
VAS_after_Pre	4	1	2	1	1	0	1	0	2	0	1
VAS_after_Post	2	2	0	1	0	0	0	1	3	0	2
meanVAS_Pre	2.7	1.9	0.7	1.9	1.1	0.3	1.1	1.2	2.2	0.6	0.9
meanVAS_Post	1.56	1	0.44	0.44	0.22	0.33	0	1.44	2.67	0.33	1.33
BF_unnormalisd_Pre	379.18	231.87	341.24	536.71	394.75	635.68	407.6	271.36	221.27	976.69	154.97
BF_unnormalised_Post	245.03	294.93	414.65	461.72	436.98	527.85	306.38	278.67	204.29	792.48	201.92
BF_normalisd_Pre	104.27	87.8	95.68	143.05	40.3	74.97	84.8	83.95	59.64	136.41	60.16
BF_normalised_Post	46.97	113	105.71	111.59	53.96	77.7	69.57	95.46	55.99	164.43	60.19
peakIsoT_Pre	209.86	269.92	222.28	359.37	341.09	265.72	209.73	288.74	234.76	290.11	290.18
peakIsoT_Post	255.95	303.47	253.99	344.57	350.2	298.52	202.42	289.42	224.33	290.09	266.56
PeakConT_Pre	222.54	250.7	234.22	259.17	276.13	199.68	164.66	208.64	172.92	292.07	129.11
PeakConT_Post	254.27	245.8	225.28	272.77	341.61	235.6	151.36	178.01	171.76	272.66	190.47
PeakEccT_Pre	293.3	303.01	295.46	422.63	421.21	417.37	273.19	303.85	370.05	360.04	406.65
PeakEccT_Post	323.29	422.96	327.02	385.63	548.39	442.85	272.12	376.13	281.52	470.7	381.62
RTD30percent_Pre	765.69	925.44	954.27	495.55	574.58	526.46	450.11	686.77	616.88	1230.04	526.62
RTD30percent_Post	809.56	888.6	1072.79	506.34	897.27	522.39	385.23	446.86	760.16	638.7	383.56
RTD60percent_Pre	854.22	797	1045.55	464.86	477.94	497.75	507.99	276.42	540	1466.89	414.74
RTD60percent_Post	792.09	830.13	1175.04	426.55	876.04	357.6	389.48	195.6	626.19	571.87	340.73
RTD90percent_Pre	530.78	218.42	579.79	268.05	131.52	81.4	145.65	76.3	152.94	1123.59	169.47
RTD90percent_Post	411.32	247.99	492.88	248.18	231.72	98.17	126.16	76.3	88.99	222.31	106.95
RTD25ms_Pre	724.75	878.99	822.86	302.2	479.32	453.91	439.08	533.9	453.56	1092.06	421.79
RTD25ms_Post	714.89	796.34	874.67	278.72	686.67	464.54	356.38	411.51	561.28	563.59	286.6
RTD50ms_Pre	882.59	1006.71	1033.12	381.96	570.51	528.61	503.57	653.48	557.52	1372.49	495.65
RTD50ms_Post	865.38	912.41	1113.4	360.97	829.89	529.24	411.57	483.47	713.36	650.69	334.52
RTD75ms_Pre	973.9	1023.29	1122.17	444.47	611.81	563.03	542	708.62	615.53	1529.58	542.11

RTD75ms_Post	943.24	974.98	1236.29	432.38	919.14	558.15	448.86	508.05	793.86	694.04	367.33
RTD100ms_Pre	981.73	974.39	1125.42	472.16	615.32	571.27	562.27	708.23	637.96	1560.74	563.65
RTD100ms_Post	941.8	994.78	1253.95	481.35	969.12	563.71	462.89	493.95	803.55	707.49	389.97
RTD125ms_Pre	918.64	915.52	1067.03	475.37	610.62	571.38	568.82	684.15	634.44	1476.84	565.32
RTD125ms_Post	897.92	975.28	1193.7	507.13	984.98	553.68	461.63	463.02	765.09	699.24	404.33
RTD150ms_Pre	839.2	863.29	978.17	474.1	607.89	572.39	566.77	655.42	614.98	1331.67	554.33
RTD150ms_Post	852.44	930.11	1105.81	515.16	973.86	532.68	458.96	429.23	707.22	675.28	411.45
RTD175ms_Pre	781.63	819.27	899.95	470.41	602	572.67	561.7	627.23	593.34	1193.54	538.46
RTD175ms_Post	815.94	879.66	1031.05	517.59	945.15	508.11	456.31	403.39	657.51	646.28	413.05
RTD200ms_Pre	743.49	782.68	842.43	458.58	589.4	567.64	549.68	598.21	576.67	1081.66	523.1
RTD200ms_Post	782.89	833.11	966.61	519.43	908.06	485.47	450.13	387.59	623.62	620.69	412.54
Hams_Pre	31	12	26	10	11	17	15	5	23	15	22
Hams_Post	2	11	25	9	4	8	13	6	23	7	23

8 Appendix of Chapter 8

8.1 Potential intervention programme for future research

Table 8.1: The exercise programme that targets local neuromuscular deficits associated with PFP, incorporating muscle performance and flexibility, adapted from Glaviano et al. (162) and Rabelo et al. (268) with the addition of exercise that target muscle power and flexibility.

Weeks	Week 1			Week 2			Week 3			Week 4			Week 5			Week 6		
Sessions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Details of Exercises in Each Session	Isometric hip abduction and external rotation	Isometric hip abduction and external rotation	Isometric hip abduction and external rotation	Isometric hip abduction and external rotation	Isometric hip abduction and external rotation	Isometric hip abduction and external rotation	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise	4-way Straight-leg raise
	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions
	Seated knee flexion and extension (50% 1RM)	Seated knee flexion and extension (50% 1RM)	Seated knee flexion and extension (50% 1RM)	Seated knee flexion and extension (50% 1RM)	Seated knee flexion and extension (50% 1RM)	Seated knee flexion and extension (50% 1RM)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (40-60% 1RM)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (70% 1RM, and 40-60% 1RM last set)	Seated knee flexion and extension (40-60% 1RM)
	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/6 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/6-8 repetitions
							progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	Repetitions performed as fast as possible	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	Repetitions performed as fast as possible
	squatting 0° to 45°	squatting 0° to 45°	squatting 0° to 45°	squatting 0° to 45°	squatting 0° to 45°	squatting 0° to 45°	squatting 0° to 45° with elastic band	squatting 0° to 45° with elastic band	squatting 0° to 45° with elastic band	squatting 0° to 45° with elastic band	squatting 0° to 45° with elastic band	squatting 0° to 45° with elastic band	Wall squats	Wall squats	Wall squats	Wall squats with elastic band	Wall squats with elastic band	Wall squats with elastic band
	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions
	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)						
	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells	Clam shells
	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	2 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions	3 sets/10 repetitions

Pelvic tilt prone 2 sets/20 seconds	Pelvic tilt prone 2 sets/20 seconds	Pelvic tilt prone 2 sets/20 seconds	Pelvic tilt prone 3 sets/20 seconds	Pelvic tilt prone 3 sets/20 seconds	Pelvic tilt prone 3 sets/20 seconds	Pelvic tilt on Swiss ball 2 sets/20 seconds	Pelvic tilt on Swiss ball 2 sets/20 seconds	Pelvic tilt on Swiss ball 2 sets/20 seconds	Pelvic tilt on Swiss ball 3 sets/20 seconds	Pelvic tilt on Swiss ball 3 sets/20 seconds	Pelvic tilt on Swiss ball 3 sets/20 seconds	Pelvic drops 3 sets/10 repetitions	Pelvic drops 3 sets/10 repetitions	Pelvic drops 3 sets/10 repetitions	Pelvic drops 3 sets/10 repetitions	Pelvic drops 3 sets/10 repetitions	Pelvic drops 3 sets/10 repetitions
Single-legged balance (eyes open) 2 sets/30 seconds	Single-legged balance (eyes open) 2 sets/30 seconds	Single-legged balance (eyes open) 2 sets/30 seconds	Single-legged balance (eyes open) 3 sets/30 seconds	Single-legged balance (eyes open) 3 sets/30 seconds	Single-legged balance (eyes open) 3 sets/30 seconds	Single-legged balance (eyes closed) 2 sets/30 seconds	Single-legged balance (eyes closed) 2 sets/30 seconds	Single-legged balance (eyes closed) 2 sets/30 seconds	Single-legged balance (eyes closed) 3 sets/30 seconds	Single-legged balance (eyes closed) 3 sets/30 seconds	Single-legged balance (eyes closed) 3 sets/30 seconds	single leg stance with 30° knee flexion 3 sets/30 seconds	single leg stance with 30° knee flexion 3 sets/30 seconds	single leg stance with 30° knee flexion 3 sets/30 seconds	single leg stance with 30° knee flexion 3 sets/30 seconds	single leg stance with 30° knee flexion 3 sets/30 seconds	single leg stance with 30° knee flexion 3 sets/30 seconds
lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 2 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions	lateral band walks 3 sets/10 repetitions
Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 2 sets/10 repetitions	Step-ups and step-downs 3 sets/10 repetitions progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	Step-ups and step-downs 3 sets/10 repetitions progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	Step-ups and step-downs 3 sets/6 repetitions Repetitions performed as fast as possible	Step-ups and step-downs 3 sets/10 repetitions progression: increase speed of concentric phase in last set (aim to reach 10 reps in last session, but not necessary)	Step-ups and step-downs 3 sets/6-8 repetitions Repetitions performed as fast as possible	Step-ups and step-downs 3 sets/6-8 repetitions Repetitions performed as fast as possible
Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 2 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions	Lateral rotation in closed kinetic chain 3 sets/10 repetitions
Planks (anterior and lateral) 1s/30 seconds	Planks (anterior and lateral) 1s/30 seconds	Planks (anterior and lateral) 1s/30 seconds	Planks (anterior and lateral) 2 sets/30 seconds	Planks (anterior and lateral) 2 sets/30 seconds	Planks (anterior and lateral) 2 sets/30 seconds	Planks (anterior and lateral) 1 set/1 minute	Planks (anterior and lateral) 1 set/1 minute	Planks (anterior and lateral) 1 set/1 minute	Planks (anterior and lateral) 1 set/1 minute	Planks (anterior and lateral) 1 set/1 minute	Planks (anterior and lateral) 1 set/1 minute	Planks (anterior and lateral) 3 sets/30 seconds	Planks (anterior and lateral) 3 sets/30 seconds	Planks (anterior and lateral) 3 sets/30 seconds	Planks (anterior and lateral) 2 sets/1 minute	Planks (anterior and lateral) 2 sets/1 minute	Planks (anterior and lateral) 2 sets/1 minute
Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 2 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions	Trunk extension on Swiss ball 3 sets/10 repetitions
Single-legged squat with mirror training 2 sets/10 repetitions	Single-legged squat with mirror training 2 sets/10 repetitions	Single-legged squat with mirror training 2 sets/10 repetitions	Single-legged squat with mirror training 2 sets/10 repetitions	Single-legged squat with mirror training 2 sets/10 repetitions	Single-legged squat with mirror training 2 sets/10 repetitions	Single-legged squat with mirror training 3 sets/10 repetitions	Single-legged squat with mirror training 3 sets/10 repetitions	Single-legged squat with mirror training 3 sets/10 repetitions	Single-legged deadlift with mirror training 2 sets/10 repetitions	Single-legged deadlift with mirror training 2 sets/10 repetitions	Single-legged deadlift with mirror training 2 sets/10 repetitions	Single-legged deadlift with mirror training 3 sets/10 repetitions	Single-legged deadlift with mirror training 3 sets/10 repetitions	Single-legged deadlift with mirror training 3 sets/10 repetitions	Single-legged deadlift with mirror training 3 sets/10 repetitions	Single-legged deadlift with mirror training 3 sets/10 repetitions	Single-legged deadlift with mirror training 3 sets/10 repetitions
Lunge with mirror training 2 sets/10 repetitions	Lunge with mirror training 2 sets/10 repetitions	Lunge with mirror training 2 sets/10 repetitions	Lunge with mirror training 2 sets/10 repetitions	Lunge with mirror training 2 sets/10 repetitions	Lunge with mirror training 2 sets/10 repetitions	Lunge with mirror training 3 sets/10 repetitions progression: increase speed of concentric phase in last	Lunge with mirror training 3 sets/10 repetitions progression: increase speed of concentric phase in last	Lunge with mirror training 3 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 2 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 2 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 2 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 3 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 3 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 3 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 3 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 3 sets/10 repetitions progression: increase speed of concentric phase in last	forward lunge with elastic band 3 sets/10 repetitions progression: increase speed of concentric phase in last

						set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)	set (aim to reach 10 reps in last session, but not necessary)
	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)	hamstrings stretching (long sitting)
	2 sets/15 seconds	2 sets/15 seconds	2 sets/15 seconds	2 sets/30 seconds	2 sets/30 seconds	2 sets/30 seconds	3 sets/15 seconds	3 sets/15 seconds	3 sets/15 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds	3 sets/30 seconds

A potential exercise programme that can be used in a future interventional study that aims to identify changes in local neuromuscular deficits of patellofemoral pain.

Materials: elastic bands, free weights, Swiss ball, mirror, seated leg extension/curl machine.

100mm pain visual analogue scale will be used to monitor patient's pain level and maintain it at ≤20/100, modify load or reps or both if pain is higher.

Resting between sets 1-3 minutes, Resting between exercises 2-3 minutes.

Exercise provided by a physiotherapist, 3 sessions per week for 6 weeks.

Physiotherapy clinic or a gym If materials and space are available.

Adherence is assessed by attendance and completion of exercises.