8-2021

Biomechanics Differ for Individuals With Similar Self-Reported Characteristics of Patellofemoral Pain During a High-Demand Multiplanar Movement Task

Matthew K. Seeley

Seong Jun Son

Hyunsoo Kim

J. Ty Hopkins

Bibliographic Information:

Journal of Sport Rehabilitation, Vol. 30 Issue 6 (860–869)

***Journal of Sport Rehabilitation*, 2021, 30, 860-869**
https://doi.org/10.1123/jsr.2020-0220

Human Kinetics
ORIGINAL RESEARCH REPORT

Biomechanics Differ for Individuals With Similar Self-Reported Characteristics of Patellofemoral Pain During a High-Demand Multiplanar Movement Task

Matthew K. Seeley, Seong Jun Son, Hyunsoo Kim, and J. Ty Hopkins

Context: Patellofemoral pain (PFP) is often categorized by researchers and clinicians using subjective self-reported PFP characteristics; however, this practice might mask important differences in movement biomechanics between PFP patients. ***Objective:*** To determine whether biomechanical differences exist during a high-demand multiplanar movement task for PFP patients with similar self-reported PFP characteristics but different quadriceps activation levels. ***Design:*** Cross-sectional design. ***Setting:*** Biomechanics laboratory. ***Participants:*** A total of 15 quadriceps deficient and 15 quadriceps functional (QF) PFP patients with similar self-reported PFP characteristics. ***Intervention:*** In total, 5 trials of a high-demand multiplanar land, cut, and jump movement task were performed. ***Main Outcome Measures:*** Biomechanics were compared at each percentile of the ground contact phase of the movement task ($\alpha = .05$) between the quadriceps deficient and QF groups. Biomechanical variables included (1) whole-body center of mass, trunk, hip, knee, and ankle kinematics; (2) hip, knee, and ankle kinetics; and (3) ground reaction forces. ***Results:*** The QF patients exhibited increased ground reaction force, joint torque, and movement, relative to the quadriceps deficient patients. The QF patients exhibited: (1) up to 90, 60, and 35 N more vertical, posterior, and medial ground reaction force at various times of the ground contact phase; (2) up to 4° more knee flexion during ground contact and up to 4° more plantarflexion and hip extension during the latter parts of ground contact; and (3) up to 26, 21, and 48 N·m more plantarflexion, knee extension, and hip extension torque, respectively, at various times of ground contact. ***Conclusions:*** PFP patients with similar self-reported PFP characteristics exhibit different movement biomechanics, and these differences depend upon quadriceps activation levels. These differences are important because movement biomechanics affect injury risk and athletic performance. In addition, these biomechanical differences indicate that different therapeutic interventions may be needed for PFP patients with similar self-reported PFP characteristics.

Keywords: electromyography, joint kinetics, joint kinematics, ground reaction force, functional data analysis, hip, knee, ankle, central activation ratio, quadriceps

Chronic knee pain often impairs physically active individuals,[1] and patellofemoral pain (PFP) is a common source of chronic knee pain.[2] PFP often exists for long durations, involves high recurrence rates, restricts physical activity, and is linked to patellofemoral osteoarthritis.[3–5] Multiple PFP etiologies likely exist, including altered lower-extremity muscle activation patterns and corresponding movement biomechanics. Specifically, altered quadriceps activation patterns are thought to contribute to PFP, and although not fully understood, quadriceps weakness is hypothesized to be a PFP risk factor.[6] PFP patients exhibit increased quadriceps activation during common movements,[7–9] and altered activation timing and amplitude between the vastus lateralis and medialis have long been hypothesized to contribute to PFP.[10]

Because the quadriceps muscles act directly on the pelvis, femur, and tibia, it is not surprising that PFP is known to alter trunk, hip, knee, and ankle joint biomechanics, and ground reaction force (GRF). Increased lateral trunk lean has been observed for PFP patients during a downward stepping task,[11] and trunk motion influences lower-extremity biomechanics for PFP patients.[12] Relative to healthy controls, PFP patients exhibit decreased hip flexion during jump landings.[13] Conversely, similar sagittal-plane hip kinematics during jump landings have been reported for individuals with and without PFP.[14] Decreased knee-flexion angle and vertical GRF during jump landings have been identified as PFP risk factors[14,15]; however, increased vertical GRF with decreased knee-flexion excursion during jump landings have also been linked to PFP.[13] These examples of altered biomechanics for PFP patients demonstrate that (1) movement biomechanics for all major lower-extremity segments and the trunk can be altered by PFP and (2) inconsistent biomechanical differences due to PFP are documented in the scientific literature.[13–15]

Subjective self-reported measures are often used to classify PFP, including the visual analog pain scale (VAS) and Kujala Anterior Knee Pain Scale (AKPS).[16,17] These self-reported measures have been used to classify certain characteristics of PFP, including pain level, during various physical activities including stair descent and ascent, squatting, kneeling, running, jumping, and landing.[13,18–21] The subjective nature of self-reported PFP characteristics, including the inherently subjective nature of pain (the cornerstone criteria for PFP), might contribute to the previously mentioned inconsistencies in some of the PFP literature.

Altered movement biomechanics are known to exist between PFP patients with similar pain levels, but different quadriceps activation levels, during a low-demand uniplanar movement task (walking).[22] It is unknown, however, whether movement biomechanics differ between PFP patients dichotomized by differing quadriceps activation levels during a high-demand multiplanar movement task. In addition, a lack of knowledge exists generally concerning PFP movement biomechanics during high-demand

---

Seeley and Hopkins are with the Department of Exercise Sciences, Brigham Young University, Provo, UT, USA. Son is with the Graduate School of Sports Medicine, CHA University, Seongnam-si, South Korea. Kim is with the Department of Kinesiology, West Chester University, West Chester, PA, USA. Seeley (matt_seeley@byu.edu) is corresponding author.

multiplanar movement. The purpose of this study was to compare movement biomechanics for the trunk and entire lower-extremity between 2 groups of PFP patients during a high-demand multiplanar landing, cutting, and jumping movement task. These 2 groups of PFP patients had similar self-reported measures of PFP, but different levels of functional quadriceps activation, objectively quantified via the superimposed burst technique and resulting central activation ratio (CAR). We hypothesized that the 2 groups of PFP patients would exhibit different biomechanics during a landing, cutting, and jumping movement task, despite the similar self-reported PFP measures. More specifically, we hypothesized that the PFP patients with greater quadriceps activation would exhibit movement biomechanics expected with increased quadriceps activation, including increased knee-flexion angles, internal knee extension moments, and vertical GRFs. Confirmation of this hypothesis would demonstrate the importance of precisely classifying PFP patients using objective measures in addition to often used self-reported measures in research and clinical settings. Findings from this study can inform researchers and clinicians by elucidating potential variance in PFP; for example, researchers attempting to reduce, or simply study, variance in a heterogeneous PFP patients or clinicians considering different therapeutic interventions for PFP patients based upon varying levels of quadriceps activation. This study was part of a larger study designed to test effects of specific therapeutic interventions on PFP; after observing that exactly half of the PFP research participants in the larger study exhibited a CAR ≥0.95, we conducted this analysis.

Materials and Methods

Participants

A total of 30 PFP patients participated in this study. PFP was categorized using the VAS, AKPS, Tampa Scale of Kinesiophobia (TSK), and Tegner Activity Level Scale (TALS), and scores for each of these metrics, for each subject, are presented in the Appendix. The participants were separated into 2 groups of 15 participants, based upon their measured CAR. Participants exhibiting a CAR <0.95 were assigned to the quadriceps deficit (QD) group (5 females and 10 males; age = 23 [3] y, mass = 70 [10] kg, height = 174 [8] cm, CAR = 0.91 [0.03]), while participants exhibiting a CAR ≥0.95 were assigned to the quadriceps functional (QF) group (9 females and 6 males; age = 22 [2] y, mass = 75 [17] kg, height = 176 [10] cm, CAR = 0.97 [0.01]).[23,24] Although this threshold CAR value (0.95) is somewhat arbitrary, the value has been considered to represent full muscle activation[23,25] and used in previous similar research.[22] Participants met the following inclusion criteria at the time of data collection: (1) participation in sport-related physical activity for at least 30 minutes per day at least 3 days per week; (2) chronic anterior knee pain (at least 3 out of 10 on a VAS[26]) for at least 4 weeks prior to data collection during stair descent and at least 2 other physical activities including stair ascent, squatting, kneeling, prolonged sitting, running, or jumping[22] ; (3) at least 90 out of 100 for the AKPS; (4) at least 30 out of 68 on the TSK; and (5) at least 5 out of 10 on the TALS.[22] In addition, participants were required to be experiencing PFP during data collection, quantified via VAS (at least 3 out of 10[26]) immediately before data collection, so that painful movement was represented during data collection. Potential participants were excluded if they reported previous lower-extremity surgery, traumatic patellar dislocation or instability, neurological disorder, meniscal or other intraarticular injury, patella tendinopathy, iliotibial band syndrome, evidence of knee joint effusion, or history of chronic back pain 6 or fewer months before data collection. Potential participants were also excluded if they could not complete the required maximal voluntary isometric contraction (MVIC) trials or the land, cut, and jump movement task due to concurrent PFP. Prior to allocation to the QF or QD group, the MVIC and CAR measures were recorded, and 2 female participants dropped out of the study— one due to discomfort during the MVIC and the other due to discomfort associated with the superimposed burst. In total, 8 of the included participants reported bilateral PFP: 4 female participants reporting bilateral PFP were in the QF group and 4 male participants were in the QD group. For participants reporting bilateral PFP, the most painful leg was considered to be the involved leg. Participants provided informed consent before data collection, and all procedures were approved by the appropriate Brigham Young University Institutional Review Board.

Quadriceps CAR

The CAR is a ratio of maximal knee extension torque during MVIC, without and with external supramaximal input to the quadriceps muscle. The CAR is thought to be useful in detecting decreased quadriceps activity due to various musculoskeletal impairments, including PFP.[22,27] Although the CAR has been previously described,[22] we briefly describe the present methods related to the superimposed burst technique and resulting CAR herein. After prepping the skin, two 7- × 12.7-cm electrodes (Dura-Stick II; Chattanooga, Hixson, TN) were applied over the distal vastus medialis and proximal vastus lateralis. Participants sat upright in a dynamometer (100 Hz; Biodex, Shirley, NY) with 90° and 85° of knee and hip flexion, respectively, confirmed via a traditional goniometer (Fabrication Enterprises Inc, White Plains, NY). After a warm-up, participants performed a knee extension MVIC. As soon as knee extension torque plateaued, a supramaximal electrical burst was manually applied by a researcher (100 pps, 600 μs, 10 trains in 100-ms duration, and 125 V, with peak output current 450 mA, Grass-Telefactor; AstroNova, Inc, West Warwick, RI). This MVIC and supramaximal burst were repeated 4 times with 30 seconds between. Verbal encouragement from the researchers and visual feedback concerning the produced torque was given to participants during the MVICs. The 2 trials resulting in the greatest knee extension torque were averaged, and the CAR was calculated using the following equation:

$$\text{CAR} = \frac{\text{MVIC knee extension torque}}{\text{MVIC knee extension torque} + \text{Supramaximal burst torque}}.$$

Landing, Cutting, and Jumping Task Data Collection

Next, to measure movement biomechanics, single reflective markers and reflective marker clusters were applied to anatomical landmarks in a previously described arrangement.[28] Participants were then required to perform 10 trials of a previously described landing, cutting, and jumping movement task.[29] The initial 5 trials were performed to familiarize participants to the movement task and to determine maximum jump height, quantified as the average maximum height of a pelvis marker during the jump prior to the observed land and cut. The final 5 trials were performed and used for the biomechanical analyses. Although this landing, cutting, and jumping task was previously described,[30] we briefly describe it herein. Participants were required to jump upward and forward off 2 legs and then land on the center of a force platform (1200 Hz;

AMTI, Watertown, MA) on only the involved leg. The height of the initial jump was required to be ±5% of the average maximum jump height of the first 5 trials. The horizontal distance of the initial jump was standardized to half of the participant's body height. After landing on the center of the force platform, participants were required to jump as quickly as possible, laterally, in the direction of the uninvolved leg and then land on the uninvolved leg on a target that was flush to the ground. This target was a standardized distance of 65% of the participant's height away from the center of the force platform. The ground contact phase for each trial was the time that the involved foot contacted the force platform; this phase will be referred to simply as ground contact hereafter. In this context, we generally considered the first and second halves of ground contact to represent landing and jumping, respectively.

Data Reduction

Spatial positions for the previously mentioned reflective markers were determined using 10 high-speed video cameras (240 Hz; Vicon, Centennial, CO). Reflective marker position data were filtered using a recursive low-pass Butterworth digital filter, with a cutoff frequency set at 10 Hz, which was determined via residual analyses of the marker trajectory data.[31] Next, the filtered position data were imported into Visual 3D software (C-Motion, Germantown, MD), where a previously described kinematic model[28] was applied to quantify 3D ankle, knee, and hip joint angles. Whole-body center of mass (COM) positions were calculated using segmental position data and published anthropometric data.[32] Synchronized joint kinematic and GRF data (also filtered at a cutoff frequency set at 10 Hz[33]) were used to estimate 3D net internal ankle, knee, and hip joint torques, using Visual 3D software (C-Motion), the previously mentioned anthropometric data,[32] and a standard inverse dynamics approach. Biomechanical variables of interest included 3D GRF; whole-body COM position; sagittal- and frontal-plane trunk angles; and sagittal-plane hip, knee, and ankle joint angles and net joint internal torques. These biomechanical variables were compared statistically throughout ground contact.

Statistical Analysis

A previously described functional approach was used to compare the biomechanical variables of interest between the QD and QF groups throughout ground contact.[34] This approach resulted in a mean difference function for each biomechanical variable; that is, a function, over time, representing the mean between-group difference for each biomechanical variable at each percentile of ground contact with a corresponding confidence interval at each percentile of ground contact.[22,35] Whenever a confidence interval did not overlap 0, significant between-group differences were presumed to exist at that point in time (percentile). In addition, independent *t* tests were performed to compare mean group demographics (age, height, and mass); self-reported PFP measures (VAS, AKPS, TSK, and TALS); CAR; and maximum jump height. All statistical tests were computed using R software (version 2.15.1) and involved an alpha of .05.

Results

Maximum Jump Height, CAR, and Self-Reported Measures of PFP

Mean maximum jump height was not significantly different between the QD (37.8 [7.8] cm) and QF (38.9 [12.3] cm) groups ($P = .51$). CAR was significantly ($P < .01$) greater for the QF group (0.97 [0.01]) relative to the QD group (0.91 [0.03]). No significant between-group differences existed for participant age ($P = .46$), height ($P = .55$), or mass ($P = .40$). The QD and QF groups were not significantly different for VAS immediately before testing ($P = .87$; QD = 3.87 [1.3] cm; QF = 3.93 [0.7] cm), AKPS ($P = .20$; QD = 82.9 [6.6]; QF = 79.3 [7.9]), TSK ($P = .60$; QD = 37.9 [4.7]; QF = 36.9 [5.2]), TALS ($P = .29$; QD = 6.3 [1.2]; QF = 6.8 ± 1.4), and MVIC strength ($P = .19$; QD = 2.75 [0.53] N·m/kg; QF = 3.06 [0.73] N·m/kg).

GRF and COM Position

Significant between-group differences were observed for each GRF component (Figure 1). Vertical GRF was as much as 90 N greater for the QF group, between 83% and 93% of ground contact (Figure 1A and 1D). Posteriorly directed GRF was as much as 60 N greater for the QF group, between 11% and 21% of ground contact (Figure 1B and 1E). Medially directed GRF was as much as 35 N greater for the QF group, between 85% and 95% of ground contact (Figure 1C and 1F). Significant between-group differences also existed for whole-body COM position in each plane of motion (Figure 2). The QF group exhibited COM positions that were more medial between 1% and 8%, and 50% and 100% (up to 33 cm more medial) of ground contact; however, COM position was up to 4 cm more lateral between 25% and 27% of ground contact for the QF group (Figure 2A and 2D). The QF group exhibited COM positions that were as much as 18 cm more posterior during the first 14% of ground contact (Figure 2B and 2E) and lower (as much as 9 cm) between 17% and 85% of ground contact (Figure 2C and 2F).

Joint Kinematics

Significant between-group differences existed for sagittal-plane ankle, knee, and hip joint angle (Figure 3). The differences that lasted for the greatest duration occurred about the knee joint, where the QF group exhibited as much as 4° more knee flexion, throughout most (15%–85%) of ground contact (Figure 3B and 3E). Differences also existed for ankle and hip joint angle; however, these differences were limited to the final 7% of ground contact: up to 4° more plantarflexion (Figure 3A and 3D) and 4° more hip extension (Figure 3C and 3F) for the QF group. In addition, the QF group exhibited significantly more sagittal- and frontal-plane trunk motion (Figure 4). The QF group exhibited nearly 10° more sagittal-plane trunk flexion during most of ground contact (Figure 4A and 4C) and up to 2° more lateral trunk flexion between 9% and 23% of ground contact (Figure 4B and 4D) in the direction of the uninvolved leg.

Joint Kinetics

Net ankle, knee, and hip sagittal-plane joint torque differed significantly between the QF and QD groups at various parts of ground contact (Figure 5). The QF group exhibited up to 26 Nm more net plantarflexion torque between 11% and 28% of ground contact (Figure 5A and 5D) and up to 13 N·m more plantarflexion torque between 85% and 90% of ground contact. Net knee extension torque was as much as 21 N·m greater for the QF group between 17% and 21% of ground contact, and up to 19 N·m greater, between 70% and 88% of ground contact (Figure 5B and 5E). Net hip extension torque was greater for the QF group for nearly all of ground contact: as much as 48 N·m greater between 3% and 16% and between 20% and 81% (Figure 5C and 5F).

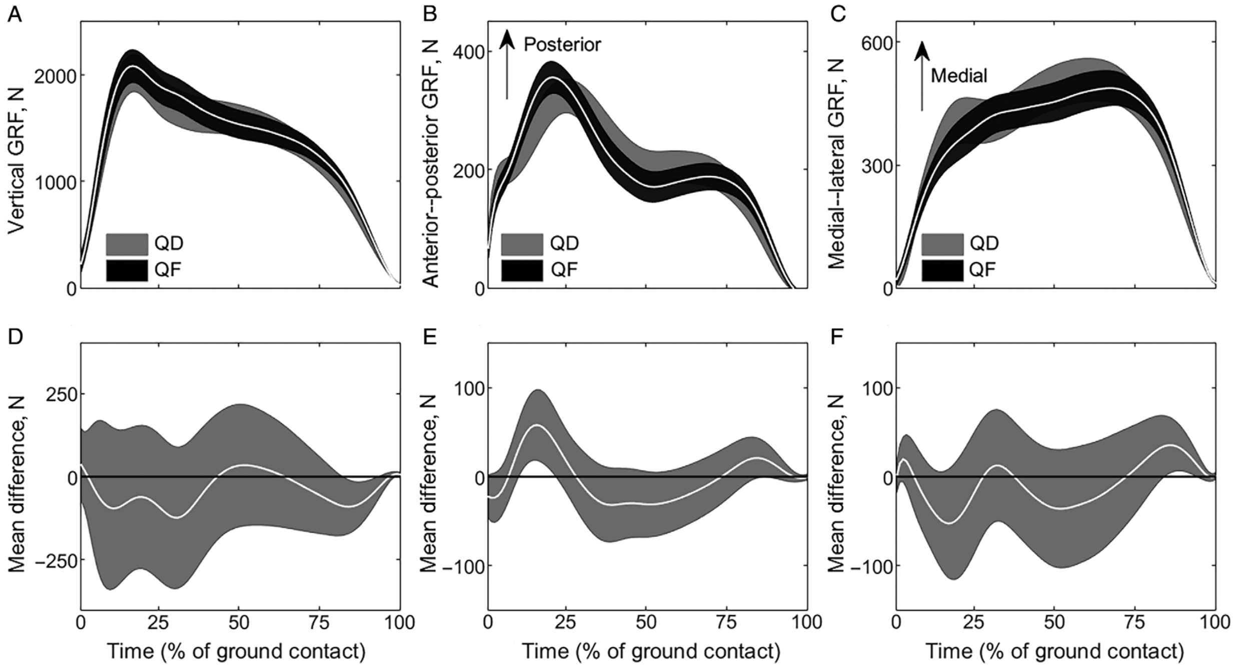

Figure 1 — (A–C) mean vertical, anterior–posterior, and medial–lateral (GRF) over the ground contact phase of a land, cut, and jump movement task for the QF and QD groups. Lines indicating group means, across time, are only included for the QF group to increase clarity. (D–F) Pairwise comparison functions, and associated 95% CI, indicating corresponding mean differences between the QF and QD groups. These mean differences equal the QF mean minus the QD mean at each percentile of the ground contact phase. Significant between-group differences existed where the 95% CI do not overlap 0. CI indicates confidence interval; GRF, ground reaction force; QF, quadriceps functional; QD, quadriceps deficiency.

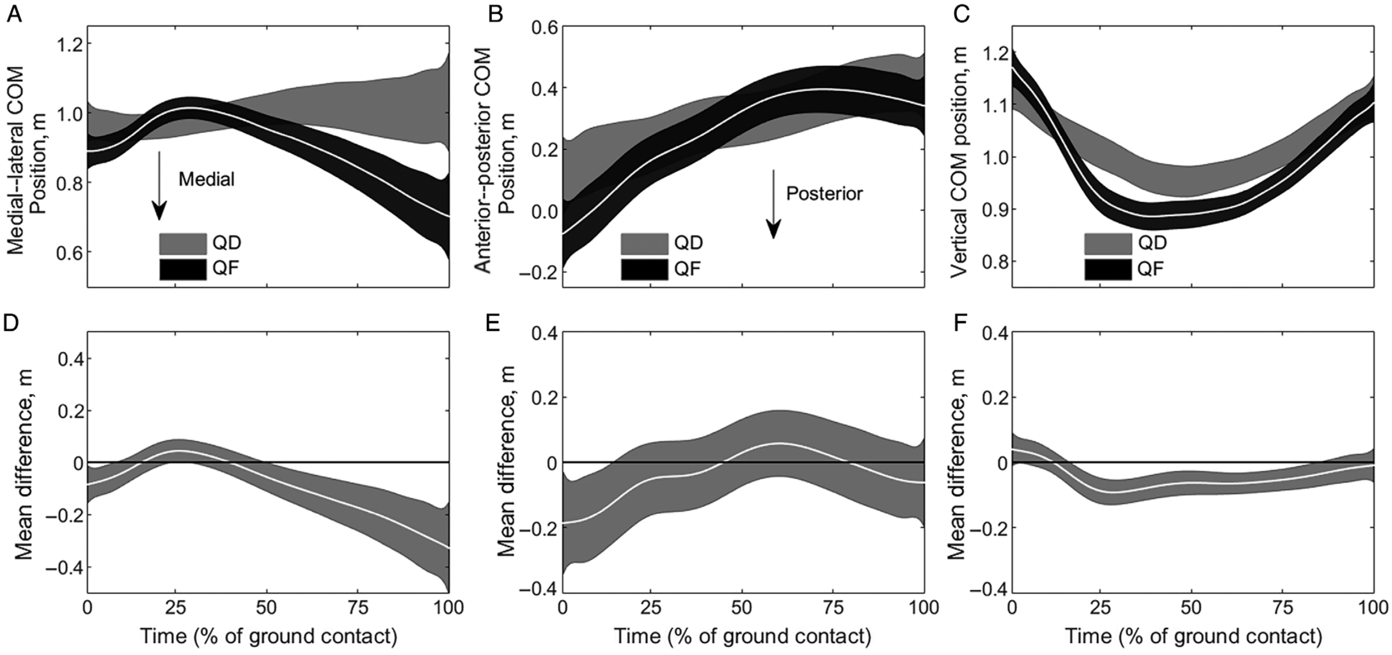

Figure 2 — (A–C) mean medial–lateral, anterior–posterior, and vertical COM position over the ground contact phase of a land, cut, and jump movement task for the QF and QD groups. Lines indicating group means, across time, are only indicated for the QF group to increase clarity. (D–F) Pairwise comparison functions, and associated 95% CI, indicating corresponding mean differences between the QF and QD groups. These mean differences equal the QF mean minus the QD mean at each percentile of the ground contact phase. Significant between-group differences existed where the 95% CI do not overlap 0. CI indicates confidence interval; COM, center of mass; QF, quadriceps functional; QD, quadriceps deficiency.

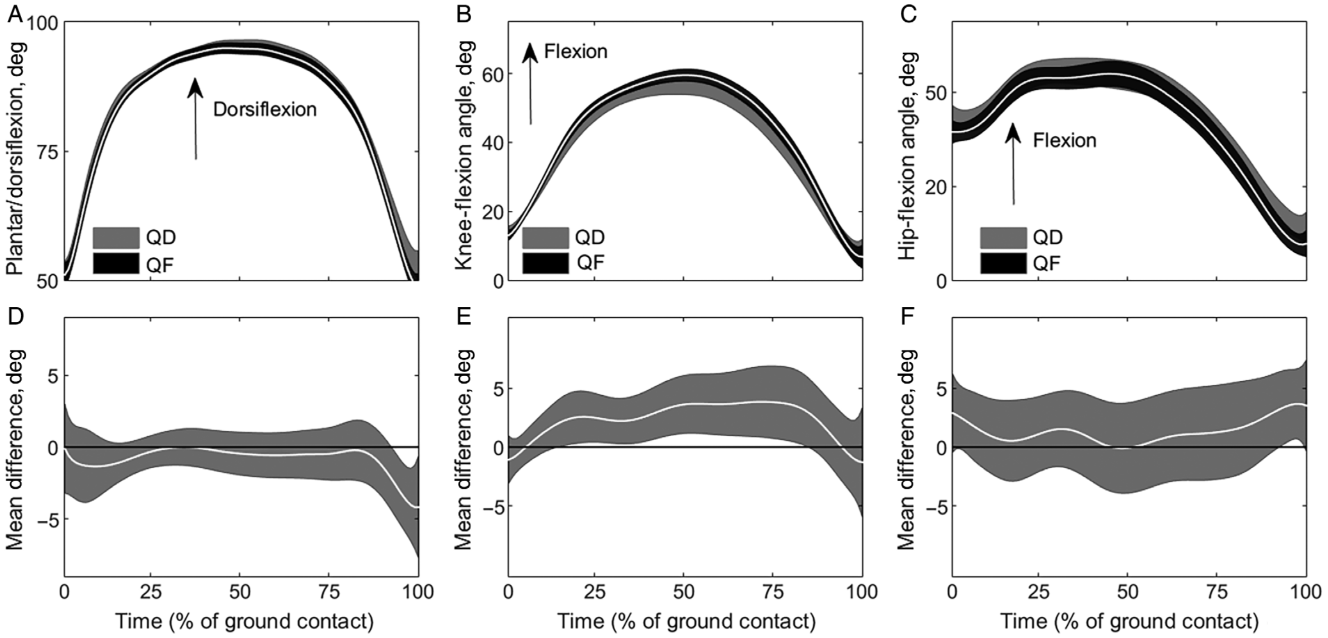

Figure 3 — (A–C) Mean sagittal-plane ankle, knee, and hip angle over the ground contact phase of a land, cut, and jump movement task for the QF and QD groups. Lines indicating group means, across time, are only included for the QF group to increase clarity. (D–F) Pairwise comparison functions, and associated 95% CI, indicating corresponding mean differences between the QF and QD groups. These mean differences equal the QF mean minus the QD mean at each percentile of the ground contact phase. Significant between-group differences existed where the 95% CI do not overlap 0. CI indicates confidence interval; QF, quadriceps functional; QD, quadriceps deficiency.

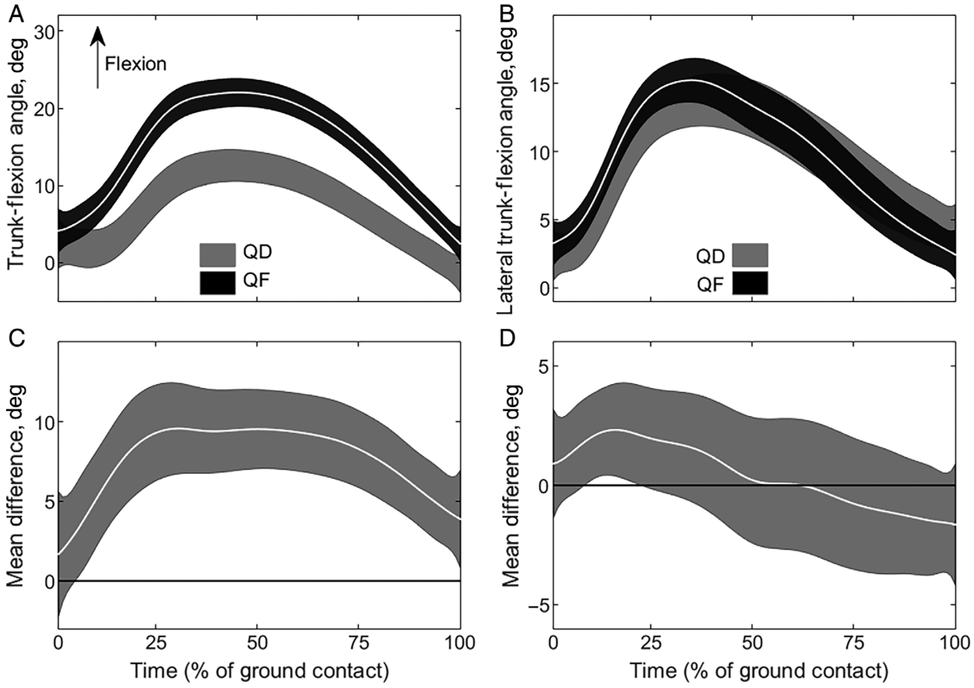

Figure 4 — (A–B) Mean sagittal- and frontal-plane trunk angle over the ground contact phase of a land, cut, and jump movement task for the QF and QD groups. Lines indicating group means, across time, are only included for the QF group to increase clarity. (C–D) Pairwise comparison functions, and associated 95% CI, indicating corresponding mean differences between the QF and QD groups. These mean differences equal the QF mean minus the QD mean at each percentile of the ground contact phase. Significant between-group differences existed where the 95% CI do not overlap 0. CI indicates confidence interval; QF, quadriceps functional; QD, quadriceps deficiency.

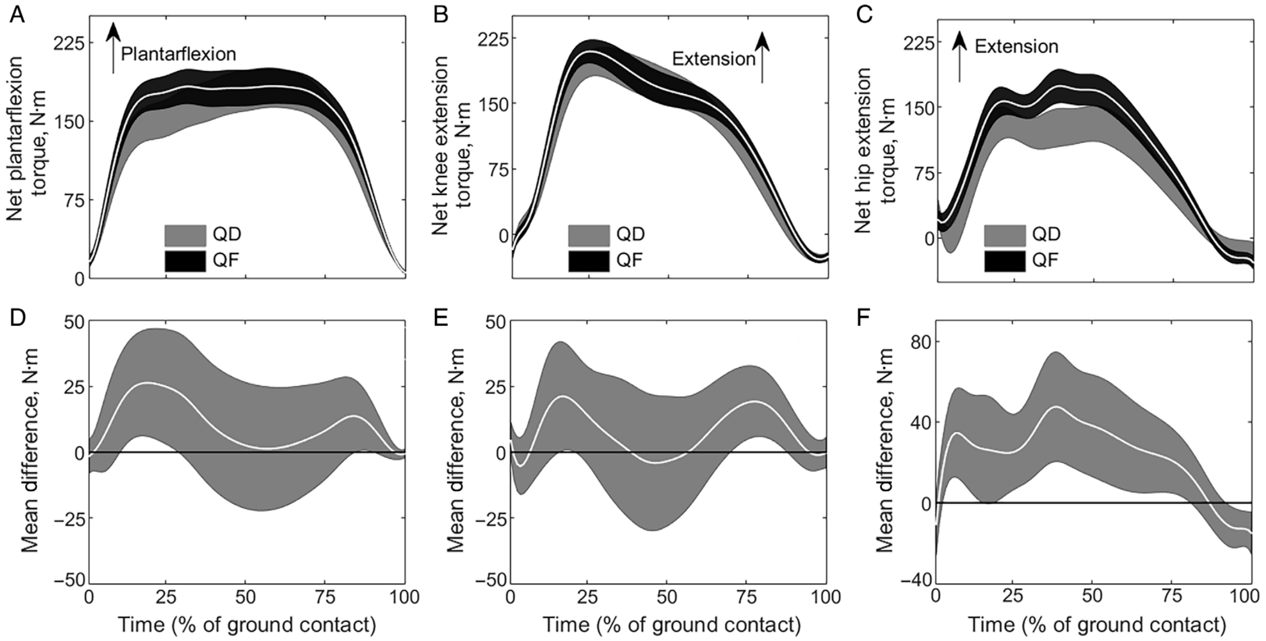

Figure 5 — (A–C) Mean sagittal-plane ankle, knee, and hip net internal torque over the ground contact phase of a land, cut, and jump movement task for the QF and QD groups. Lines indicating group means, across time, are only included for the QF group to increase clarity. (D–F) Pairwise comparison functions, and associated 95% CI, indicating corresponding mean differences between the QF and QD groups. These mean differences equal the QF mean minus the QD mean at each percentile of the ground contact phase. Significant between-group differences existed where the 95% CI do not overlap 0. CI indicates confidence interval; QF, quadriceps functional; QD, quadriceps deficiency.

Discussion

The purpose of this study was to compare movement biomechanics during a high-demand multiplanar movement task between 2 groups of PFP patients with similar self-reported PFP measures but different quadriceps activation levels. We hypothesized that biomechanical variables associated with increased quadriceps activation (knee-flexion angle, knee extension moment, and vertical GRF) would be greater for the group of PFP patients with increased quadriceps activation (the QF group). The present results supported this hypothesis. The QF group exhibited biomechanical patterns reflecting a more dynamic completion of the movement task: increased COM excursion, joint angular displacement and net joint torque, and GRF. Specifically, the QF group exhibited greater posterior GRF during early ground contact and greater vertical and medial GRF later in ground contact (Figure 1). These GRF differences, respectively, demonstrate an increased ability to slow a forward moving COM during initial landing and then accelerate the COM upward and laterally later during ground contact. The GRF findings fit with the COM position data. COM trajectory for the QF group was more posterior during early ground contact (landing) and more medial throughout the rest of ground contact (Figure 2). The COM underwent greater vertical displacement throughout the movement task (Figure 2C and 2F) for the QF group. During early ground contact, the QF group exhibited more lateral trunk flexion in the direction of the target the participants were instructed to jump toward and more forward trunk flexion during early ground contact. The QF group also increased plantarflexion and hip extension during late ground contact (jumping) and knee flexion throughout ground contact (Figures 3 and 4). Furthermore, the QF group produced more net internal plantarflexion and knee and hip extension torque throughout the landing, cutting, and jumping task (Figure 5). This is the first study to document that PFP patients with similar self-reported PFP characteristics (eg, VAS and AKPS) exhibit different biomechanics during a high-demand multiplanar movement task.

These findings are important because the 2 groups of PFP patients differed in biomechanical characteristics known to influence injury risk for PFP and other lower-extremity musculoskeletal injuries. Several of the observed kinematic variables have been linked to altered patellofemoral joint stress, which is believed to contribute to PFP.[36] The increased trunk flexion observed for the QF group (Figure 4) is known to be associated with decreased patellofemoral joint stress during running.[37,38] The increased knee flexion observed in the QF group (Figure 3B and 3E) is associated with increased patellofemoral contact area in a static weight-bearing position[39] and increased patellofemoral joint stress during running.[40] Corresponding increases in patellofemoral contact area and stress have been previously observed simultaneously and are presumably due to corresponding increases in knee extension moment, which (1) has been associated with increased PFP and (2) was presently observed (Figure 5B and 5E).[41] In addition, in a recent systematic review, decreased knee flexion during jump landings, relative to healthy controls, was identified as a PFP risk factor.[42] In addition to altering patellofemoral joint biomechanics, the decreased knee flexion (Figure 3B and 3E) exhibited by the QD group may result in increased load applied to the skeletal system and other passive load bearing structures (eg, tendons and ligaments) of the lower-extremity, rather than quadriceps musculature. Furthermore, decreased knee-flexion excursion has been observed for other impaired populations known to suffer from quadriceps activation deficits and decreased ranges of motion (eg, anterior cruciate ligament reconstruction and knee osteoarthritis patients).[43–45] The reduced sagittal-plane knee excursion presently demonstrated by the QD group indicate a more conservative and rigid strategy with less range of motion and a COM more directly over the base of support (the involved foot), perhaps more stability, but decreased ability to accelerate in a desired direction. The QD group exhibited what appeared to be a quadriceps avoidance strategy represented by reduced knee-flexion angle and extension torque (Figures 3B, 3E, 5B, and 5E).

The present results indicate heterogeneity in quadriceps activation for PFP patients reporting similar PFP characteristics. This heterogeneity relates interestingly to the idea of arthrogenic muscle inhibition (AMI), which is defined as an ongoing reflexive inhibition of musculature surrounding an injured joint,[46] and could have implications on PFP physical rehabilitation. AMI is thought to be a protective mechanism that limits motion and/or force. AMI is thought to result from afferent pain receptors and/or mechanoreceptors in and around the injured joint, as well as other potential neurophysiological causes. This study, involving 2 different groups of PFP patients dichotomized by high and low CAR, shows that not all PFP patients suffer from AMI and that pain does not always cause quadriceps inhibition for PFP patients. The research participants in both the QF and QD groups reported similar levels of PFP pain but exhibited different levels of objectively measured quadriceps activation. Perhaps variance in quadriceps activation within PFP patients with similar self-reported PFP characteristics and a lack of variance in PFP therapeutic approaches contribute to poor therapeutic outcomes due to one therapeutic approach for numerous patients with differing underlying impairments. Clinicians should consider the possibility that physically active individuals with similar self-reported PFP characteristics might have different quadriceps activation levels, different corresponding movement biomechanics, and require different therapeutic approaches. Clinicians should also consider therapeutic modalities known to overcome effects of AMI for PFP patients with confirmed or suspected quadriceps inhibition. Therapeutic interventions, such as transcutaneous electrical neural stimulation or cryotherapy, in addition to traditional strength training, may improve quadriceps activation for physically active individuals suffering from PFP and impaired quadriceps activation.[47] We concede that many clinicians do not have access to technical instrumentation required to objectively measure the CAR; however, other measures can/should be considered as potential surrogates. We recommend that researchers explore relationships between the CAR and potential CAR surrogates for PFP patients. Potential surrogate measures that are available to clinicians should be evaluated to make the objective evaluation of functional quadriceps activation more feasible for clinicians.

Although performance was not quantified in this study, some of the observed biomechanical differences could be interpreted to reflect potential for improved sport performance for the QF group, relative to the QD group. For example, medial GRF toward the end of ground contact, was substantially greater for the QF group: up to 35 N, or nearly 5% of mean body weight (Figure 1C and 1F). This GRF difference would have directly assisted the QF participants in cutting and jumping medially toward the designated target. Furthermore, whole-body COM position was more medial for the QF group (Figure 2A and 2D), relative to the QD group, which could have also assisted the QF subjects in successfully performing the movement task. This between-group difference for medial-lateral COM position (1) was partly due to increased lateral trunk flexion (Figure 4B and 4D) for the QF group, (2) was quite large (up to 33 cm), and (3) resulted in a COM for the QF subjects that was closer to the designated target during the second half of ground contact (Figure 2A and 2C). In addition, the decreased COM height (Figure 2C and 2F) and increased knee flexion (Figure 3B and 3E) for the QF participants, throughout most of ground contact, could reflect more potential strain energy stored in certain passive structures of the involved lower-extremity; this idea fits with the observed increases for joint torque (Figure 5) and vertical GRF (Figure 1A and 1D) for the QF group. Although the biomechanical differences described in this paragraph could reflect increased performance potential for the QF group, this idea should be further tested via comparisons between a QF group and a healthy control group.

This study has some important limitations. The most important limitation is probably the disparate numbers of male and female participants in the QD (5 females and 10 males) and QF (9 females and 6 males) groups. As mentioned previously, the present participants were part of a larger study (n = 30) designed to test effect(s) of certain therapeutic interventions on PFP. In this larger study, after observing that exactly half of the PFP participants exhibited a CAR greater than or equal to 0.95, we determined to conduct this analysis. There were no between-group differences for any of the self-reported PFP characteristics or, importantly, MVIC knee extension strength; however, movement biomechanics are known to differ between sexes, and the difference in numbers of males and females in the 2 present groups makes it difficult to determine whether the present differences are due to differences in quadriceps activation or sex. The lack of a between-group difference for MVIC knee extension strength, even though quadriceps activation was significantly different between groups, could have been due (at least partly) to differences in the numbers of male and female participants for the 2 groups. Future research is needed investigating more closely differences in CAR between females and males. Another limitation to this study is the lack of a healthy control group. Future research should compare biomechanical characteristics of the present land, cut, and jump movement task for QF and QD participants to a healthy control group to better inform clinicians concerning appropriate therapeutic objectives for PFP rehabilitation. Another limitation is that perceived anterior knee pain was only quantified once before data collection to determine participant inclusion in the study. In hindsight, measures of perceived anterior knee pain should have been collected at multiple time points (eg, during the MVIC, and immediately before and after the dynamic movement trials). This would have allowed an investigation of the effects of pain on the observed movement biomechanics. Finally, the superimposed burst technique and resulting CAR is only one way to objectively quantify quadriceps activation. Other methods might produce varying results. Similarly, there are other approaches that can be used to determine self-reported PFP characteristics.

Conclusions

This study shows that the biomechanics of a high-demand multiplanar landing, cutting, and jumping movement task can vary within a group of PFP patients reporting similar subjective characteristics of PFP. These biomechanical differences appear to depend, at least in part, upon quadriceps activation level. Relative to PFP patients with decreased quadriceps activation, PFP patients with greater quadriceps activation completed the land, cut, and jump movement task in a way that involved greater GRF; increased joint motion (trunk, hip, knee, and ankle); and more net joint torque (hip, knee, and ankle). It is important to consider these neuromechanical differences when studying and treating PFP in competitive athletes and other physically active individuals.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. There are no conflicts of interest to report.

References

1. Rathleff MS, Roos EM, Olesen JL, Rasmussen S. High prevalence of daily and multi-site pain–a cross-sectional population-based study among 3000 Danish adolescents. *BMC Pediatr*. 2013;13(1):191. PubMed ID: 24252440 doi:10.1186/1471-2431-13-191
2. Smith BE, Selfe J, Thacker D, et al. Incidence and prevalence of patellofemoral pain: a systematic review and meta-analysis. *PLoS One*. 2018;13(1):e0190892. PubMed ID: 29324820 doi:10.1371/journal.pone.0190892
3. Crossley KM, Stefanik JJ, Selfe J, et al. 2016 Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 1: Terminology, definitions, clinical examination, natural history, patellofemoral osteoarthritis and patient-reported outcome measures. *Br. J. Sports Med*. 2016;50(14):839–843. PubMed ID: 27343241 doi:10.1136/bjsports-2016-096384
4. Stathopulu E, Baildam E. Anterior knee pain: a long-term follow-up. *Rheumatology*. 2003;42(2):380–382. PubMed ID: 12595641 doi:10.1093/rheumatology/keg093
5. Blønd L, Hansen L. Patellofemoral pain syndrome in athletes: a 5.7-year retrospective follow-up study of 250 athletes. *Acta Orthop Belg*. 1998;64(4):393–400.
6. Crossley KM, van Middelkoop M, Barton CJ, Culvenor AG. Rethinking patellofemoral pain: prevention, management and long-term consequences. *Best Pract Res Clin Rheumatol*. 2019;33(1): 48–65. PubMed ID: 31431275 doi:10.1016/j.berh.2019.02.004
7. Glaviano NR, Saliba S. Differences in gluteal and quadriceps muscle activation during weight-bearing exercises between female subjects with and without patellofemoral pain. *J Strength Cond Res*. 2019: 1533–4287 (Epub ahead of print).
8. Mirzaie GH, Rahimi A, Kajbafvala M, Manshadi FD, Kalantari KK, Saidee A. Electromyographic activity of the hip and knee muscles during functional tasks in males with and without patellofemoral pain. *J Bodyw Mov Ther*. 2019;23(1):54–58. PubMed ID: 30691762 doi:10.1016/j.jbmt.2018.11.001
9. Briani RA-O, De Oliveira Silva D, Flóride CS, et al. Quadriceps neuromuscular function in women with patellofemoral pain: Influences of the type of the task and the level of pain. *PLoS One*. 2018; 13(10):e0205553. PubMed ID: 30304030 doi:10.1371/journal.pone.0205553
10. Sisk D, Fredericson M. Update of risk factors, diagnosis, and management of patellofemoral pain. *Curr Rev Musculoskelet Med*. 2019;12(4):534–541. PubMed ID: 31773479 doi:10.1007/s12178-019-09593-z
11. Nakagawa TH, Moriya ÉTU, Maciel CD, SerrãO FV. Frontal plane biomechanics in males and females with and without patellofemoral pain. *Med Sci Sports Exerc*. 2012;44(9):1747–1755. PubMed ID: 22460471 doi:10.1249/MSS.0b013e318256903a
12. Baldon Rde M, Piva SR, Scattone Silva R, Serrão FV. Evaluating eccentric hip torque and trunk endurance as mediators of changes in lower limb and trunk kinematics in response to functional stabilization training in women with patellofemoral pain. *Am J Sports Med*. 2015;43(6):1485–1493.
13. Nunes GS, Barton CJ, Viadanna Serrão F. Females with patellofemoral pain have impaired impact absorption during a single-legged drop vertical jump. *Gait Posture*. 2019;68:346–351. PubMed ID: 30579038 doi:10.1016/j.gaitpost.2018.12.013
14. Boling MC, Padua DA, Marshall SW, Guskiewicz K, Pyne S, Beutler A. A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *Am J Sports Med*. 2009;37(11):2108–2116. PubMed ID: 19797162 doi:10.1177/0363546509337934
15. Boling MC, Nguyen AD, Padua DA, Cameron KL, Beutler A, Marshall SW. Gender-specific risk factor profiles for patellofemoral pain. *Clin J Sport Med*. 2019;24:1536–3724 (Electronic). doi:10.1097/jsm.0000000000000719
16. Plastaras C, McCormick Z, Nguyen C, et al. Is hip abduction strength asymmetry present in female runners in the early stages of patellofemoral pain syndrome? *Am J Sports Med*. 2016;44(1):105–112. PubMed ID: 26566993 doi:10.1177/0363546515611632
17. Ferber R, Bolgla L, Earl-Boehm JE, Emery C, Hamstra-Wright K. Strengthening of the hip and core versus knee muscles for the treatment of patellofemoral pain: a multicenter randomized controlled trial. *J Athl Train*. 2015;50(4):366–377. PubMed ID: 25365133 doi:10.4085/1062-6050-49.3.70
18. Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys*. 2009;39(1):12–19. PubMed ID: 19131677 doi:10.2519/jospt.2009.2885
19. Boling MC, Bolgla LA, Mattacola CG, Uhl TL, Hosey RG. Outcomes of a weight-bearing rehabilitation program for patients diagnosed with patellofemoral pain syndrome. *Arch Phys M*. 2006;87(11):1428–1435. PubMed ID: 17084115 doi:10.1016/j.apmr.2006.07.264
20. Lewinson RT, Wiley JP, Humble RN, Worobets JT, Stefanyshyn DJ. Altering Knee Abduction angular impulse using wedged insoles for treatment of patellofemoral pain in runners: a six-week randomized controlled trial. *PLoS One*. 2015;10(7):e0134461. PubMed ID: 26230399 doi:10.1371/journal.pone.0134461
21. Glaviano NR, Saliba SA. Immediate effect of patterned neuromuscular electrical stimulation on pain and muscle activation in individuals with patellofemoral pain. *J Athl Train*. 2016;51(2):118–128. PubMed ID: 26967547 doi:10.4085/1062-6050-51.4.06
22. Seeley MK, Son SJ, Kim H, Hopkins JT. Walking mechanics for patellofemoral pain subjects with similar self-reported pain levels can differ based upon neuromuscular activation. *Gait Posture*. 2017; 53:48–54. PubMed ID: 28092813 doi:10.1016/j.gaitpost.2017.01.005
23. Park J, Hopkins JT. Quadriceps activation normative values and the affect of subcutaneous tissue thickness. *J Electromyogr Kinesiol*. 2011(21):136–140.
24. Lynch AD, Logerstedt DS, Axe MJ, Snyder-Mackler L. Quadriceps activation failure after anterior cruciate ligament rupture is not mediated by knee joint effusion. *J Orthop Sports Phys*. 2012;42(6): 502–510. PubMed ID: 22523081 doi:10.2519/jospt.2012.3793
25. Son SJ, Kim H, Seeley MK, Feland JB, Hopkins JT. Effects of transcutaneous electrical nerve stimulation on quadriceps function in individuals with experimental knee pain. *Scand J Med Sci Sports*. 2016;26(9):1080–1090. PubMed ID: 26346597 doi:10.1111/sms.12539
26. Bolgla LA, Malone TR, Umberger BR, Uhl TL. Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome. *J Orthop Sports Phys*. 2008;38(1): 12–18. doi:10.2519/jospt.2008.2462
27. Norte GE, Frye JL, Hart JM. Reliability of the Superimposed-Burst technique in patients with patellofemoral pain: a technical report. *J Athl Train*. 2015;50(11):1207–1211. PubMed ID: 26636730 doi:10.4085/1062-6050-50.10.03

28. Ford KR, Shapiro R, Myer GD, Van den Bogert AJ, Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc*. 2010;42(10):1923–1931. PubMed ID: 20305577 doi:10.1249/MSS.0b013e3181dc99b1
29. Kim H, Son SJ, Seeley MK, Hopkins JT. Kinetic compensations due to chronic ankle instability during landing and jumping. *Med Sci Sports Exerc*. 2016;50(2):308–317. doi:10.1249/MSS.0000000000001442
30. Son SJ, Kim H, Seeley MK, Hopkins JT. Movement strategies among groups of chronic ankle instability, coper, and control. *Med Sci Sports Exerc*. 2017;49(8):1649–1661. PubMed ID: 28350716 doi:10.1249/MSS.0000000000001255
31. Winter DA. *Biomechanics and Motor Control of Human Movement*. 2nd ed. USA: John Wiley & Sons; 1990.
32. Dempster W. *Space Requirements of the Seated Operator. WADC Technical Report (TR-55-159)*. OH: Wright-Patterson Air Force Base; 1955.
33. Bisseling RW, Hof AL. Handling of impact forces in inverse dynamics. *J Biomech*. 2006;39(13):2438–2444. PubMed ID: 16209869 doi:10.1016/j.jbiomech.2005.07.021
34. Park J, Denning WM, Pitt JD, Francom D, Hopkins JT, Seeley MK. Effects of experimental anterior knee pain on muscle activation during landing and jumping performed at various intensities. *J Sport Rehabil*. 2017;26(1):78–93. PubMed ID: 27632828 doi:10.1123/jsr.2015-0119
35. Park J, Seeley MK, Francom D, Reese CS, Hopkins JT. Functional vs. traditional analysis in biomechanical gait data: an alternative statistical approach. *J Hum Kinet*. 2017;60(1):39–49. PubMed ID: 29339984 doi:10.1515/hukin-2017-0114
36. Powers CM, Witvrouw E, Davis IS, Crossley KM. Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3. *Br J Sports Med*. 2017;51(24):1713. PubMed ID: 29109118 doi:10.1136/bjsports-2017-098717
37. Teng HL, Powers CM. Sagittal plane trunk posture influences patellofemoral joint stress during running. *J Orthop Sports Phys*. 2014;44(10):785–792. doi:10.2519/jospt.2014.5249
38. Atkins LT, Smithson C, Grimes D, Heuer N. The influence of sagittal trunk posture on the magnitude and rate of patellofemoral joint stress during stair ascent in asymptomatic females. *Gait Posture*. 2019; 74:121–127. PubMed ID: 31499406 doi:10.1016/j.gaitpost.2019.08.016
39. Besier TF, Draper CE, Gold GE, Beaupré GS, Delp SL. Patellofemoral joint contact area increases with knee flexion and weight-bearing. *J Orthop Res*. 23(2):345–350. doi:10.1016/j.orthres.2004.08.003
40. Willson JD, Sharpee R, Meardon SA, Kernozek TW. Effects of step length on patellofemoral joint stress in female runners with and without patellofemoral pain. *Clin Biomech*. 2014;29(3): 243–247. PubMed ID: 24439063 doi:10.1016/j.clinbiomech.2013.12.016
41. Liao TC, Keyak JH, Powers CM. Runners with patellofemoral pain exhibit greater peak patella cartilage stress compared with pain-free runners. *J Appl Biomech*. 2018;34(4):298–305. PubMed ID: 29485362 doi:10.1123/jab.2017-0229
42. De Bleecker C, Vermeulen S, De Blaiser C, Willems T, De Ridder R, Roosen P. Relationship between jump-landing kinematics and lower extremity overuse injuries in physically active populations: a systematic review and meta-analysis. *Sports Med*. 2020;50(8):1515–1532. PubMed ID: 32514700 doi:10.1007/s40279-020-01296-7
43. Edd SN, Favre J, Blazek K, Omoumi P, Asay JL, Andriacchi TP. Altered gait mechanics and elevated serum pro-inflammatory cytokines in asymptomatic patients with MRI evidence of knee cartilage loss. *Osteoarthr. Cartil*. 2017;25(6):899–906. PubMed ID: 28064033 doi:10.1016/j.joca.2016.12.029
44. Nagano Y, Naito K, Saho Y, et al. Association between in vivo knee kinematics during gait and the severity of knee osteoarthritis. *The Knee*. 2012;19(5):628–632. PubMed ID: 22192889 doi:10.1016/j.knee.2011.11.002
45. Erhart-Hledik JC, Chu CR, Asay JL, Andriacchi TP. Longitudinal changes in knee gait mechanics between 2 and 8 years after anterior cruciate ligament reconstruction. *J Orthop Res*. 2018;36(5):1478–1486. PubMed ID: 28984381 doi:10.1002/jor.23770
46. Hopkins JT, Ingersoll CD. Arthrogenic muscle inhibition: a limiting factor in joint rehabilitation. *J Sport Rehabil*. 2000;9(2):135–159. doi:10.1123/jsr.9.2.135
47. Bazett-Jones DM, Huddleston W, Cobb S, O'Connor K, Earl-Boehm JE. Acute responses of strength and running mechanics to increasing and decreasing pain in patients with patellofemoral pain. *J Athl Train*. 2017;52(5):411–421. PubMed ID: 28388232 doi:10.4085/1062-6050-53.3.04

Appendix: Scores for Each Subject in the Quadriceps Functional and Quadriceps Deficit Groups for Perceived Pain (Visual Analog Scale and Anterior Knee Pain Scale), Fear of Movement (Tampa Scale of Kinesiophobia), and Physical Activity Level (Tegner Activity Level Scale)

Group	Subject	Visual analog scale	Anterior Knee Pain Scale	Tampa Scale for Kinesiophobia	Tegner Activity Level Scale
Quadriceps functional	1	3	89	37	6
	2	5	73	45	6
	3	3	89	29	5
	4	3	89	46	7
	5	3	89	42	6
	6	3	85	38	6
	7	6	69	36	8
	8	6	77	30	5
	9	6	74	35	5
	10	5	80	42	7
	11	3	81	34	7
	12	3	86	38	9
	13	3	86	39	5
	14	3	87	37	7
	15	3	89	41	5
Quadriceps deficit	1	4	85	35	6
	2	3	86	30	8
	3	4	80	37	6
	4	5	82	44	5
	5	4	65	48	5
	6	4	82	40	8
	7	3	72	27	9
	8	4	83	37	9
	9	5	89	33	9
	10	4	82	43	6
	11	4	82	37	6
	12	4	76	35	7
	13	4	89	38	7
	14	3	75	34	6
	15	6	61	36	5