THESIS

Master of Applied Science

HL84

Kinematics and Kinetics of the Nordic Hamstring Curl

Principal Supervisor – Dr Anthony Shield
Associate Supervisor – Prof. Graham Kerr

School of Exercise and Nutrition Sciences
Queensland University of Technology

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Shaun Muggleton, QUT HL84 Masters by Research Thesis,
n7476116
shaun.muggleton@gmail.com
Abstract

Hamstring strains are the most prevalent soft tissue injury in sports that involve sprinting efforts. However, hamstring injury rates have been shown to be significantly reduced by eccentric strength training programs, most of which utilise the Nordic hamstring curl. There is, however, limited literature available on the kinematics of this exercise and no current descriptions of the forces involved (its kinetics).

Study 1

Objectives: This study was designed to determine the test-retest reliability of peak knee flexor torque, the knee joint angle of peak torque and the knee angle velocity of peak torque observed during the performance of the Nordic hamstring curl in individuals without prior hamstring injury. Methods: Twenty-six males (age = 24.2±4.2 years, height = 1.83±0.07m and mass = 85.4±10.81kg) and six females (age = 23.0±3.3 years, height = 1.68±0.06m and mass = 62.8±9.9kg), who were predominantly recreationally trained, completed a familiarisation session with the Nordic hamstring curl which involved six submaximal and three maximal effort repetitions before test and retest sessions from which data was analysed. Test and retest sessions involved the performance of three maximal repetitions of the Nordic hamstring curl. Session frequency was fortnightly. Knee flexor force was measured via load cells mounted to ankle restraints and knee joint angle was assessed via electrogoniometer. Results: Test-retest reliability of summed peak torque (left + right limb torque), left limb and right limb peak torque during the Nordic hamstring curl were highly reliable with intraclass correlation coefficients (ICC) of 0.97 (95%CI =
Typical errors as coefficients of variation (%TE) were 5.3% (95%CI = 4.2-7.1%), 6.4% (95%CI = 5.1-8.7) and 6.2% (95%CI = 4.9 – 8.5) for summed, left limb and right limb torques, respectively. There were, however statistically significant 4% increases in peak torques between test sessions (p<0.05) with effects sizes for these increases of 0.16, 0.18 and 0.17 for summed, left limb and right limb torques, respectively. The knee angle at which peak summed torque occurred was not reliable with an ICC of 0.18 (95%CI = -0.18-0.50) and %TE of 10.9 (95%CI = 8.7-14.6). The knee joint angle velocity at which peak torque occurred was similarly unreliable with an ICC of 0.60 (95%CI = 0.32-0.78) and %TE of 22.7 (95%CI = 18.2-30.4). **Conclusion:** Peak eccentric knee flexor torques during the Nordic hamstring curl are highly reliable although some learning effect is evident given the current familiarisation protocol. Knee joint angles and knee joint angle velocities at these peak torques are not reliable.

**Study 2**

**Objectives:** To describe the knee joint kinematics and kinetics of the Nordic hamstring curl in uninjured adults. **Methods:** Twenty-six male (age = 24.6±5.3 years, height = 1.82±0.08m and mass = 85.0±11.9kg) and seven females (age = 23.0±3.3 years, height = 1.68±0.05m and mass = 63.5±9.2kg), who were predominantly recreationally trained, performed three maximal repetitions of the Nordic hamstring curl after a single familiarisation session. Torque and joint angle were measured as described for Study 1 and surface electromyographic (EMG) data was collected via electrodes placed above the lateral and medial hamstrings. Data for each repetition was averaged across 5° ranges of motion (bins) and the average for each bin across
the three repetitions was determined. For each participant, torque, joint angle velocity and surface EMG were then normalised to the respective highest values obtained across the Nordic hamstring curl range of motion. **Results:** Peak knee flexor torques generally occurred between 35 and 45° from full extension. Surface EMG activity peaked between 50 and 65° for male and female participants and was declining by the joint angles at which torque reached its peak. Knee joint angle velocity remained slow and relatively constant between 90 and approximately 75° of knee flexion, after which it increased rapidly and reached its peak between 15-20° from full extension for both males and females. While some participants generated their peak knee flexor torques at slow angular velocities (6-30°.s⁻¹) immediately before the velocity at which the forward fall increased (an inflection point), a majority generated their peak torques after this inflection point at velocities in the region of 60-120°.s⁻¹. **Conclusions:** Throughout the performance of the Nordic hamstring curl, torque progressively increased until it typically peaked within the middle third of the range of motion. Surface EMG measures reached peak values prior to peak torque. The inflection-point for knee angle velocity occurred, on average, at ~75° from full extension, and did not necessarily coincide with peak knee flexor torque. For most participants, peak torques occur well after the initial event of knee joint angle acceleration.

**Study 3**

**Objectives:** To describe the effects of extra loads held on the chest on the knee joint kinematics and kinetics of the Nordic hamstring curl. **Methods:** Sixteen males (age = 26.6±7.4 years, height = 1.82±0.07 and mass = 86.9±14.9kg) who were recreationally
trained athletes participated in a familiarisation session and then a single test session at which they performed two Nordic hamstring curls with body mass, 5, 10, 15 and 20kg of extra loads in randomised order. Knee flexor torque, joint angle, joint angle velocity and surface EMG from the lateral and medial hamstrings were collected as described in study 2. **Results:** Extra loading resulted in the generation of increased summed (p<0.001), left (p<0.001) and right (p<0.001) limb knee flexor torques during the performance of the Nordic hamstring curl, however, this effect plateaued at 15kg of extra load. No significant effect of extra load was found on the knee angle at which peak torque was reached, however, joint angle velocity at peak torque was increased with extra loads (p<0.001). Hamstring muscle activation, according to surface EMG, did not vary with loading condition. Extra load had no significant effect on the between limb asymmetries that were observed. **Conclusions:** Knee flexor torques developed during the traditional Nordic hamstring curl performed with body mass are not the highest torques that can be generated. The augmentation of knee flexor torque with extra loading in the absence of increases in muscle activation or changes in knee angle of peak torque is likely to be explained by faster rates of muscle lengthening.

**Summary statement**

Measures of eccentric strength during the Nordic hamstring curl appear highly reliable although some improvements in performance occurred in the current study suggesting the possibility that the familiarisation involving nine practice repetitions may be inadequate to eliminate further learning effects. The knee angle and knee angle velocities at which torque reaches its peak are not reliable and this has
significance for attempts, in the literature, to use these as surrogate measures of knee flexor strength. Extra loads held to the chest during the Nordic hamstring curl result in larger knee flexor torques and higher velocities of knee extension and this method may prove of value in injury prevention programs.

Keywords

Biceps femoris, bilateral asymmetry, biomechanics, eccentric, eccentric strength, electromyography, football, force, hamstring, hamstring injury, hamstring tear, injury prevention, injury rehabilitation, injury risk, joint angle, joint angle velocity, kinematics, kinetics, Nordic hamstring curl, posterior thigh, reliability, Russian hamstring, semitendinosus, semimembranosus, sport, strain, surrogate measures and torque.
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<td>EMG</td>
<td>Electromyography</td>
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<td>NFL</td>
<td>National Football League</td>
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<td>QUT</td>
<td>Queensland University of Technology</td>
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<tr>
<td>SD</td>
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<td>UEFA</td>
<td>Union of European Football Association</td>
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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature: ________________________________

Date: 04/05/2015
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Chapter 1: Introduction

1.1 Introduction to the problem

Sports participation involves some risk of injury and these are of notable personal significance to athletes at both amateur and professional levels of competition. Additionally, for professional athletes, severe injury can come at the cost of lost future opportunity. For example, injured players suffer reduced performance and may even be seen as less employable, particularly as they approach retirement. For professional sporting clubs, the high prevalence of time-loss injuries incurs financial costs for treatment and has a detrimental impact on team performance, particularly when key players are unable to compete. For recreational to sub-elite athletes, sporting injuries may curtail physical activity and this may predispose them towards a sedentary lifestyle.

Research in injury prevention has traditionally followed a model first presented by van Mechelen and colleagues (1992) who proposed a four stage approach which involves; 1) establishing the extent of the problem; 2) establishing the mechanism of injury and the risk factors that predispose towards that injury; 3) introducing preventative measures which address the risk factors; and 4) assessing their effectiveness by repeating stage 1 [1]. While advances on this approach have been proposed [2] the model remains simplistic. For example, some previous research into hamstring injuries has identified strength as a risk factor [3-7], however, there appears to be little recognition of the multifaceted nature of strength [8-14]. Intervention studies have employed a variety of strength training methods [15-20],
often without due consideration of the influence of contraction mode, velocity and range of motion required to reduce injury rates.

In the past 15 years there has been an increasing recognition of the hamstring strain prevention benefits of the Nordic hamstring curl (NHC) [15, 16, 19, 21]; which is an eccentric exercise for the knee flexors and therefore the hamstring muscles. In a number of studies the introduction of the Nordic hamstring curl was associated with a significant reduction in the rates of hamstring injury in recreational to sub-elite soccer players [15, 16, 19, 21]. However, despite promising evidence, theoretical limitations to the exercise have been recognised [22] and it remains possible that there are better hamstring exercises or that modifications to the Nordic hamstring curl may increase efficacy in the gain of eccentric strength.

The Queensland University of Technology (QUT) hamstring research group, led by Tony Shield has also developed a novel field testing device to assess strength in the Nordic hamstring curl [23]. This device measures peak eccentric knee flexion forces during the exercise and elite Australian Rules footballers who are weak in this movement have been shown to be at significantly elevated risk of hamstring strain injuries [7]. At present, however, it is not known where in the range of motion or at what angular velocities these peak forces and torques are reached. Nor do we know whether the knee flexor torques reached in the conventional body mass Nordic hamstring curl are the maximum that can possibly be achieved.

So while little is known about the kinematics of this exercise, there is no published literature describing the forces and torques involved in the movement (i.e. its kinetics). It is possible that a more thorough understanding of these parameters will
reveal alternative approaches to hamstring injury prevention such as modifications to the exercise. This improved insight may also assist in interpretation of the relationship between Nordic hamstring curl strength and injury rates in sport.

1.2 Purposes/Aims

This research was comprised of three separate studies. In sequence, these studies:

1. Assessed the test-retest reliability of peak knee flexor torque, knee angle at the instant of peak torque and knee angle velocity at the instant of peak torque during the Nordic hamstring curl.
2. Described the knee flexor torque - knee joint angle, knee joint velocity - knee joint angle and lateral and medial hamstring electromyographic activity – knee joint angle relationships observed in the Nordic hamstring curl; and
3. Described the effects of performing the Nordic hamstring curl with extra loads held to the chest on knee flexor torques, knee joint angles of peak torque, the knee joint velocities of peak torque and the electromyographic activity from the lateral and medial hamstrings in the 200ms prior to peak torque.

1.3 Hypotheses

Studies 1 and 2, which were designed to address aims 1 and 2 above are largely descriptive and, as such, were not designed to test specific hypotheses. Study 3, while again being largely descriptive of the effects of extra loads on kinematics and...
kinetics of the Nordic hamstring curl, was, nevertheless, designed to test the following hypotheses:

1.3.1 First Hypothesis

That the addition of extra load (held to the chest) will result in higher peak knee flexor torques than observed when the Nordic hamstring curl is performed with body mass alone.

1.3.2 Second Hypothesis

That the addition of extra loads will result in an increase in the knee angle at which peak knee flexor torque is reached (i.e. peak torque will occur earlier in the range of motion).

1.3.3 Third Hypothesis

That the addition of extra loads will result in an increase in the knee angle velocities at which peak knee flexor torque is reached.

1.3.4 Fourth Hypothesis

That the addition of extra loads will not result in any changes in either the relative contribution or magnitude of activity in the electromyographic activity of the lateral or medial hamstrings in the 200ms prior to peak knee flexor torque being reached.
Chapter 2: Literature Review

2.1 Methodology

The methodology employed for the collection of relevant literature pertaining to this narrative review was chiefly through papers available through electronic databases namely, Academic Search Elite, Medline, Cinahl, SportDiscus and Academic Search Premier which are all subsidiaries of EBSCOhost. Some papers were obtained from within the bounds of the QUT library periodicals section if not accessible electronically at the previously mentioned databases. All papers were peer reviewed and were retrieved from published literature.

The key words that were used to search for journal articles included: hamstring, biceps femoris, semitendinosus, semimembranosus, posterior thigh, kinematics, biomechanics, strain, sport, football, soccer, eccentric, strength, Nordic hamstring, Russian hamstring, injury risk, risk factors and injury.

The reference list of this review was emailed to all members of QUT’s Hamstring Injury Group, led by Tony Shield, as to ensure there were no prominent omissions.

2.2 The Significance of Hamstring Strain Injuries in Sport

Hamstring strain injuries are the leading cause of lost training and competition time in Track and Field [24, 25], Australian Rules Football [26-28] and Soccer [29-31] while also being very prominent in Rugby Union [32], cricket [33, 34] and American Football [35]. In Rugby Union, hamstrings strains are the number one training injury [36] and second most prevalent game-day injury [32]. In cricket, hamstring injuries
are typically reported to be one of the most common injuries across an entire cricket season [33] and the most common injury in the emerging cricket program Twenty20 [34] and fifth ranked cause of time away from the game in pace bowlers [33]. Within these and numerous other sports that involve high speed running, the high incidence, prevalence and reoccurrence rates, as well as the severity of hamstring strain injury demands the development of more effective intervention and rehabilitation protocols [30, 37-42].

The incidence of sport injuries are typically presented in peer reviewed literature as the number of injuries incurred per 1000 exposure hours. Alternatively the Australian Football League (AFL) typically define incidence as the number of new injuries per team per season. Injury severity is typically defined by the duration of convalescence and/or the number of missed training weeks or matches. Injury prevalence is typically defined as the number of matches, training sessions or days missed as a result of injury per team per season. Alternatively, it can also be given as a percentage of an athletic population that is affected by a particular injury over the course of a competitive season. It is therefore the product of injury incidence and severity.

Elite sprinters in track and field typically endure the worst consequences from hamstring strain injury, with a median return to pre-injury performance of sixteen weeks with a range from six through to 50 weeks [43]. Athletes from other sports typically spend less time away from competition, presumably because their games are not solely reliant upon maximal running speed. According to the 2012 Australian Football League (AFL) injury report, as a 10 year average, there were 3.8 games
missed per recorded hamstring strain injury and six new injuries per team per season [28]. As a consequence, AFL teams typically experience 21 player-games lost to hamstring strains per 22-23 game season. The negative effects of hamstring injury are also noted after the return to competition as players typically perform less well than they normally do for at least two matches after they return to play [44].

In the elite Union of European Football Association’s (UEFA) Champion’s League, hamstring injuries account for 12% of all lost training and playing time, with typical layoffs of 19 ± 18 days. In the National Football League (NFL) hamstring injuries result in an average of 9 days (range 7-21) away from training and competition while in English Rugby Union there are, on average, 17 days lost per new injury and 25 days lost per recurrent injury [38].

The observation above that recurrent injuries are more severe than initial injuries in Rugby [32] has also been made in elite soccer [45] and the AFL [46]. Furthermore, hamstring injuries are also renowned for their relatively high recurrence rates [24, 30, 32, 45, 47]. The AFL injury report classifies reoccurrence as a second or subsequent injury to the same muscles during a single season [48]. Reoccurrence in a subsequent season is defined as a new injury [48]. In the 2011 season the AFL injury report published a new injury incidence rate of 4.8 hamstring injuries per club, per season and a reoccurrence rate of 12%, with an average of 16.5 games missed per club across the season [48]. In 2012 there was a new injury rate of 5.7 injuries per club per season and a reoccurrence rate of 14% per season, with an average of 21.5 games missed per club across the season [48]. Finally, in 2013, a new rate of 5.2 new injuries per club per season and a spike in reoccurrence rate to 24%, with an average
of 20.8 games missed per club across the season [47]. Across a 21 year period in AFL from 1992-2012 there were 2253 new and 588 recurrent hamstring strains, providing, as averages, 6.0 new hamstring strains per club per season, 20.4 missed matches per club per season and a reoccurrence rate of 26% [28]. Despite annual fluctuations, hamstring strains remain the most prevalent cause of games missed in AFL [28, 48]. Furthermore, the official AFL injury survey only considers missed matches as evidence of an injury. As a consequence, injuries in the pre-season training period are not recorded and the total number of hamstring strains is significantly under-reported.

Hamstring strain injury costs professional sporting teams in two ways. The first is financial because player salaries continue to be paid during recovery and the team incurs the direct costs of treatment [49]. The second is diminished team performance and consequently commercial value of the team, which is especially problematic when key players suffer injury [50].

Even without modelling for the indirect financial costs of diminished team performance, all injuries in the English professional football league across the 1999-2000 season were calculated to cost €74.7 million [41]. The National Football League (NFL) in the United States is another team sport with high athlete salaries; an individual defensive player with a career beginning and ending between 2000 and 2008 earned, on average, $USD3.3 million [51]. Within the NFL, hamstring strain injury represented 13.0% of all injuries across a 10 year study between 1989 and 1998 [47]. Clearly, the financial burden of hamstring strain injury is enormous in professional leagues of sport with high commercial value. While player salaries are
significantly smaller in the Australian Football League (AFL), clubs still spend roughly $A246,000 per year paying those who are absent due to hamstring strains [52]. The cost of AFL hamstring injuries has risen substantially as a consequence of dramatically rising player salaries combined with injury rates that remain stagnant, thus the financial burden of hamstring injuries continues to rise [52].

2.3 Classification of hamstring strain injuries

There are four grading systems for hamstring injury severity. The first grading system involves diagnosis via ultrasound or magnetic resonance imaging (MRI) techniques, from which ascending roman numeral values (I-III) indicate increasing severity of hamstring injury [53]. MRI is acknowledged as offering increased sensitivity and therefore improved detection of minor lesions [53]. In addition to grades one to three, grade zero lesions were introduced in a second classification system proposed by Peetrons (2002) as an update to the initial system. These are considered the most minor presentations of hamstring injury and upon ultrasonic imaging, present no visible lesion [54]. Grade one lesions present with a lesion extending less than five percent of the muscle’s length, that may be accompanied by significant pain, but which palpation cannot locate to a discrete point of injury along the muscle [53]. Grade two lesions present as a partial tear involving 5-50% of muscle volume or cross-sectional diameter, which under ultrasound imaging should present torn muscle fragments [53]. Grade three lesions represent complete tear of the muscle and retraction of the muscle from the site of injury will be evident during ultrasonic imaging [53]. However, it has been acknowledged that the differentiation between the grades of tear is somewhat unimportant; that from the practical perspective of
treatment, it is only important to classify lesions as presenting without bundle tears, with bundle tears and/or intramuscular hematomas [55].

The third system approaches classification from the perspective of evaluating the financial cost and team performance impacts hamstring injury has across a sport [15]. Arnason and colleagues (2008) proposed that hamstring injury should be graded in relation to the period of convalescence [15]. Minor hamstring tears are those where the convalescent period is less than seven days [15]. Respectively, moderate and severe tears represented 8-21 days and >21 days of convalescence [15]. In a two-season injury surveillance study of Icelandic and Norwegian soccer employing these definitions, 29% of hamstring injuries were minor (n=28), 21% moderate (n=20) and 50% were (n=49) severe [15].

The most recent grading system put forward by Malliaropoulos and colleagues (2010) propose that hamstring tears can be assessed using four grades which classify active range of motion deficits of the knee and that this method is superior in that it minimises the cost associated with imaging minor injuries and predicts the period of convalescence [56]. These active range of motion deficits were assessed immediately post the acute phase of injury at 48 hours and were quantified via comparison of injured and uninjured limbs [56]. Importantly, this measure has only been proven valid in first time unilateral injuries, thus avoiding cross reference to a previously injured contralateral limb or obfuscation of active range of motion in the injured leg perhaps induced by a previous injury [56]. Grade I was classified as having a deficit of less than 10° and correlated with a convalescence of 6.9 (SD=2.0) days [56]. Grade II was classified as having a deficit of between 10°-19° and correlated with a
convalescence of 11.7 (SD=2.4) days [56]. Grade III was classified as having a deficit of between 20⁰-29⁰ and correlated with a convalescence of 25.4 (SD=6.2) [56]. Grade IV was classified as having a deficit of greater than 30⁰ and correlated with a convalescence of 55 (SD=13.5) days [56]. The overall Pearson’s correlation between convalescence and active range of motion deficit was r = 0.830 [56]. Given the correlation between this grading method and the period of convalescence, this method may prove valuable in the consideration of future diagnoses and injury management, particularly given the reduced cost when compared with diagnosis via imaging.

2.4 Risk Factors for Hamstring Strain Injuries

2.4.1 Non-Modifiable Risk Factors

2.4.1.1 Age

Several studies across AFL [57-60] and soccer [41, 61-63] have identified increasing age as an independent risk factor for hamstring injury. Within the AFL, the ages of 23 [60] or 24 [57] years have been reported as cut-offs for being at increased risk for hamstring injury. In soccer, players beyond 23 years of age have been identified as being at significantly increased risk in comparison with younger players [41]. Even after accounting for confounding variables, such as previous injury, age remained a significant independent risk factor across several studies that utilised regression or multivariate analysis [41, 57-63].
2.3.1.2 Previous Injury

In AFL [57, 58, 60] and soccer [63] previous hamstring injury has been reported to elevate the risk of subsequent hamstring injury. In Rugby Union, a history of previous hamstring strain has been associated with an increase in the severity of subsequent hamstring injury [32]. Maladaptations noted as arising from hamstring injury include the formation of scar tissue across injury lesions [64], shifts in the angle of peak torque towards shorter muscle lengths [65], reduced eccentric strength [66-69], reduced flexibility [56, 67, 70, 71], atrophy [72], changes to biomechanics during submaximal sprinting [68] and altered mechanics of muscle tissue during lengthening [73]. More importantly, one maladaptation is an increase in the strain experienced by muscle fibres adjacent to inelastic scar tissue during active lengthening [72]. It is possible that some combination of these maladaptations adversely affect performance and capacity of the injured muscle, making it more susceptible to re-injury [64, 73, 74].

Fyfe and colleagues (2013), have recently proposed that a persistent neuromuscular inhibition, which has been shown to occur after hamstring strain injury [75], may account for the persistence of several of the maladaptations mentioned above [76]. Inhibition in the neural drive that can be delivered to skeletal muscles could potentially account for persistent strength deficits [76], particularly in eccentric contractions and at long muscle lengths, muscle atrophy and fascicle shortening [77] that have been observed months to years after athletes return to full training and sport.
2.3.1.3 Ethnicity

It has been suggested that athletes of Aboriginal [58], Black African or Caribbean [38, 41] ethnicity have a greater risk of hamstring injury than Caucasians. However, only one study has identified a significantly higher hamstring injury rate in Aboriginal by comparison with white Australian Rules footballers (OR 11.2, 95%CI 2.1-62.5, p =0.005) [58]. There have been no studies that have established why this increased risk exists.

2.3.2 Modifiable Risk Factors

2.3.2.1 Eccentric strength

Using isolated rabbit muscles undergoing stretch, Garret and colleagues (1996) found that higher levels of electrical stimulation lead to greater energy absorption prior to muscle-tendon failure or ‘tearing’ [78]. However, the length at which tears occurred was not statistically different between stimulated and non-stimulated muscles [79]. Using the same experimental procedures, Mair and colleagues subsequently found that strength loss induced by fatigue reduced the amount of energy absorbed prior to muscle-tendon failure [78]. The results of these studies are consistent with the possibilities that weaker muscles are more prone to strain injury during active lengthening and that improving eccentric strength might potentially reduce hamstring injury risk [78, 80].

A number of human studies have shown that eccentric knee flexor weakness predisposes athletes to hamstring strain injury [3, 7, 81, 82]. For example, Opar and colleagues (2014), showed that elite Australian rules footballers who were weak

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during performance of the Nordic hamstring curl were 2.7-4 times more likely to sustain a hamstring strain than stronger players [7]. This is the first and only study at present to have prospectively employed the Nordic hamstring curl as a test of strength and its use was motivated by the fact that this exercise is already well known for its hamstring injury prevention benefits [7]. Goossens and colleagues (2014) reported that physical education students with lower eccentric knee flexor strength levels, according to hand-held dynamometry, were at greater risk of hamstring strain injuries than their stronger counterparts [82].

2.3.2.2 Strength Imbalances

Croisier and colleagues (2008) reported that in a large cohort (n = 462) of Belgian, French and Brazilian soccer players, those with isokinetically identified strength ‘imbalances’ were significantly more likely to sustain a subsequent hamstring injury (relative risk = 2.89, 95%CI 2.01-10.8) [3]. Imbalance was assessed with reference to knee flexor strength differences between left and right limbs (bilateral asymmetry) and the hamstrings/quadriceps ratio (eccentric hamstring torque/concentric quadriceps torque), although these categories were not presented as discrete groups [3]. This study also showed that players who corrected their initial strength imbalance(s) demonstrated similar hamstring injury rates as those with no initial imbalance [3]. This study also found that eccentric strength imbalance was more prevalent than concentric imbalance which suggests that eccentric tests are more sensitive means of detecting imbalance [3, 81].
As previously mentioned, Sugiura and colleagues (2008) found significance between eccentric strength imbalances and the risk of hamstring injury in a sample of 42 elite Japanese sprinters, but only when isokinetic testing was performed at -60°.s⁻¹ [81]. Only the weaker limbs sustained hamstring strains [81]. The lack of significance with concentric velocities, is further evidence for increased sensitivity of eccentric strength in identifying risk of hamstring injury.

Orchard and colleagues (1997) found hamstring weakness revealed during concentric isokinetic testing at 60°.sec⁻¹ was associated with an increased risk of hamstring injury in 37 AFL footballers [4]. Specifically, the best measures in predicting increased hamstring injury risk were the concentric hamstrings/quadriceps ratio and between limb imbalance [4].

Bennell and colleagues (1998) found that isokinetic strength testing and specifically the hamstrings/quadriceps ratio, did not predict the risk of hamstring injury [83]. They did however report that the risk for hamstring strain was increased where players had incurred a previous hamstring injury [83]. Analysis of methods and results reveals no apparent reason why this study is not congruent with other studies [3, 7, 81, 82].

2.3.2.3 Angle of Peak Knee Flexion Torque

On the basis of observations that prior hamstring strain injury is associated with a shift in the torque-joint angle relationship towards shorter muscle lengths, it has been proposed that the angle of peak knee flexor torque may be a risk factor for
hamstring strain [43]. The theoretical basis for this observation stems from the work of Morgan and colleagues (2001 and 2004) who have proposed that muscles are particularly prone to strain injury when they create significant forces or do a lot of work on the descending limb of their force-length curves [21, 65]. At these long muscle lengths it is proposed that sarcomeres may over-stretch (‘pop’) and lose their overlap between actin and myosin filaments [21, 84, 85]. A small degree of sarcomere popping is thought to at least partially explain the normal experience of delayed onset muscle soreness which occurs in the 8-72 hours after unaccustomed eccentric exercise such as a first gym session or a long downhill walk or run [84]. This soreness is non-pathological and involves so few sarcomeres that the damage is considered microscopic and soreness is markedly reduced in a second exercise session, even if it is performed several weeks after the first [21]. However, Morgan and colleagues (2004) have proposed that a muscle strain injury occurs when the microscopic damage associated with a single exercise session accumulates as a consequence of frequently repeated eccentric exercise, as might be performed by athletes engaged in running programs [21, 84, 86]. Hamstring muscles that generate their peak torques at short lengths are thought to have fewer sarcomeres in series and therefore be prone to sarcomere over-stretch and muscle damage while those with peak torques at long muscle lengths and extra in-series sarcomeres should theoretically experience significantly less damage and therefore less risk of strain injury [21, 22, 65].

Despite some acceptance of the abovementioned concepts, evidence for the angle of peak knee flexor torque being a risk factor for hamstring strain has not been
produced and the one small (n = 44) study that has prospectively examined this possibility has reported that the angle of peak knee flexor torque had no impact on injury [60]. Nevertheless, larger scale studies in this area are required before ruling out the possibility of an effect.

2.3.2.4  Fatigue

As mentioned previously, Mair and colleagues (1996), published an in situ study of fatigued muscle tissue which showed that both fatigued and unfatigued muscle fails at the same lengths [78]. However, fatigued muscle provided lower levels of force throughout active lengthening, consequently failing after absorbing significantly less energy [78]. This presents the possibility that fatigued muscle tissue is less able to resist strain applied during the terminal swing phase of sprinting gait and may consequently approach longer lengths with kinetic energy that has not yet been dissipated [78].

Some studies have suggested fatigue is a risk factor for hamstring injury in sport [78, 87, 88] because the risk of hamstring injury increases further into playtime and towards the end of training sessions in a range of sports [30, 38, 41, 89, 90]. Furthermore, treadmill and overground running protocols designed to mimic the physiological effects of soccer matches have been shown to reduce eccentric knee flexor strength with little or no effect on concentric strength [91-93], so running appears to preferentially affect the strength parameter that is most often associated with elevated hamstring injury risk. It must be acknowledged, however, that more direct evidence for the role of fatigue in hamstring strain is not available at this time.
2.3.2.5 Flexibility

Some studies have shown that hamstring flexibility is a risk factor for hamstring strain injury [61, 94, 95]. However, it is difficult to reliably test the flexibility of the hamstrings. All of the studies that implicated flexibility with hamstring injury risk utilised stretch movements that could not stabilise the hip and spine and because of this it is possible that a quantity of the range of motion may have occurred as a result of posterior rotation of the pelvis and flexion of the spine [61, 94, 95]. Only one of these studies additionally utilised an active stretch to overcome participant neural inhibition, although the force of the active component was not recorded [61]. All three studies lacked the capacity to measure the tension under which maximal stretch was achieved, which is pertinent given that variable tension will achieve different endpoints of stretch [61, 94, 95].

Arnason and colleagues (2004), however, utilised a tension meter or myometer and camera-based biomechanical analysis to take flexibility measurement of the hip extensors in the supine position [62]. This permitted a set tension to determine end of range rather than a passive or active component with unknown forces [62]. Interestingly, this study found that hamstring flexibility was not associated with increased injury risk in soccer players [62]. This study represents the strongest and most reliable evidence against the use of flexibility in the prediction of hamstring injury, however it is not alone in making this assertion as this is the position held by the majority of studies [4, 6, 59, 96, 97].
Three studies have found that very poor flexibility is associated with an increase in hamstring injury risk [61, 94, 95]. In consideration of the available literature, increasing flexibility past normal levels would appear unlikely to decrease risk of hamstring injury risk in most athletes [4, 6, 59, 96, 97], although in circumstances where flexibility is very poor, such a program may prove a worthwhile intervention [61, 94, 95].

Flexibility is however diminished acutely [98], and in some circumstances chronically [67], following hamstring injury [56]. As mentioned previously, Malliaropoulous and colleagues (2010) have proposed a statistically valid method for utilising deficits in active range of motion 48 hours post hamstring injury to grade the injury and predict the period of convalescence [56]. Current literature suggests that while flexibility deficits result from hamstring injuries [56, 67, 98], they are unlikely to be a valid means of predicting hamstring injury risk in previously uninjured or fully rehabilitated athletes [4, 6, 59, 62, 96, 97].

2.4 Evidence from Injury Prevention Programs

The identification of proposed modifiable risk factors typically leads to intervention studies which aim to reduce injury rates. The effects of flexibility and strength training interventions are the most commonly reported.

2.4.1 Flexibility Programs

Arnason and colleagues (2008) researched the efficacy of a flexibility program in the intervention of hamstring injury in soccer [15]. The program involved warm-up stretching prior to sprinting or goal shooting exercises, and flexibility training three
times per week during the preseason and two times per week during the competitive season [15]. While the distribution of hamstring injury severity significantly favoured the intervention sample when comparing to the control sample, there was no significant difference in injury rate in the intervention sample compared to the previous season in which an intervention did not occur [15].

van Mechelen and colleagues (1993) found that hamstring stretching interventions caused no significant reduction in the rate of hamstring injury [99]. Those who participated in the intervention experienced 5.9 hamstring injuries per 1000 hours and those assigned to control experienced 4.9 injuries per 1000 hours [99]. Another study by Sherry and Best (2004) found no significant differences (P=0.25) between the convalescent periods of athletes who utilised stretching and those who did not [100]. These two studies suggest that stretching interventions neither reduce the rate of hamstring injury, nor the resultant convalescent period.

2.4.2 Strength Programs

Terminal swing phase, which is the eccentric deceleration of joint angle velocity about the knee prior to foot strike, has been widely recognised as the moment during which hamstring strain occurs [101-103]. Specifically this has been attributed to high speed running through to sprinting efforts [104]. Initial research efforts into strength as a risk factor for hamstring injury were directed to concentric knee flexor movements [71], but scope was then widened to include eccentric strength and a significant relationship between hamstring injury rate and knee flexor strength was established [67]. In recent times, most strength training interventions aimed at
decreasing hamstring injuries have employed a significant emphasis on eccentric
strength.

Askling and colleagues (2003) performed a small scale (n = 30) study on the efficacy
of an eccentrically-biased strength intervention in the prevention of hamstring injury
[20]. Rather than using the Nordic hamstring curl, they utilised a yo-yo flywheel
ergometer (YoYo Technology AB, Stockholm, Sweden). This device works by
transferring kinetic energy across the full range of concentric hamstring action into a
flywheel, the user then restricts eccentric resistance to a partial range of motion
between 90° flexion and full extension [20], thereby involving higher torques than
observed in the concentric portion of the movement. This exercise was completed
every fifth day in the first four weeks and every fourth day in the last six weeks [20].
The study reported a significant reduction in hamstring injury within the intervention
sample, although the small number of participants and the unusually large injury
rate (10/15 players) in the control group possibly limit applicability [20].

2.4.2.2 Evidence for the Nordic Hamstring Curl in Injury Prevention
Programs

Most of the eccentric strength training intervention programs that have been
published so far have employed the Nordic hamstring curl as the sole exercise in
their intervention programs [15-20]. In a study by Arnason and colleagues (2008),
the Nordic hamstring curl was reported to lower the incidence of hamstring strain
injury by 65% in Icelandic and Norwegian football teams who participated in an
eccentric strengthening intervention, when compared to teams that did not use the
intervention program, however, the study was not randomised [15]. Petersen and
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colleagues (2011), conducted research that did involve a randomisation process in the allocation of the same 10-week Nordic hamstring curl protocol used by Arnason and colleagues (2008), this time utilising Danish football players [16]. This study found that players using the specified protocol experienced 3.8 hamstring strain injuries per 100 player seasons compared to 13.1 hamstring strain injuries per 100 player seasons for control players who did not employ the Nordic hamstring curl program [16]. Pertinently, the rate of recurrent injury in the invention group dropped to 7.1 versus 45.8 hamstring injuries per 100 players seasons in the control group (P = 0.003) [16]. Additionally, the number of interventions needed to treat to prevent a single injury recurrence was three (95%CI = 2-6) which suggests the Nordic hamstring curl is an extremely effective and efficient intervention [16]. Similarly, van der Horst and colleagues (2014) have released preliminary results of a long term study in amateur Dutch soccer showing that two of 309 players in their intervention group sustained hamstring strains while 12 of 310 control participants were injured [19]. Finally, Seagrave and colleagues (2014) recently conducted a non-randomised investigation of professional baseball players across the 2012 on-season and reported that none of 65 players who participated in a Nordic hamstring curl intervention program incurred a hamstring strain injury [18]. By contrast, the control group consisting of 34 participants, incurred 3 hamstring injuries across the 2012 on-season [18]. For every 11.3 players who were compliant with the invention, one hamstring injury was prevented [18].

Not all Nordic hamstring curl interventions have reported statistically significant benefits in terms of reduced hamstring injury rates [17, 105]. Engelbretnsen and
colleagues (2008) reported no benefits of a Nordic hamstring curl injury prevention program in a study involving 508 athletes, despite utilising the same program as Arnason and colleagues (2008) and Petersen and colleagues (2011) [15, 16, 105]. However, the authors of this study concede that compliance was very poor with fewer than 21.1% of players participating in more than 20 sessions, where full compliance would have been represented by 27 sessions in total [15]. This study also involved injury prevention exercises for a range of other potential injuries including ankle sprains and groin strains which were to be completed outside of normal training sessions by players who were deemed to be at high risk of each specific injury. It is possible, in these circumstances, that the intervention became too onerous for many players. By comparison, the Arnason and Petersen interventions were adopted as a normal part of squad-wide training and compliance was very high.

Gabbe and colleagues (2006) also reported no significant benefits of a Nordic hamstring curl intervention on hamstring injury rates in community level Australian Rule Football. However, only 46.8% of participants completed two or more injury prevention sessions, so compliance was again a significant problem [17]. The protocol utilised by this group involved a voluminous 72 repetitions from the very first session and this caused very significant levels of soreness which were reported as a major reason for participant drop-out [17]. By comparison the highly effective interventions designed by Arnason and colleagues (2008) and Petersen and colleagues (2011) utilised lower volumes of work and a more gradual progression in exercise load. For example, the training sessions consisted of only two sets of five repetitions for the first week, through to 30 repetitions per session in the fifth to
tenth week onwards [15, 16]. Another major limitation of the study by Gabbe and colleagues (2006) is the training frequency of one Nordic hamstring curl session every two weeks which is not consistent with well accepted recommendations for two to three strength training sessions per week [106]. Nevertheless, in the study by Gabbe and colleagues (2006), only 4% of players who completed two or more Nordic hamstring curl training sessions sustained hamstring injuries in the subsequent season compared to 13% of control participants and this difference approached significance (p = 0.098) [17].

A recent systematic review of controlled eccentric hamstring interventions [107] suggests that eccentric interventions are not effective in reducing hamstring strains (relative risk of injury = 0.59 (95%CI = 0.24 – 1.44) [20]. However, the authors of this review noted that this estimate of risk was imprecise, showed high heterogeneity and depended significantly on compliance rates [20]. Participants who were compliant with their intervention programs were significantly less likely to sustain a hamstring strain (relative risk = 0.35 (95%CI = 0.23 – 0.55) than control participants and this estimate was precise and homogenous [20]. It should also be noted that this review was published too recently to have included the recent randomised Nordic hamstring curl trial by van der Horst and colleagues.

Together, the abovementioned studies provide an argument for the protective effects of the Nordic hamstring curl when it is implemented and complied with in preseason injury prevention programs. The proposed mechanisms for these benefits include increases in eccentric knee flexor strength [108, 109], improvements in the hamstrings/quadriceps ratio [108] and shifts in the torque-joint angle relationship.
towards longer muscle lengths [21, 110] all of which have been established to occur after Nordic hamstring curl exercise interventions.

It should be noted that several other hamstring exercises also increase knee flexor strength [111] and shift the torque-joint angle relationship towards longer lengths [112, 113], so alternatives are available and it is unknown whether they will prove more effective in the future if utilised in large scale intervention studies, however, given the development of findings in the Nordic hamstring curl it is the first priority for further research.

2.4.3 Other Interventions

Kraemer and colleagues (2009) found that balance training, which employed single leg standing and jumping exercises with single leg landings, reduced the rate of hamstring injury from 22.4 to 8.2 per 1000 hours of exposure (P=0.022) [114]. However, no further studies have yet confirmed that balance training is effective at reducing the rate of hamstring injury.

The effects of ‘sports-specific training’ involving an increase in high velocity running, static stretching when fatigued and running in a stooped position in a deliberate attempt to overstretch the hamstrings have also been examined in a non-randomised trial conducted at one Australian Football club [115]. Hamstring injury rates in the two seasons after the intervention commenced were significantly lower than they had been in the two previous seasons. While this sort of multi-faceted intervention is potentially a model that can be copied by practitioners, it is not possible to tell which of their elements are effective.
2.4.4 Muscle Involvement and the Kinematics of the Nordic Hamstring Curl

Ono and colleagues (2011) have shown that exercises which predominantly extend the hip, preferentially activate the lateral hamstrings, particularly the long head of the biceps femoris [116, 117]. In contrast, hamstring exercises which predominantly flex the knee, preferentially activate medial hamstrings, semimembranosus and semitendinosus [116, 117]. These observations suggest the possibility that the Nordic hamstring curl, which involves movement about the knees, may not optimally stimulate the long head of biceps femoris, the muscle that sustains 60-80% of all hamstring strain injuries in sports that involve sprinting [76]. Indeed, preliminary evidence from our laboratory shows that the semitendinosus is significantly more heavily recruited in the Nordic hamstring curl than the long head of biceps femoris (unpublished observations).

However, in contrast to the findings of Ono and colleagues (2011), Zebis and colleagues (2012) found that the Nordic hamstring curl preferentially activates the lateral hamstrings because normalised surface EMG activity was 82% of that observed in an isometric MVC in semitendinosus and 91% in biceps femoris [118]. Together these studies indicate that there is a lack of clarity on the topic of preferential activation during the Nordic hamstring curl and that more research is required. The study by Zebis and colleagues (2012) also found that peak EMG for semitendinosus occurred at 67° and for the biceps femoris at 63° [118].

Ditroilo and colleagues (2013) found, in a group of recreationally active university students, similarly to Zebis and colleagues (2012) that peak EMG of biceps femoris occurred at a mean knee angle of 65.4°. However, what was notably different was
the finding that during the forward fall of the Nordic hamstring curl the participants produced an EMG reading that was 134.3% of maximum voluntary eccentric contraction, however this is most likely due to a difference in the exercise against which the Nordic hamstring curl was scaled [119]. Another study by Iga and colleagues (2012) found that peak EMG signals are recorded in the middle third of the range of motion (between knee angles of 60° and 31°)[109]. Ebben and colleagues (2009) found the Nordic hamstring curl produced significantly higher levels of muscle activation when compared with seated leg curl, stiff leg deadlift, single leg stiff deadlift, good morning and squat [120].

2.5 Unexplored Areas in the Published Literature

2.5.1 Reliability of Performance Factors during Performance of the Nordic Hamstring Curl

While our group has published a reliability study using an earlier prototype of our hamstring testing device [23], there have been some significant modifications to it since and it is possible that its reliability will have changed accordingly. Furthermore, the effects of repeated testing (familiarisation) on measures of knee flexor strength held at least two weeks apart are unknown. Similarly, there is no published data on the reliability of the knee joint angle or velocities at which peak torques are reached.

2.5.2 Effects of Extra Load on the Nordic Hamstring Curl

Knee-joint torque during the Nordic hamstring curl may be increased by the addition of extra resistance in the form of a weighted jacket or weights held by the participant, however, this concept has not yet been explored in literature. The
addition of extra loads may produce further protective benefits for participants via the potentially higher forces. It is prudent that the effects of additional mass on performance indices in the Nordic hamstring curl, such as force/torque, knee-angle velocity and EMG, are established. This may give indications of whether or not extra loads should be used in injury prevention programs.

2.6 Research Problem

The instrumenting of the Nordic hamstring curl [23] raises a number of questions. For example, the relationships between knee flexor torque and knee angle velocity and hamstring muscle activation have not been characterised. Furthermore, it is not known whether the peak knee flexor torques observed during the conventional Nordic hamstring curl represent the maximal capacity of the knee flexors. The resistance offered during this exercise is essentially the body mass above the knee so it is possible that shorter and lighter individuals will not be challenged to the same extent as taller and heavier ones. Thus body mass and height may limit the maximal performances that are possible. It is conceivable then that the addition of extra loads held to the chest, for example, may increase knee flexor torque during the exercise.
Chapter 3

Study 1 – Reliability of the Nordic Hamstring Curl

3.1 Research Design

3.1.1 Objectives

Study 1 aimed to determine the test-retest reliability of peak knee flexor torque measurements, the knee angle and knee angle velocity at the instant of peak torque in the Nordic hamstring curl. In addition, the effects of familiarisation or learning were assessed by examining the changes across two testing sessions after a single familiarisation session containing nine repetitions of the movement.

3.1.2 Participants

Thirty-two young, recreationally active adults (six females) gave informed consent to participate in this study. All of the studies reported here (1, 2 and 3) were approved by QUT’s Human Research Ethics Committee (HREC) (approval number 1400000088).

3.1.3 Methodology

Participants attended the laboratory on three occasions with 14 days between consecutive visits. Each visit involved the performance of nine repetitions of the Nordic hamstring curl, the first six of which constituted a warm-up set with progressively increasing but submaximal consecutive efforts. Two minutes was then allowed before the performance of three maximal repetitions which were performed with less than three seconds between them. Participants commenced the exercise
from a kneeling position (knee angles approximately 90°) with hips and trunk extended and were instructed to lean forward at the slowest possible speed while resisting the movement maximally with both lower limbs. The hands were held, palm forwards and fingers pointing upwards, by the side of the trunk at the level of the xiphoid process so that participants could catch their falls at the last possible moment in a push-up position (Figure 1). The investigator gave verbal encouragement throughout the range of motion to improve the prospect of maximal effort. Technique was monitored visually and repetitions rejected and repeated if the participants displayed excessive hip flexion. The first laboratory visit served as a familiarisation session before two formal test sessions (Test 1 and Test 2).
Figure 1. The start (top), mid (middle) and near final (bottom) positions of the Nordic hamstring curl.

Participants performed the Nordic hamstring curl with their ankles secured by restraining straps, each attached to a uniaxial load cell (MLP-1K, Transducer Techniques, CA, USA). The middle of each ankle strap was aligned with the lateral
malleoli and the knees were positioned on a padded surface such that the ankle restraints were vertical and perpendicular to the shank (Figure 1). Data recorded from both load cells and a custom made electrogoniometer (PRV6 5K potentiometer) on the left knee was transferred to a personal computer at 1000 Hz via a 16-bit PowerLab26T AD recording unit (ADInstruments, New South Wales, Australia). Knee joint angle data was low pass filtered with a cut-off frequency of 4 Hz. Knee joint angle velocity was calculated by differentiating the joint angle signal and smoothing the subsequent velocity-time data was performed via application of a 100ms moving window averaging technique. The load cells were calibrated immediately prior to and at the end of the testing period by progressively applying known ~200N loads up to a load of ~800N (~600 N forces are the highest our group has previously recorded in tests of the Nordic hamstring curl). The electrogoniometer was also calibrated immediately before and after the completion of testing. Errors in force measurements were <1% across the range of calibration forces and in the region of 1-2° across 90° for angle measurements.

Left and right leg forces were added together to create a summed knee flexor force for both limbs. Subsequent analysis identified the peak summed, left and right leg forces for each of three maximal efforts and these values were multiplied by shank length to obtain knee flexor torques. Shank length was determined for the right limb only and was measured from the most prominent point of the lateral malleolus through to the lateral condyle of the femur. Note that the summed torque in any single repetition is not simply the sum of the peaks from the right and left limbs because slight differences in the timing of these three peaks often occurred (see
Figure 2). Knee joint angles and angular velocities at the instant of summed peak forces were also determined.

3.1.4 Statistical Analysis

The normality of peak torques, knee angle and knee angular velocities at the instant of peak summed torque was determined by Shapiro-Wilk’s tests using OriginPro 8.5.0 (OriginLab, Northampton, MA). To assess the reliability of peak torque measurements and the knee angle and knee angular velocity at the instant these peaks were reached, intraclass correlation coefficients (ICCs), typical errors (TEs), and TEs as a co-efficient of variation (%TE) were calculated to determine the magnitude of variability from the first to the second testing session [121]. These analyses were carried out according to the methods described by Hopkins using an Excel (Microsoft) spreadsheet [121]. Effect sizes (ES = (test 2 score – test 1 score) / (average of test 1 & test 2’s SD’s)) were determined to evaluate the magnitude of systematic bias and paired t-tests were performed to determine the statistical significance of these effects. Data was reported as means ± standard deviations (SD) or means and 95% confidence intervals (95%CI).
3.2 Results

Sample size, sex, age and anthropometric data for participants of Study 1 are shown below in Table 1.

Table 1. Study 1. Gender, sample size and mean age, stature and mass of participants

<table>
<thead>
<tr>
<th>Sex</th>
<th>N</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>26</td>
<td>24.2 ±4.2</td>
<td>1.83 ±0.07</td>
<td>85.4 ±10.81</td>
</tr>
<tr>
<td>Female</td>
<td>6</td>
<td>23.0 ±3.3</td>
<td>1.68 ±0.06</td>
<td>62.8 ±9.90</td>
</tr>
</tbody>
</table>

3.2.1 Example data output

An example of the Labchart output with three maximal repetitions of the Nordic hamstring curl is shown in Figure 2. Note that the left and right limb forces and the summed knee flexor force in this example reach their peaks at different times. Note that the peak summed torque in the final repetition (shown by a vertical black line) was achieved at 33.13° from full knee extension and at a knee angle velocity of -16.52°.s⁻¹ (the absolute value for velocity was used for subsequent analysis).
Figure 2. An example screen shot showing the three maximal Nordic hamstring curl efforts performed by one male participant.
3.2.2 Reliability Measures

A scatter plot of peak summed torque from tests 1 and 2 is shown below in Figure 3. The scatter plots for left and right limb torques were almost identical to that of summed torque and have not been shown as a consequence.

![Figure 3](image.jpg)

**Figure 3** – A scatter plot for summed knee flexor torque data from tests 1 and 2. Some bias or improvement between tests is shown by the predominance of data points above the 45° line.

Measures of reliability and consistency of peak summed, left and right limb torques are shown in Table 2. Summed peak \((p = 0.002)\), left limb peak \((0.004)\) and right limb peak torque \((p = 0.01)\) all increased significantly between the two testing sessions. The ICCs for torques measures were, nevertheless, high. The knee joint angles and velocities at the instant that summed torque reached its peak did not change significantly between tests (angle of peak torque, \(p = 0.676\); velocity of peak torque,
p = 0.845), although neither variable was reliable according to the ICCs or typical errors.

Table 2. Reliability measures of peak torque, knee angle and knee angle velocity of peak torque in tests 1 and 2 (n = 32). SD = standard deviation, ES = Effect size, ICC = Intra-class correlation coefficient, TE = typical error, %TE = typical error as a coefficient of variation. 95% confidence intervals are shown in brackets. * significant (p < 0.05) difference between test 1 and 2 scores.

<table>
<thead>
<tr>
<th></th>
<th>Test 1 (Nm) (Mean±SD)</th>
<th>Test 2 (Nm) (Mean±SD)</th>
<th>ES</th>
<th>ICC</th>
<th>TE</th>
<th>%TE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summed Peak Torque</td>
<td>265.6 ±64.9</td>
<td>276.4 * ±72.0</td>
<td>0.16</td>
<td>0.97 (0.93-0.98)</td>
<td>13.2 Nm (10.6-17.5 Nm)</td>
<td>5.3 (4.2-7.1)</td>
</tr>
<tr>
<td>Left Peak Torque</td>
<td>131.9 ±32.6</td>
<td>137.8 * ±33.8</td>
<td>0.18</td>
<td>0.95 (0.90-0.97)</td>
<td>7.8 Nm (6.2-10.3 Nm)</td>
<td>6.4 (5.1-8.7)</td>
</tr>
<tr>
<td>Right Peak Torque</td>
<td>136.1 ±35.4</td>
<td>142.0 * ±37.0</td>
<td>0.17</td>
<td>0.95 (0.89-0.97)</td>
<td>8.7 Nm (6.9-11.5 Nm)</td>
<td>6.2 (4.9-8.5)</td>
</tr>
<tr>
<td>Angle at Peak Torque</td>
<td>40.6 ±11.6</td>
<td>40.7 ±12.4</td>
<td>0.005</td>
<td>0.18 (-0.18-0.50)</td>
<td>10.9° (8.7-14.6°)</td>
<td>32.6 (25.1-46.4)</td>
</tr>
<tr>
<td>Velocity at Peak Torque</td>
<td>53.7 ±32.8</td>
<td>54.7 ±37.6</td>
<td>0.009</td>
<td>0.60 (0.32-0.78)</td>
<td>22.7°s⁻¹ (18.2-30.4°s⁻¹)</td>
<td>55.2 (42.1-80.0)</td>
</tr>
</tbody>
</table>

3.3 Discussion

While Opar and colleagues [28], in our laboratory, have previously reported the reliability of knee flexor force measurements in the Nordic hamstring curl, the current study was the first to assess the reliability of joint angles and joint angle velocities at peak torque. Furthermore, this study assessed the reliability of summed peak torque in addition to left and right limb torque.
The current study revealed high levels of reliability and repeatability of Nordic hamstring curl strength, with ICC’s in the region of 0.95 to 0.97 and %TE of 5.3 to 6.4%. Opar and colleagues recruited male recreational to sub-elite athletes and reported lower ICCs of 0.83 (95%CI = 0.67-0.91) and 0.90 (95%CI = 0.81-0.95) and %TEs of 8.5 (95%CI = 6.7-11.6) and 5.8 (95%CI = 4.6-7.9) for left and right knee flexor peak forces respectively [28]. In the current study both trained and untrained males and females with a larger range of strength scores were recruited. As ICCs tend to be greater when the range of scores increases, the superior correlations in the current study may be partly explained by this difference in the spread of scores between the two samples of participants.

Although the effect sizes might be characterised as trivial, the statistically significant four percent average improvement between test sessions suggests the possibility of a small learning effect, despite a familiarisation session which involved six submaximal and three maximal repetitions of the exercise. In the previous study by Opar and colleagues (2013), no learning effect was reported [23], however, the ES for left and right limb peak forces (0.12 and 0.20) were similar to those reported here. In the current study, the increase in knee flexor torques between test one and two were statistically significant, whereas the increases in knee flexor forces in the previous study were not [23]. It is possible that the familiarisation employed in the current study was inadequate to bring about a plateau in performance during the Nordic hamstring curl. Future studies might be warranted to examine the number of practice repetitions required before participants can be said to have mastered the Nordic hamstring curl technique.
The presence of a learning effect, or systematic bias, despite very high ICCs suggests that the changes in torques between testing sessions was relatively uniform across the participant pool in the current study.

It is also possible that the differences in samples may have introduced the learning effect seen in this study, but not in the previous study by Opar and colleagues (2013) [23]. The previous study’s relatively homogenous group of well-trained athletes would have been more likely to have lower levels of remaining adaptive reserve due to training and competition loads at the time of data collection. However, in the opinion of this researcher, the small learning effect observed in this study was predominantly due to an inadequate volume of Nordic hamstring curl prescribed during familiarisation.

It is impossible to determine the mechanisms for a ‘learning effect’ in this study. The sizeable rest of 14 days between all sessions would have minimised the training effect on the knee flexor muscles, however some muscular adaptation cannot be eliminated as a minor contributor [122]. It is more likely that this increase in strength arose from a learning effect such as improved coordination or a preparedness to exert greater efforts [123].
Figure 4. Top – the old prototype utilised by Opar and colleagues (2013) [23]. Bottom – the new prototype utilised in the current study. New prototype allowed less deviation between alignment of the load cell and the vertical plane, as well as the tibia and the horizontal plane. Additionally the new prototype employed chain linkages, spherical and transverse bearings that would have reduced torsion and flexion forces to minimal levels, whereas the old prototype utilised a rigid linkage.

There were significant design improvements in the new Nordic hamstring device prototype when compared to that used by Opar and colleagues (2013) [23] and these may have partly explained the favourable reliability results reported in the current study. The current prototype was comprised of a rigid steel frame with aluminium skin; the kneeling pad consisted of a thinner and harder piece of foam and was upholstered in vinyl (see bottom left, Figure 4). The initial device utilised by Opar and colleagues (2013) was a timber and medium-density fibreboard construction and the kneeling pad was a single layer of thick soft foam [23] (see top
left, Figure 4). By comparison the thinner kneeling pad of the new prototype was elevated from the steel frame with several layers of medium-density fibreboard to bring the cuff into alignment with the kneeling pad (see top versus bottom Figure 4). As a result, the angle of the tibia was much closer to being parallel to the horizontal plane and the load cells with the vertical plane. Additionally, the thinner harder foam was less susceptible to significant variation in compression arising from participant mass ranges.

The linkage system for the load cells was improved, (see bottom right, Figure 10) as the new prototype utilised four eyelets mounted with spherical bearings. These were connected via d-shackles to the cuffs. The inferior eyelets were mounted to bases on the metal frame via chain links. The bases themselves incorporated greased bearings that allowed transverse rotation. This new linkage system may have further minimised torsion and flexion forces being transmitted through the load cells. Also the position of the ankle cuffs were standardised for the midpoint of the cuff to be over the malleolus, so that force could be converted to torque via shank length.

The test-retest reliability for knee flexor torques produced by the Nordic hamstring curl reported here is comparable to those reported for handheld [124] and isokinetic dynamometry [13-16]. For example, Whiteley and colleagues (2012) reported for hand held dynamometry, an ICC of 0.90 for eccentric hamstring contractions in a large cohort (216) of Qatari Footballers [12]. It should be noted, however, that lower reliability coefficients (0.6-0.8) have also been reported for hand held dynamometers [125, 126].
ICCs for isokinetic dynamometry typically range between ~0.8 and 0.97 [13-16]. However, the reliability of isokinetic dynamometry decreases with increasing movement velocity [13]. For example, Feiring and colleagues (1990) found ICCs for peak torque of 0.93-0.98 at joint angle velocities of 120-240°.s⁻¹ respectively while an ICC of 0.82 was reported for peak torque at 300°.s⁻¹[127]. In the current study, the highest joint angle velocity recorded at peak torque was 121.8°.s⁻¹, so comparisons of ICCs between the Nordic hamstring curl test and isokinetic speeds below 120°.s⁻¹ seem most appropriate.

By contrast with the high levels of reliability for strength measures in the Nordic hamstring curl, measures of joint angle and joint angle velocity at peak torque had very poor reliability. These results were unexpected and remain hard to explain, particularly in light of the high reliability of peak torque performances. Muscle force output is highly dependent upon lengths and velocities of length change. The current results suggest that very repeatable torques were obtained despite a high degree of variability in the joint angles and joint angle velocities at which these torques were achieved. It is possible that some error in our results may have come about as a consequence of goniometry errors [128, 129] and well known errors introduced in the process of differentiating joint angle to joint angular velocity [130]. To reduce this error, the displacement data must first be smoothed via a low pass filter. It is possible that the low pass smoothing technique employed here was not optimal and that this led to errors in calculations of velocity. In the future it may be necessary to utilise 3D motion analysis to eliminate errors that may have potentially arisen from the use of goniometry.
Further variability in the kinematic measures associated with the Nordic hamstring curl may have been introduced by interactions between torque-velocity relationships [12-14], force-length relationships [8-11] and changing participant strategies between testing sessions. Faster rates of lengthening, across the range of -1 to -600°.s⁻¹ are known to increase eccentric force/torque outputs from skeletal muscles, including the knee flexors [13]. Isokinetic dynamometry also shows that knee flexor torques generally increase between knee angles of 90° to around 30° from full extension [131]. It seems possible that simultaneous changes in velocities at peak torque and joint angles at peak torque may have essentially countered each other’s effects.

Additionally, there was a diversity of ‘strategies’ employed between participants in this study (as described in study 2). Some fell slowly and reached a peak torque at this slow ‘speed’ and then fell rapidly offering little further resistance. Others displayed increases in torque for longer after the commencement of this acceleration. These strategies also shifted for some individuals between testing sessions, so it is possible that some changed their strategy and that the concurrent changes in velocity and angle had roughly equal and opposite effects on peak torque.

Another potential explanation of inconsistent angles and velocities of peak torque is that hip angle and trunk position are free to vary between repetitions. This effect seems unlikely to have been too large, however, because torque measures were reliable and changes in hip and trunk angles would have changed this.
3.4 Conclusions

Measures of peak eccentric knee flexor torque during the Nordic hamstring curl are highly reliable, although a small learning effect is not completely eliminated with a low volume familiarisation session. The joint angle and velocities at which peak torque occurs are, however, not reliable measures.
Chapter 4

Study 2 – Kinematics and Kinetics of the Nordic Hamstring Curl

4.1 Research Design

4.1.1 Objectives

Descriptions of the Nordic hamstring curl in the literature are limited to kinematic variables of knee velocity and surface EMG studies of hamstring activity. Missing from these studies are descriptions of knee flexion torques and the relationships between torque and joint angle, knee angle velocity and hamstring muscle activation patterns. This study is designed to address this gap in the literature.

4.1.2 Participants

Twenty-six males and seven females gave informed consent to participate in this study (QUT HREC approval number 1400000088). A significant number of the participants in this study were also recruited for study 1 and this data was extracted from the first of their post-familiarisation sessions.

4.1.3 Methodology

Forces, knee joint angle and velocity were measured and knee flexor torque calculated as described in study 1. Additionally, surface EMG was recorded from the lateral and medial hamstrings of the right leg in 21 male and three female participants [132].
The methods utilised previously by Opar and colleagues (2013) were repeated in this study [75]. Bipolar pre-gelled Ag/AgCl surface EMG electrodes (10 mm diameter, 20 mm inter-electrode distance) were utilised on both the medial and lateral hamstrings to collect electromyography measurements. Firstly, preparation of the skin involved shaving, light abrasion and sterilisation with alcohol wipes. As per SENIAM guidelines [132], the locations of electrode placement were on the posterior thigh half way between the ischial tuberosity and tibial epicondyles with electrodes oriented parallel to the line between these two landmarks. The ground electrode was placed on the ipsilateral head of the fibula. The appropriateness of electrode placement was determined by having participants perform internal and external rotations of the knee held at 90° of flexion. If external rotation was accompanied by high lateral EMG output with minimal medial output and if medial rotation was accompanied by the opposite response the electrodes were considered to be placed appropriately. When moderate to high levels of antagonistic EMG (e.g., medial EMG during external rotation) were observed the lateral and medial electrode pairs were detached and reapplied slightly further apart (in the medio-lateral direction).

As in study 1, participants performed six consecutive submaximal Nordic hamstring curl repetitions followed two minutes later by three consecutive maximal repetitions with less than three seconds rest between repetitions. Data recording and signal processing from load cells and electrogoniometer were performed as described for study 1. In addition, data from surface EMG electrodes on the right limb was transferred to a personal computer at 1000 Hz via a 16-bit PowerLab26T AD recording unit (ADInstruments, New South Wales, Australia). Surface EMG signals
were band pass filtered between 10 and 500 Hz (common mode rejection ratio = 110dB) and then rectified and smoothed over moving 100ms windows.

4.1.4 Data Analysis

Data from the left limb, right limb and summed force traces, knee angle and knee angle velocity traces, along with smoothed rectified lateral and medial hamstring surface EMG traces was averaged across five degree bins across the range of motion for each repetition of the Nordic hamstring curl (90-85°, 85-80°, 80-75°... 15-10°). The data from each bin was then exported to excel and averaged across the three repetitions of Nordic hamstring curls. This effectively created an ‘average’ trial from each participant’s three maximal efforts. For each participant, knee flexor forces, smoothed surface EMG and knee joint velocities were normalised to the joint angle bin which contained their respective highest values. For example, if the highest forces and torques were observed to fall in the 40-45° knee flexion bin, this bin was assigned the value of 1 and all other bin values were expressed as a proportion of 1. So, if the average force in the 35-40° bin was 95% of that in the 40-45° bin it was assigned the value of 0.95. This allowed the averaging of all participants’ results without stronger participants exerting more influence on the shape of the torque-joint angle relationship than weaker participants. For many of the participants, the Nordic hamstring curl movement was terminated (participants caught their fall with their hands) before reaching 10° from full knee extension. In these cases data was missing beyond the terminating angle so some participants have data across a smaller range of motion than others. This created no significant problems because
the critical peaks in torque and surface EMG occurred before the angles at which data was lost.

4.1.5  Statistical Analysis

Participant knee flexor strength, age, body mass and stature was reported for male and female participants as means ± standard deviations (SD). The goal of this study was to describe the shape of the torque – joint angle, joint velocity – joint angle and surface EMG – joint angle relationships in the Nordic hamstring curl. As a consequence there was no further statistical analysis.

4.2  Results

4.2.1  Participant Information

Sample size, sex, mean age, mean body mass and mean heights are shown below in Table 3.

Table 3. Sex, sample size, mean ages, heights and body masses of participants in Study 2.

<table>
<thead>
<tr>
<th>Sex</th>
<th>n</th>
<th>n with EMG</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>26</td>
<td>21</td>
<td>24.6 ± 5.3</td>
<td>1.82 ± 0.08</td>
<td>85.0 ± 11.9</td>
</tr>
<tr>
<td>Female</td>
<td>7</td>
<td>3</td>
<td>23.0 ± 3.3</td>
<td>1.68 ± 0.05</td>
<td>63.5 ± 9.2</td>
</tr>
</tbody>
</table>

4.2.2  Relationships Between Knee Joint Angle and Torque, Hamstring EMG and Knee Angle Velocity.

Average summed, left and right limb peak torques from each participant’s best repetition are shown below in Table 4.
Table 4. Averages for peak summed, left and right limb knee flexor torques for male and female participants. Values are means ± standard deviations.

<table>
<thead>
<tr>
<th></th>
<th>Summed Peak Torque (Nm)</th>
<th>Left Peak Torque (Nm)</th>
<th>Right Peak Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>284.5 ± 50.4</td>
<td>146.0 ± 25.0</td>
<td>145.2 ± 28.4</td>
</tr>
<tr>
<td>Female</td>
<td>173.4 ± 25.0</td>
<td>86.3 ± 13.7</td>
<td>90.1 ± 13.9</td>
</tr>
</tbody>
</table>

The results of this study were employed to describe the relationships between torque, knee joint angle velocity and surface EMG and joint angle across the Nordic hamstring curl’s range of motion. The value of knee angle velocity and peak torque were not calculated but they were reported for participants in study 1 (Table 2).

4.2.3 Male Participants

When averaged across the entire pool of 26 male participants, peak summed, left and right limb torques were found within the 40-45° knee angle bin (Figure 5).

Surface EMG from the hamstrings reached peaks earlier in the range of motion, in the 50-55° bin for lateral and in the 60-65° bin for medial hamstrings. Knee angle velocity peaked late in the movement in the 15-20° knee angle bin.
There was significant diversity in the velocity at which peak summed knee flexor forces (and torques) were reached. Some participants reached their peak forces while ‘falling’ extremely slowly (5-20°.s⁻¹) as shown on the right of Figure 5. Others reached peak forces at considerably higher knee angle velocities as shown on the left of Figure 6.
Figure 6. Contrasting data traces from participants who reached peak forces at relatively high (-111.33°.s⁻¹, left) and low angular velocities (-6.41°.s⁻¹, right). Vertical black lines in the Summed force traces show the instant of peak torque.

4.2.4 Female Participants

When averaged across the pool of seven female participants, peak summed and right limb torques were found within the 35-40° knee angle bin while the peak left limb torque was found within the 40-45° bin (Figure 7). Both lateral and medial hamstrings surface EMG reached peaks in the 60-65° bin. As was observed for the male participants, knee angle velocity peaked in the 15-20° knee angle bin. The plateau of the female’s joint angle–torque relationship was markedly flatter than that observed for male participants.
4.3 Discussion

This is the first study to have described the torques generated across the range of motion during the Nordic hamstring curl. Previous studies of this exercise have been limited to observations of knee angle velocities and surface EMG [109, 119, 133], however, understanding the torques involved and their relationship with joint angles and joint angle velocities is important for a number of reasons, as discussed below.

While some concerns must be expressed as to the test-retest reliability of the joint angle measures in the current study, peak knee flexor torques generally reached their maximum values at around 35-45° from full extension for male and female participants and hamstring EMG peaked earlier than this in the range of motion and...
was declining as peak torque was reached. When velocities were normalised to the maximum values across the entire male and female participant pools it appeared that the knee angle velocities were relatively low and constant between the commencement of the movement at \( \sim 90^\circ \) of knee flexion and approximately \( 70-75^\circ \), after which they rose steadily until reaching their peak at approximately \( 15-20^\circ \) from full knee extension. Interestingly, the normalised average data showed no clear acceleration at the mid-portion of the range of motion as has been described previously by Sconce and colleagues (2014) although the current results are similar to the examples shown in Figures 2 and 3 in the paper by Ditroilo and colleagues (2013) [119, 133]. Some individuals who were particularly adept at the exercise were able to control their velocity until reaching knee angles of approximately \( 30^\circ \).

The knee joint angle at which falling velocities increase (termed by others as the ‘break-point angle’) has been reported to correlate with isokinetically derived measures of eccentric strength [133, 134] and it has been proposed that this may be a useful surrogate measure of knee flexor strength when more direct measurements of force or torque cannot be made [133, 134]. The most significant limitation in this proposal is that such a measure is determined by the summed torque created by both limbs, so athletes with one strong limb and one weak limb may not be identified as at risk by this field test. By contrast, the instrumented Nordic hamstring curl described here and in previous studies [7, 23, 135] allows for strength measures of each limb and of between-limb imbalance both of which have been proposed to contribute to hamstring injury risk [81, 136]. The current results also highlight that while some individuals reach their peak knee flexor torques at what may be
described as a ‘break-point’, many reach peak torques at higher velocities after moving beyond this angle (See Figures 5, 6 and 7). Considering the two results depicted in Figure 5, an assessment of the break-point angles (~19° v 47°) would assume that the two individuals have markedly different levels of strength, but they actually produced similar peak torques.

In this study, data was averaged across 5° bins and was not subsequently curve fitted as others have done with isokinetically derived torque – joint angle relationships [21, 65]. This strategy was chosen because good fits are hard to achieve for torque-joint angle curves across the full range of motion and poorly fitted relationships tend to distort the location of the peak torques. Furthermore, accuracy to within a 5° range was considered sufficiently accurate for the purposes of the current study.

A conceptual model of the torques involved in the Nordic hamstring curl is presented below in Figure 11. Early in the range of motion, the peak torque generating capacity of the knee flexors exceeds that produced by the participant’s body mass. As a consequence slow and relatively constant knee angle velocity can be maintained for the first portion of the range of motion. The model below in Figure 8 shows the peak torque capacities of a weak, a strong and an extremely strong participant where body mass, height and centre of mass are identical. The longer the torque of body mass remains less than peak knee-flexor torque capacity throughout the range of motion, the slower and more constant the rate of ‘fall’. An apparent assumption in the literature is that peak torque is reached at the ‘break-point angle’ after which acceleration commences [119, 133], however, while some of the participants in the current study demonstrated this pattern of torque generation, a significant portion
of the cohort generated their peak torque at joint angles beyond those at which they commenced acceleration. These results question the validity of proposed Nordic hamstring curl tests that involve assessment of velocity alone as an indicator of eccentric knee flexor strength [133, 134].

4.4 Conclusions

After the commencement of the Nordic hamstring curl, torque progressively increases and reaches a peak most frequently during the middle third of the range of motion. Surface EMG measures of lateral and medial hamstring activation reach peak values prior to peak torque. As has been previously described, knee angle velocity increases relatively sharply at around 70-75° from full knee extension [119]
the ‘break-point’ angle but peak torques do not always occur here. For the significant portion of participants in the current study, peak torques occur at relatively fast velocities well after the commencement of acceleration (see the left side of Figure 5).
Chapter 5

Study 3 – The Effects of Extra Load on Performance Variables of the Nordic Hamstring Curl

5.1 Research Design

5.1.1 Objectives

The objective of this study was to determine the effect of extra loads held to the chest on peak knee flexor torque, knee joint angle and knee angle velocity at peak torque and muscle activation in the 200ms prior to peak torque from lateral and medial hamstrings during the performance of the Nordic hamstring curl. An additional objective was to examine the effect of extra loads on between limb asymmetries in knee flexor torque.

5.1.2 Participants

Sixteen males gave informed consent to participate in this study (QUT HREC approval number 1400000088). By demonstrating slow rates of fall in the familiarisation session, these participants were deemed strong enough to perform the Nordic hamstring curl with reasonable control with extra loads of up to 20kg held on their chests.

5.1.3 Methodology

After a familiarisation session, identical to the one previously described (see study 1), participants attended the laboratory to perform the Nordic hamstring curl with
body mass and with a range of extra loads (5, 10, 15 and 20kg) held to the chest. These loads were assigned to each participant in a randomised sequence, which was performed twice so that a total of 10 repetitions were performed. Two minute rest periods were allowed between repetitions.

Participants held extra loads, in the form of weight plates, to their chests so that the bore of each plate was at the level of xyphoid process throughout the full range of motion (see Figure 9). As a consequence of this technique the hands and upper limbs were held in a similar position to that employed in the body mass only condition as shown in Figure 9. A gym mat was employed to allow a relatively soft ‘landing’ at the end of each Nordic hamstring curl.

Figure 9. A participant with a 10kg extra load held to the chest. The bore of the plate is held at the level of the xyphoid process.

Knee angle, knee angle velocity, knee flexor torque and surface EMG from lateral and medial hamstrings were assessed as described in studies 1 and 2. Surface EMG was recorded in 12 of the 16 participants (EMG data was lost or corrupted during the tests
of three participants as a consequence of electrodes falling off and one participant performed the test without EMG). For each of these measures, the average of the two trials with each loading condition was employed in the analysis. Between limb asymmetry in knee peak knee flexor forces was determined by dividing the absolute difference between limbs by the larger of the two scores and multiplying by 100.

5.1.4 Data Analysis

Knee flexor forces, joint angle and joint angle velocity was recorded and processed as described for Study 1. In this study, however, the smoothed rectified surface EMG for both the lateral and medial hamstrings was averaged over the 200ms period prior to the instant of peak summed torque.

5.1.5 Statistical Analysis

Peak knee flexor torque, knee angle at the instant of peak torque, knee angle velocity at the instant of peak torque and smoothed, rectified EMG in the 200ms prior to peak torque for each loading condition (body mass, +5, +10, +15, +20kg) were obtained by averaging the two repetitions performed with each load. The Shapiro-Wilk’s test was employed to assess the normality of each variable’s distribution. The effect of extra loading on each of these variables was then determined by one-way repeated-measures analyses of variance. Huynh-Feldt adjustments were applied when assumptions of sphericity were not met. Where significant main effects were found, Tukey’s post-hoc analyses were employed for
pairwise comparisons. All statistical procedures were carried out using OriginPro
8.5.0 (OriginLab, Northampton, MA).

5.1.6  Limitations

5.1.6.1  Sampling

The participants in the current study were sampled from the student body of the
University and from local gyms in the Brisbane region. It is possible that this group is
not completely representative of athletes for whom the Nordic hamstring curl might
be employed in formal training programs. Certainly, a mixture of recreationally
trained and highly trained participants was used in this study. Nevertheless, strength
levels of male participants in this study compared favourably with those of AFL [7],
elite and sub-elite Rugby Union (Bourne et al., unpublished observations) and A-
League Soccer players (Timmins et al., unpublished observations) that have been
recruited for other studies conducted by our group.

5.1.6.2  Data Acquisition

In the current studies, force was measured for each limb, but knee angle and surface
EMG were sampled only from the left and right limbs respectively. It is possible that
small differences in knee angle between limbs may be evident during the Nordic
hamstring curl, but these are likely smaller than the error of measurement
associated with goniometry [129]. Certainly, there was no visible asymmetry
observed during these trials. By sampling surface EMG only from the right limb, it is
assumed that the results are representative of hamstring muscle activation in both
limbs. This assumption is supported by one previous report of symmetrical
 hamstring activation in the right and left limbs during the Nordic hamstring curl [109].

5.2 Results

5.2.1 Participant Age and Anthropometric Data

Sample size, sample size from which valid EMG data was collected, mean age, mean body mass and mean height are shown for male participants below in Table 5.

<table>
<thead>
<tr>
<th>Sex</th>
<th>N</th>
<th>n with EMG</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>16</td>
<td>12</td>
<td>26.6 ±7.4</td>
<td>1.82 ±0.07</td>
<td>86.9 ±14.9</td>
</tr>
</tbody>
</table>

The extra loads of 5, 10, 15 and 20kg represented 5.9, 11.8, 17.7 and 23.6% of the group’s average body mass, respectively.

5.2.2 Knee Flexor Torques

Shapiro-Wilks tests showed that torque data across all loading conditions was normally distributed (body mass, p = 0.740; 5kg, p = 0.436; 10kg, p = 0.576; 15kg, p = 0.687; 20kg, p = 0.644). A one way repeated measures ANOVA revealed statistically significant effects of extra load on summed, left limb and right limb knee flexor torques (p < 0.001 for all three analyses), as shown in Figure 9a. The findings support hypothesis 1.3.1. The same results were obtained whether strength was expressed in terms of absolute knee flexor force (N), torque per unit body mass (Nm.kg⁻¹) and
force per unit body mass (N. kg⁻¹) so only the results for absolute torque are reported here. Peak summed knee flexor torques normalised to those generated in the body mass only condition increased with extra loads normalised to body mass (Figure 9b).
Figure 10. Effect of extra loads on knee flexor torques in the Nordic hamstring curl.  
A) Absolute summed, left limb and right limb torques against load. * Significant main effects for extra load (p<0.05). For the sake of clarity, the pairwise comparisons are included in Table 5 below rather than in this figure. B) Black squares are normalised KF torque (summed knee flexor torque normalised to that generated in body mass only trials) against loads normalised to body mass. Clear circles show the line of exact proportionality between normalised KF torque and normalised load.

Tukey’s post-hoc analyses revealed a number of statistically significant pairwise differences in the summed, left and right limb torques produced with different extra
loads as seen in Table 6. For all three of these measures, all extra loads allowed the
generation of greater knee flexor torques by comparison with the body mass only
condition. For peak summed torques, there was also a statistically significant
difference between the knee flexor torques produced with 5kg and 15 kg extra
loads, with the heavier of these two loads associated with the greater torque (Table
6). For the left limb there were also statistically significant differences between the
knee flexor torques produced with 5 and 15 kg and 5 and 20kg. In each of these
pairwise comparisons, the heavier of the two loads was associated with the greater
torque. For the right limb there were no statistically significant differences between
any of the extra load conditions.
Table 6. Pairwise differences in knee flexor torque per kilogram of body mass between loading conditions (body mass, 5, 10, 15 and 20 kg). * denotes significance (p < 0.05).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Load comparison</th>
<th>Mean difference (95%CI)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summed (left + right limb) peak knee flexor torque</td>
<td>body mass vs. +5</td>
<td>-19.3 (-33.3 – -5.3)</td>
<td>0.002*</td>
</tr>
<tr>
<td></td>
<td>body mass vs. +10</td>
<td>-24.1 (-38.1 – -10.1)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td></td>
<td>body mass vs. +15</td>
<td>-37.6 (-51.6 – -23.6)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td></td>
<td>body mass vs. +20</td>
<td>-31.0 (-45.0 – -17.0)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td></td>
<td>+5 vs +10</td>
<td>-4.8 (-18.8 – 9.1)</td>
<td>0.866</td>
</tr>
<tr>
<td></td>
<td>+5 vs +15</td>
<td>-18.3 (-32.3 – -4.3)</td>
<td>0.004*</td>
</tr>
<tr>
<td></td>
<td>+5 vs +20</td>
<td>-11.7 (-25.7 – 2.3)</td>
<td>0.142</td>
</tr>
<tr>
<td></td>
<td>+10 vs +15</td>
<td>-13.5 (-27.5 – 0.5)</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>+10 vs +20</td>
<td>-6.9 (-20.9 – 7.1)</td>
<td>0.642</td>
</tr>
<tr>
<td></td>
<td>+15 vs +20</td>
<td>6.6 (-7.4 – 20.6)</td>
<td>0.675</td>
</tr>
<tr>
<td></td>
<td>+5 vs +10</td>
<td>-3.5 (-11.1 – 4.1)</td>
<td>0.698</td>
</tr>
<tr>
<td></td>
<td>+5 vs +15</td>
<td>-11.0 (-18.6 – 3.4)</td>
<td>0.001*</td>
</tr>
<tr>
<td></td>
<td>+5 vs +20</td>
<td>-8.0 (-15.6 – 0.4)</td>
<td>0.033*</td>
</tr>
<tr>
<td></td>
<td>+10 vs +15</td>
<td>-7.5 (-15.1 – 0.05)</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>+10 vs +20</td>
<td>-4.6 (-12.2 – 3.0)</td>
<td>0.450</td>
</tr>
<tr>
<td></td>
<td>+15 vs +20</td>
<td>-3.0 (-4.6 – 10.6)</td>
<td>0.803</td>
</tr>
<tr>
<td></td>
<td>+5 vs +10</td>
<td>-1.7 (-9.8 – 6.4)</td>
<td>0.975</td>
</tr>
<tr>
<td></td>
<td>+5 vs +15</td>
<td>-7.7 (-15.8 – 0.4)</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>+5 vs +20</td>
<td>-4.7 (-12.8 – 3.4)</td>
<td>0.485</td>
</tr>
<tr>
<td></td>
<td>+10 vs +15</td>
<td>-6.0 (-14.1 – 2.1)</td>
<td>0.245</td>
</tr>
<tr>
<td></td>
<td>+10 vs +20</td>
<td>-3.0 (-11.1 – 5.1)</td>
<td>0.839</td>
</tr>
<tr>
<td></td>
<td>+15 vs +20</td>
<td>3.0 (-5.1 – 11.1)</td>
<td>0.835</td>
</tr>
</tbody>
</table>
5.2.3 Knee Flexor Torque Asymmetry in the Nordic Hamstring Curl

The average asymmetry between right and left limb peak knee flexor forces was in the region of 7.2-8.5% across the five loading conditions. No effect of load on this parameter was revealed by one-way repeated measures ANOVA (p=0.456) (See Table 7).

Table 7. The Effect of Loading Condition on Knee Flexor Torque Asymmetry.

<table>
<thead>
<tr>
<th>Load</th>
<th>Between Limb Peak Torque Asymmetry (%) (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>body mass</td>
<td>7.4 (4.3 – 10.4)</td>
</tr>
<tr>
<td>body mass + 5kg</td>
<td>8.6 (4.9 – 12.3)</td>
</tr>
<tr>
<td>body mass + 10kg</td>
<td>7.2 (3.8 – 10.5)</td>
</tr>
<tr>
<td>body mass + 15kg</td>
<td>6.8 (3.5 – 10.2)</td>
</tr>
<tr>
<td>body mass + 20kg</td>
<td>6.2 (2.9 – 10.6)</td>
</tr>
</tbody>
</table>

5.2.4 Knee Angle and Knee Angle Velocity at Peak Torque

Contrary to hypothesis 1.3.2, one-way repeated measures ANOVA revealed no significant effect of extra loads on the knee angles at which torque reached its peak during the Nordic hamstring curl (p=0.326). There was, however, a significant effect of load on the velocity at which peak torque was reached (p <0.001) with greater loads resulting in higher knee angle velocities at peak summed torque (see Figure 11). This finding was supportive of hypothesis 1.3.3. There was however, no difference in knee angle velocities between the 15kg and 20kg extra load conditions, so this effect appears to plateau. For some individuals this plateau effect occurred at
5kg or 10kg of extra load, while for a small few there was no plateau in the range of extra loads employed in this study.

Figure 11. Effect of extra loads on knee angle and knee angle velocity at peak torque in the Nordic hamstring curl. * Significant main effects for extra load (p<0.05). For the sake of clarity, the pairwise comparisons are included in Table 8 below rather than in this figure.

For the sake of clarity in Figure 11, pairwise comparisons between different loading conditions shown in Table 8, below.
Table 8. Pairwise differences in knee angle velocity at the instant of peak torque between loading conditions (body mass, 5, 10, 15 and 20 kg). * denotes significance (p < 0.05).

<table>
<thead>
<tr>
<th>Load comparison</th>
<th>Mean difference (95%CI) (°.s⁻¹)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>body mass v +5</td>
<td>10.9 (-10.7 -- 32.5)</td>
<td>0.615</td>
</tr>
<tr>
<td>body mass vs +10</td>
<td>17.3 (-4.3 -- 38.9)</td>
<td>0.173</td>
</tr>
<tr>
<td>body mass vs +15</td>
<td>36.1 (14.46 -- 57.65)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>body mass vs +20</td>
<td>33.2 (11.6 -- 54.8)</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>+5 vs +10</td>
<td>6.4 (-15.2 -- 28.0)</td>
<td>0.919</td>
</tr>
<tr>
<td>+5 vs +15</td>
<td>25.1 (3.5 -- 46.7)</td>
<td>0.015*</td>
</tr>
<tr>
<td>+5 vs +20</td>
<td>22.3 (0.71 -- 43.9)</td>
<td>0.039*</td>
</tr>
<tr>
<td>+10 vs +15</td>
<td>18.7 (-2.9 -- 40.3)</td>
<td>0.119</td>
</tr>
<tr>
<td>+10 vs +20</td>
<td>15.9 (-5.7 -- 37.5)</td>
<td>0.246</td>
</tr>
<tr>
<td>+15 vs +20</td>
<td>-2.8 (-24.4 -- 18.8)</td>
<td>0.996</td>
</tr>
</tbody>
</table>

5.2.5 Hamstring Surface EMG activity

Hamstring muscle activity during the Nordic hamstring curl, as revealed by surface electromyography, did not change significantly with increasing loads as shown in
Figure 12 below. This result was supportive of hypothesis 1.3.4.

![Graph: EMG (mV) vs Extra Loads (kg)]

Figure 12. The effect of loading condition on the smoothed rectified surface EMG from lateral and medial hamstrings during the Nordic hamstring curl.

5.3 Discussion

5.3.1 Effects of Extra Load

At present the published literature describing the Nordic hamstring curl has not considered the effects of adding extra loads to those imposed by the torque created by the upper body. This study showed that the addition of hand held loads on the chest generally increased the peak knee flexor torques and the velocities at which they were reached while having no significant effect on the joint angle at which they were reached or the surface EMG of the hamstrings in the 200ms prior to these peaks. The results suggest the possibility that extra knee flexor torques provided by
extra loading are produced by faster rates of muscle lengthening rather than by differences in joint angles or the extent of hamstring muscle activation.

The torque-joint angle relationship for skeletal muscle shows a plateau across most of its eccentric portion [12-14]. However, between $0.\text{s}^{-1}$ and approximately $-60.\text{s}^{-1}$, torque typically increases in a manner consistent with the current results [13]. Knee angle velocities at peak summed torque averaged $-35.9^\circ \text{s}^{-1}$ (95%CI = $-24.1--47.8^\circ \text{s}^{-1}$) when body mass alone was employed and $-72.0^\circ \text{s}^{-1}$ (95%CI = $-48.4--95.6^\circ \text{s}^{-1}$) with 15kg of extra load. As a consequence, extra torque may have been produced simply because the knee flexors were stretched at faster speeds when heavier loads were employed.

These results suggest the possibility that when training for strength, well trained athletes may benefit from carrying loads in addition to body mass during the Nordic hamstring curl. The knee flexor torques generated with 15kg of extra load were 12.4% higher than those generated with body mass alone. It is important to consider however, that participants in the current study were chosen because they were deemed strong enough to perform this exercise with considerable extra load. As a consequence their falling rates were relatively slow by comparison with participants in Study 1 who, with body mass only, exhibited knee angle velocities at peak torque of $-53.7\pm32.8^\circ \text{s}^{-1}$ and $-54.7\pm37.6^\circ \text{s}^{-1}$ in tests one and two, respectively. Because a significant portion of these participants were ‘falling’ at knee angle velocities between $-60$ and $-120^\circ \text{s}^{-1}$ as they reached peak torques it is possible, given the plateau in the torque-velocity curve at these speeds, that they would not generate
higher torques with extra loads. Obviously a future study would be required to confirm this.

It seems feasible that heavier and taller performers of the Nordic hamstring curl who experience greater knee extension torques as a consequence of their anthropometry might also have the opportunity to generate greater peak knee flexor torques during the movement. However, Opar and colleagues (2014) reported that there were no significant relationships between peak Nordic hamstring curl torques and body mass ($r^2=0.04$) or height ($r^2=0.02$) in a cohort of 186 AFL players. Nevertheless, the current results do suggest the possibility that reasonably strong athletes who gain mass would potentially be able to generate greater knee flexor torques as a result of the faster fall rates that would result.

These findings may also have implications for the interpretation of the results of our group’s previously published prospective study of hamstring injuries in the AFL. Opar and colleagues (2014) showed that athletes with low strength during the Nordic hamstring curl were significantly more likely to sustain hamstring strain injuries than stronger players. In that study however, the Nordic hamstring curl was performed with body mass alone, so it can be argued that maximal knee flexor torques were not measured. It remains to be seen whether or not extra loading protocols such as the one employed in the current study would have improved the capacity to identify players at risk of injury.

It has been proposed that between limb asymmetries in knee flexor strength may expose athletes to an elevated risk of hamstring strains. Indeed, there is a small amount of evidence supporting this [3, 81]. Our group has also recently found an
association between Nordic hamstring curl strength asymmetries and hamstring injury in a cohort of 170 Rugby Union players (unpublished observations) although no such association was found in a study of AFL players [7]. The results of the present study suggest, however, that the addition of loads during the Nordic hamstring curl has no impact on the degree of between limb knee flexor asymmetry, at least not in previously uninjured people.

Previous studies have shown that skeletal muscles are generally less completely activated during eccentric actions than they are during moderate to fast speeds of shortening [12, 75]. In the current study however, levels of hamstring activation across the range of speeds observed do not appear to be affected by lengthening velocity. However, several limitations are currently recognised when employing surface EMG to assess muscle activation [137]. Muscle length for example has a significant effect on surface EMG [137]. In the present study the joint angles at which peak torque was reached did not differ significantly between loading conditions, as a consequence the comparison of surface EMG between loading conditions seems reasonable. As previously discussed in methods, participants in the current studies performed external and internal rotation of their flexed knees so that a judgement could be made as to the appropriate placement of surface electrodes. When, for example, significant medial hamstring activation was observed during external rotation, the electrodes were removed from the original location and replaced with a larger gap between the medial and lateral electrode pairs. This should have minimised crosstalk between medial and lateral hamstrings, but it does not address the issue of crosstalk from adductor muscles, such as the gracilis, which has
previously been shown to be particularly active during the Nordic hamstring curl [116]. Fine wire EMG may allow for greater certainty regarding individual muscle activity and should be considered in future studies.

It should be acknowledged that averaging just two trials at each loading condition is not optimal, particularly given the highly random nature of sEMG. However, the performance of more than 10 Nordic hamstring curls, eight with extra loads, caused a great deal of fatigue in pilot testing so that repetitions beyond the 10th were typically very poor. Even with the 10 repetitions employed here there was some fatigue evident in the final two to three repetitions but the randomisation of the order of loading condition would have minimised the effects on the results reported here.

5.4 Conclusions

5.4.1 Response to First Hypothesis

The results confirm the hypothesis that extra loads held to the chest during the Nordic hamstring curl enable higher peak knee flexor torques to be generated. The effect of extra load plateaus, however, at a certain level of resistance which differs between individuals. For the current group of participants this effect plateaus at an average extra load of 15kg.

5.4.2 Response to Second Hypothesis

Contrary to the original hypothesis, addition of extra loads has no effect on the knee angle at which peak knee flexor torque is reached during the Nordic hamstring curl.

5.4.3 Response to Third Hypothesis
The results confirm the hypothesis that the addition of extra loads result in a significant increase in the knee angle velocities at which peak knee flexor torque is reached during the Nordic hamstring curl.

5.4.4 Response to Fourth Hypothesis

The results support the hypothesis that electromyographic activity of the lateral and medial hamstrings in the 200ms prior to peak torque being reached during the Nordic hamstring curl does not change as a consequence of extra loads.

Together, the findings from Study 3 strongly suggest that the increased knee angle velocities associated with extra loads during the Nordic hamstring curl are responsible for the greater knee flexor torques that are observed.

Chapter 6: Concluding Statements

While the kinematics of the Nordic hamstring curl have been described previously, [109, 119] this is the first study to describe the kinetics of the movement. Without reference to torque, previous descriptions of the exercise have been limited to the rates of knee angle velocity or ‘fall’ rates and to electromyographic activity across the range of motion. This is the first study to describe how knee flexor torques and muscle activations change across the range of motion. As a consequence this is the first study to describe; 1) where in the range of motion and at what angular velocities the peak torques occur; 2) the reliability of these angles and velocities of peak torques; and 3) the effects of extra loads on knee flexor torques and the knee
angles, movement velocities and the electromyographical activity of the lateral and medial hamstrings during the Nordic hamstring curl.

These findings may provide valuable information for injury prevention and rehabilitation programs in the future. For example, the current results suggest that performing the Nordic hamstring curl with extra loads may optimise strength improvements in well trained athletes because muscle torque and force is increased. This may prove of value in future injury prevention intervention studies. The current results also suggest the possibility that extra loads increase knee flexor torque via their effect on the rate at which the knee flexors lengthen. Finally, it has been proposed in previous studies that the inflection point in the relationship between knee joint angular velocity and knee joint angle may be a useful surrogate measure of knee flexor strength, although the current results suggest that this is a highly unreliable measure and that direct measurements of knee flexion forces or torques is much more reliable. Indeed the reliability of direct strength measures during the Nordic hamstring curl has similar reliability as isokinetic dynamometry.

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