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High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: Is PFP itself a predictor for subsequent ACL injury?

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Abstract

Background—Identifying risk factors for knee pain and anterior cruciate ligament (ACL) injury can be an important step in the injury prevention cycle.

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Objective—We evaluated two unique prospective cohorts with similar populations and methodologies to compare the incidence rates and risk factors associated with patellofemoral pain (PFP) and ACL injury.

Methods—The 'PFP cohort' consisted of 240 middle and high school female athletes. They were evaluated by a physician and underwent anthropometric assessment, strength testing and three-dimensional landing biomechanical analyses prior to their basketball season. 145 of these athletes met inclusion for surveillance of incident (new) PFP by certified athletic trainers during their competitive season. The 'ACL cohort' included 205 high school female volleyball, soccer and basketball athletes who underwent the same anthropometric, strength and biomechanical assessment prior to their competitive season and were subsequently followed up for incidence of ACL injury. A one-way analysis of variance was used to evaluate potential group (incident PFP vs ACL injured) differences in anthropometrics, strength and landing biomechanics. Knee abduction moment (KAM) cut-scores that provided the maximal sensitivity and specificity for prediction of PFP or ACL injury risk were also compared between the cohorts.

Results—KAM during landing above 15.4 Nm was associated with a 6.8% risk to develop PFP compared to a 2.9% risk if below the PFP risk threshold in our sample. Likewise, a KAM above 25.3 Nm was associated with a 6.8% risk for subsequent ACL injury compared to a 0.4% risk if below the established ACL risk threshold. The ACL-injured athletes initiated landing with a greater knee abduction angle and a reduced hamstrings-to-quadriceps strength ratio relative to the incident PFP group. Also, when comparing across cohorts, the athletes who suffered ACL injury also had lower hamstring/quadriceps ratio than the players in the PFP sample ($p<0.05$).

Conclusions—In adolescent girls aged 13.3 years, >15 Nm of knee abduction load during landing is associated with greater likelihood of developing PFP. Also, in girls aged 16.1 years who land with >25 Nm of knee abduction load during landing are at increased risk for both PFP and ACL injury.

INTRODUCTION

Patellofemoral pain (PFP) is the most common disorder of the knee, with its greatest incidence in young, physically active girls.[1-5] Early identification of risk factors related to PFP may be critical for the prevention of PFP in young and highly active female athletes.

In young girls, injuries to the anterior cruciate ligament (ACL) result in the greatest total time lost from sport and recreational participation.[6] Adolescent girls are affected with ACL injury 2–10 times more often than their male counterparts.[7-9]

Abnormal neuromuscular control strategies and anthropometric differences in patients with symptomatic PFP and following ACL injury are observed in both sexes (figure 1A). Several retrospective sex-specific investigations sought to identify risk factors for knee pain and injury in female populations (figure 1B).[10-19] However, these retrospective study designs limit the potential to determine if the differences in lower extremity power and static alignments found in male and female patients with symptomatic PFP also contribute to the genesis of PFP.

Prospective studies of the risk factors predictive of the development of debilitating PFP and ACL injury in girls are lacking (figure 1C). Increased external knee abduction moment (KAM) during a drop vertical jump (DVJ) task is associated with increased risk for primary ACL rupture[20] and the development of PFP.[19] There is substantial ACL-related research focused on retrospective analysis[21-44] and mixed populations;[2245-61] this limits the potential to determine sex-specific risk factors that predispose young girls to ACL injury (figure 1).

The purpose of this study was to evaluate two prospective datasets with similar populations and methodologies with injury surveillance methods focused on incidence rates and risk factors for increased risk of PFP or ACL injury. The similar methods and populations provide an opportunity to compare incidence rates and risk factors. We hypothesised that the prospective measure of external KAM would be increased in magnitude in those athletes who sustained an ACL injury compared to those who sustained incident PFP.

METHODS

The current study evaluated and compared two different prospective datasets with similar populations and methodologies with injury surveillance methods focused on incidence rates and risk factors for increased risk of PFP or ACL injury.

PFP incident cohort

Two hundred-and-forty adolescent female athletes were recruited from a county public school district in Kentucky, USA, with five middle schools and three high schools. Participants were evaluated by a physician for prevalence of PFP (n=39) and other exclusionary (N=49) criteria prior to the surveillance period. PFP was operationally defined as retropatellar or peripatellar pain around the patellofemoral joint. At screening, participants were also evaluated for anthropometrics, lower extremity strength and landing biomechanics (DVJ) prior to their basketball season. Participants (N=152; 4 excluded at postseason follow-up) were monitored by certified athletic trainers for PFP during their competitive season. Fourteen participants developed incident PFP during the competitive season.[19]

ACL injury cohort

A similar prospective investigation in our laboratory also evaluated anthropometrics, lower extremity strength and landing biomechanics of 205 young female athletes preseason and monitored for ACL injury during their competitive season. Nine participants sustained an ACL rupture during their competitive season.[20] Therefore, the outcome of interest was the development of pathology in these two cohorts and the involved limb was utilised for between-group comparisons. The cumulative incidence rate for new PFP was 2.2-fold greater (95% CI 1.1 to 4.3) relative to ACL injury when normalised per 100 athlete seasons (PFP 9.7 vs ACL 4.4) in the two compared datasets.

The Institutional Review Board approved the data collection procedures and consent forms. Parental consent and athlete assent were obtained before data collection. Participants were tested prior to the start of their competitive season. The average age, height and mass for the combined cohorts was 15.0 (95% CI 14.7 to 15.2 years), 162.6 (95% CI 161.8 to 163.4 cm) and 57.2 (95% CI 56.1 to 58.2 kg), respectively (table 1).

Landing biomechanics

Three-dimensional (3D) hip, knee and ankle kinematic and kinetic data were quantified for the contact phase of three DVJ tasks. Following instrumentation with retro-reflective markers, a static trial was conducted in which the participant was instructed to stand still with foot placement standardised to the laboratory coordinate system. This static measurement was used as each participant's neutral (zero) alignment; subsequent kinematic measures were referenced in relation to this position. The DVJ involved the participant standing on top of a box (31 cm high) with her feet positioned 35 cm apart. Each athlete was instructed to drop directly down off the box and immediately perform a maximum effort vertical jump, raising both arms while jumping for a basketball that was suspended overhead at a height corresponding to her predetermined maximum vertical jump height.[62]

Data analysis

For each participant, biomechanical variables were calculated during the DVJ manoeuvre and the mean of three trials was utilised for analyses. Specifically, lower limb joint data were generated via the 3D coordinates of externally mounted skin markers.[6263] Net external KAM was described in this paper and has previously demonstrated high reliability for outcome measurement in our laboratory.[63]

Athlete surveillance

The athletes were monitored on a weekly basis for athletic exposures (AEs) for either incident ACL injury or PFP by a certified athletic trainer. AEs were defined as one game or practice session. The AEs of participants with preseason PFP, or other participants who were excluded, were not included in the compilation of total AEs. These data were compiled to calculate in-season injury incidence for each of the compared studies.[64]

Statistical analyses

Statistical analyses were conducted in SPSS (SPSS, V.21.0, Chicago, Illinois, USA). A one-way analysis of variance was used to evaluate potential group (PFP vs ACL) differences in anthropometrics, strength and landing biomechanics. Logistic regression analyses were used to determine threshold KAM cut-off scores that provided the maximal sensitivity and specificity for prediction of PFP and ACL injury risk. The predictive accuracy of the multivariable regression model was quantified with the use of the C statistic, which measures the area under the receiver operating characteristic curve. Incidence rates were expressed per 100 athlete competitive seasons. Statistical significance was established a priori at $p<0.05$.

RESULTS

Maximal sensitivity and specificity for prediction of PFP increased in athletes who demonstrated a peak external KAM>15.4 Nm; ACL injury risk increased with peak landing KAM>25.3 Nm. Cut-scores relative to ACL injury and PFP incidence were compared between the two evaluated investigations (figure 2). KAM during landing above 15.4 Nm was associated with a 6.8% risk to develop PFP compared to a 2.9% risk if below the PFP risk threshold in our sample. Likewise, a KAM above 25.3 Nm was associated with a 6.8% risk for subsequent ACL injury compared to a 0.4% risk if below the established ACL risk threshold. The study participants who developed PFP demonstrated reduced initial contact knee abduction angle relative to the ACL-injured cohort. Specifically, the incident PFP group initiated landing with 1.4° (95% CI −0.5° to 3.2°) compared to ACL injured who impacted the ground with 5.0° (3.4° to 6.5°; p<0.05) of knee abduction angle.

Hamstring flexibility and vertical jump height were not different between the ACL injured and incident PFP groups (p>0.05). The hamstrings-to-quadriceps (HQ) strength ratio was lower in the ACL-injured group than the PFP group. The ACL-injured group demonstrated a 51% HQ strength ratio (42–59%) and the PFP group demonstrated a 68% HQ strength ratio (57–79%; p<0.05). The ACL-injured group demonstrated higher quadriceps strength force production compared to the PFP group (p<0.05), but did not show a similar adaptive increase in hamstrings strength (p>0.05). As noted in table 1, the overall study cohorts were not entirely homogenous in sampling. However, there were group differences in demographic and anthropometric measures between the subsample of incident PFP and ACL-injured cohorts. The ACL-injured group was 15.8 years old compared to the incident PFP group who were 12.7 years of age (p<0.05). Likewise, the ACL-injured cohort was 5.2% taller than the PFP group (p<0.05); however, there were no group differences in participant mass (p>0.05).

DISCUSSION

The purpose of this study was to evaluate two prospective datasets with similar populations to compare the incidence rates and risk factors associated with increased risk of PFP and ACL injury. We hypothesised that the external KAM would be increased in magnitude in those athletes who had an ACL injury compared to those who sustained incident PFP. The results of this study found that girls who demonstrated >15 Nm of knee abduction during landing may be at increased risk for the development of PFP and those who demonstrate >25 Nm of knee abduction during landing may be at increased risk for both PFP and ACL injury.[192065] The increased incidence of PFP compared to that of ACL injury may be associated with the reduced threshold of knee abduction associated with increased risk of PFP. In other words, increased prevalence of PFP may be related to the chronic mechanisms of aberrant knee loading that do not reach the magnitude required for ACL injury during early maturation years. However, as young girls increase in height (specifically tibia length) and mass, small magnitude knee abduction loads naturally increase and can exceed ACL injury risk thresholds in the later adolescent years.[6667]

Differences in anthropometric and strength measures between athletes with PFP and those with ACL injury may also help explain their unique risk profiles. The ACL-injured group was both older and taller than the PFP group, indicating that PFP may be more likely to occur earlier in the maturation cycle. HQ strength measures were also different between groups. While the ACL-injured group demonstrated higher quadriceps strength than the PFP group, their HQ ratio was lower than that of their counterparts. Previous work has highlighted HQ ratios less than 60% as a risk factor for ACL injury,[68] and this may have implications for the jump-landing strategies of these athletes. Girls land with greater net knee extensor compared to net hip extensor moments.[69] In addition, female athletes tend to increase quadriceps activation with increased plyometric intensity without a balanced increase in hamstrings activation.[70] Conversely, during changes through maturation, boys exhibit an increase in net hip extensor torque compared to net knee extensor torque during a landing task.[69] These opposing strategies may, in part, explain the divergence in relative injury risk of girls and boys during the maturation process. Adequate co-contraction of the knee flexors may balance contraction of the quadriceps, compress the joint and potentially limit high knee abduction torques during landing.

Aberrant neuromuscular strategies appear to manifest as reduced frontal plane control of the knee in young female athletes.[71] Reduced lower extremity frontal plane control, combined with a reduction in posterior chain strength, is exacerbated as young girls grow both in height and mass with maturation.[677072] Therefore, focused training on the posterior chain at early maturational stages may be warranted in girls that exhibit high risk (eg, increased KAM) for ACL or PFP.[73-78]

The high recurrence rate of PFP and second ACL injury combined with the poor long-term prognosis indicate that prevention strategies are the best approach to reduce the morbidity associated with PFP developed during youth. Work in our laboratory has successfully employed neuromuscular training interventions to correct the abnormal knee biomechanics that manifest during maturational development in young girls.[19737476] Preseason exercise interventions targeted at the neuromuscular deficits known to increase knee injury risk may be warranted for maturing, adolescent girls. Specifically, adolescent female athletes who land with >15 Nm of knee abduction, may benefit from only preseason training, while those girls who land with >25 Nm of knee abduction may benefit from increased treatment dosage gained from both preseason and in-season neuromuscular training protocols aimed to reduce knee abduction and PFP/ACL injury incidence.[657379] Particularly, training protocols that focus on improved neuromuscular control, with technical feedback provided in the maturing years, appear most effective in the reduction of risk factors and knee injury incidence in female athletes.[7680-82] In addition, in young, adolescent (middle-school aged) girls in whom new PFP incidence appears to peak, increased knee abduction during landing appears to be an early indicator of increased PFP risk and is highly related to increased ACL injury during later adolescence.[19]

An optimal window of opportunity may be present for the initiation of integrative neuromuscular training based on measures of somatic maturity (growth). From these data, it appears most beneficial to initiate integrative training programmes during preadolescence *prior* to the period of peak height velocity, when youth are growing the fastest. Children with earlier growth may particularly benefit from earlier participation in integrative neuromuscular training.[8384] While growth helps define periods optimal for gaining motor competence with integrative training, it is ultimately the child's psychosocial status (ability to follow coaching instructions, adhere to safety rules and handle the attention demands of a training programme) that is paramount in the decision process regarding his or her participation in a structured training programme.[8384] In a recent longitudinal study, it was noted that pubertal girls have an increase in abnormal landing mechanics over time.[72] Contributing risk factors for knee injury were significantly greater across consecutive years in young postpubertal female athletes compared to males. Importantly, integrative neuromuscular training programmes successfully reduce these abnormal biomechanics[73747685] and appear to decrease PFP and ACL injury rates in female athletes.[8687] Therefore, preadolescence may be the optimal time to institute programmes aimed to reduce neuromuscular deficits (increased knee abduction) that accelerate during maturation and lead to increased musculoskeletal injury risk.[192065]

The point prevalence of active symptomatic PFP at the beginning of the season in a cohort of adolescent female athletes followed by our research group was 16.3 per 100 participants (age 13.4 years; range 9.6–18.2). The cumulative incidence risk and rate for the development of new unilateral PFP over the subsequent competitive season was 9.7 per 100 participants and 1.1 per 1000 athlete-exposures, respectively.[19] These incidence data are nearly identical to the 10% reported in a study of older student athletes (age 18.6 years; range 17–21).[4] However, if the participants identified with preseason PFP were included in the analyses, our monitored sample population demonstrated a prevalence of 22.0 per 100 participants. Cumulatively, these data provide strong indications of the need for preseason screening in younger female athletes to identify and minimise the effect of predisposing risk factors of PFP and future ACL injury as young girls mature.[19] Longitudinal data indicate knee pain and injury influences an immediate increase in BMI z-score and body fat percentage in the year of reported incidence.[88] Future research should focus on determination of the underlying pathomechanics of PFP that increase its prevalence in young growing girls to development of sex-specific and age-appropriate interventions. Based on the current report it may be speculated that effective interventions implemented at an early age could be beneficial to prevent PFP prevalence and potentially reduce future risk of ACL injury.

The current report raises the important issue of the use of exercise interventions for prevention. Prior prospective biomechanical reports indicate that exercise interventions may reduce the KAM risk factor common to PFP and ACL injury risk reported in this study.[737685] A more clear understanding of whether reductions in KAM translate into subsequent reductions in injuries such as PFP and ACL will need to be tested in a randomised controlled trial setting.

The clinical interventions that have reduced lower limb injuries appear to be most effective when implemented in younger athletes[81] and must provide adequate dosage of prescribed exercise.[89] Relative to exercise selection, plyometric, strengthening and proximal neuromuscular control exercises appear to reduce ACL injury incidence to a greater extent than programmes without these exercise components.[90] Likewise, it is also likely that proper supervision and feedback of exercises are the common thread throughout the effective training protocols.[81] Qualified instruction is integral to ensure that young athletes are performing exercises properly and not reinforcing bad movement mechanics such as high KAM strategies which may put them at risk for PFP and ACL injury.[769192] Clinical tools that can identify athletes with increased KAM for targeted neuromuscular training might further optimise the efficacy and efficiency of exercise interventions focused to reduce PFP and ACL injury.[92-95] While the evidence is accumulating, further research in children and adolescents is warranted to further determine the potential to prevent PFP and ACL injury risk with interventions targeting underlying KAM mechanics.

LIMITATIONS

We evaluated two prospective datasets to compare the risk factors associated with increased risk of PFP and ACL injury. Future studies should prospectively screen and identify, within the same population, the predictive value of knee abduction to identify risk of both PFP and ACL rupture. Specifically, future studies with homogeneity in anthropometrics and demographics that are longitudinally monitored for PFP and ACL injury incidence are needed to validate our speculations of the current report.

The generalisability of this study is limited to girls performing a DVJ with similar methodology. Lastly, ACL injury and PFP likely have multifactorial aetiology, with unmeasured factors influencing outcome that were not compared in the current investigation. Injury data demonstrate that many physical and psychological parameters affect injury rates. There are several possible contributing and confounding variables that were not controlled for in the study design, which included school, team, age/grade, aggressiveness, foot pronation, quadriceps angle, femoral notch width, reliable menstrual status reporting and blood hormone levels (figure 1). However, neuromuscular parameters appear to be a major determinant of risk for knee injury. Future investigations with larger sample sizes should aim to develop more robust prediction models which include other potential contributing parameters (eg, sport, training error, hormonal measures and potentially psychological parameters) to further elucidate risk factors for PFP or ACL injury.

CONCLUSIONS

The current data indicate that there is minimal overlap between incident ACL injured and incident PFP in the magnitude of the KAM values as their risk factor for injury. It appears that this kinetic parameter measured during landing is, in itself, a risk factor common to both conditions, but lower values are able to predispose young girls to PFP risk and higher values predispose to both PFP and ACL injury. Specifically, young girls who demonstrate >15 Nm of knee abduction during landing may be at increased risk for the development of PFP and is likely reflective of their reduced mass and height (ie, lighter and shorter stature).

Likewise, the limited number of younger female athletes who demonstrate >25 Nm of knee abduction during landing suggests that the increase in mass and height increases frontal plane knee loads. We speculate that this increased frontal load likely propagates beyond just increased risk for the development of PFP to the more severe ACL injury in maturing young girls. Young girls with PFP may possess risk factors that put them at future risk for ACL injury. This may be due to increased mass and height during their adolescent years. Bearing in mind the limitations of our data (above), we contend that preventive exercise interventions for girls with a history of PFP during their growing years may benefit from a targeted neuromuscular training programme to reduce KAM landing mechanics. Similarly, adolescent girls who land with >25 Nm of knee abduction may benefit from such a programme.

What are the new findings?

- ▶ Knee abduction moment during landing above 15.4 Nm is associated with a 6.8% risk to develop patellofemoral pain (PFP) compared to a 2.9% risk if below the PFP risk threshold in our sample.
- ▶ Knee abduction moment above 25.3 Nm is associated with a 6.8% risk for subsequent anterior cruciate ligament (ACL) injury compared to a 0.4% risk if below the established ACL risk threshold.
- ▶ Young girls with PFP may have risk factors that put them at future risk for ACL injury as they mature during their adolescent years.

How might it impact on clinical practice in the near future?

- ▶ Preseason exercise interventions focused on plyometric, strengthening and proximal neuromuscular control exercises may be warranted for girls with a history of patellofemoral pain (PFP) during their growing years.
- ▶ Adolescent girls with a history of PFP and/or who land with >25 Nm of knee abduction may benefit from increased treatment dosage gained from both preseason and in-season neuromuscular training protocols to lower risk of PFP and/or ACL injury.

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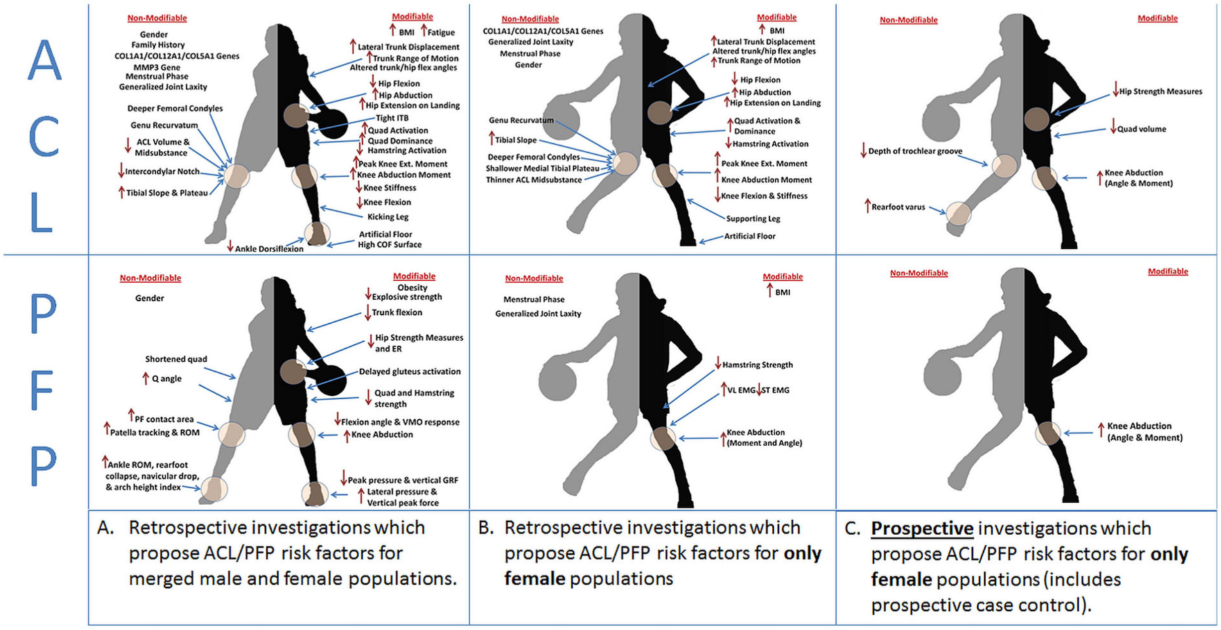

Figure 1.

Graphical illustration of reported risk factors for ACL injury and PFP incidence. (A) **ACL**[224547-4952-5456-586061] **PFP**[19]; (B) **ACL**[21-445596] **PFP**[10-18] and (C) **ACL**[3442515962666897-99] PFP[19]. ACL, anterior cruciate ligament; BMI, body mass index; Ext, external; PFP, patellofemoral pain. ITB, iliotibial band; COF, center of force; ROM, range of motion; PF, patellofemoral; ER, external rotation; VMO, vastus medialis oblique; GRF, ground reaction force; VL, vastus lateralis; EMG, electromyography; ST, sartorius.

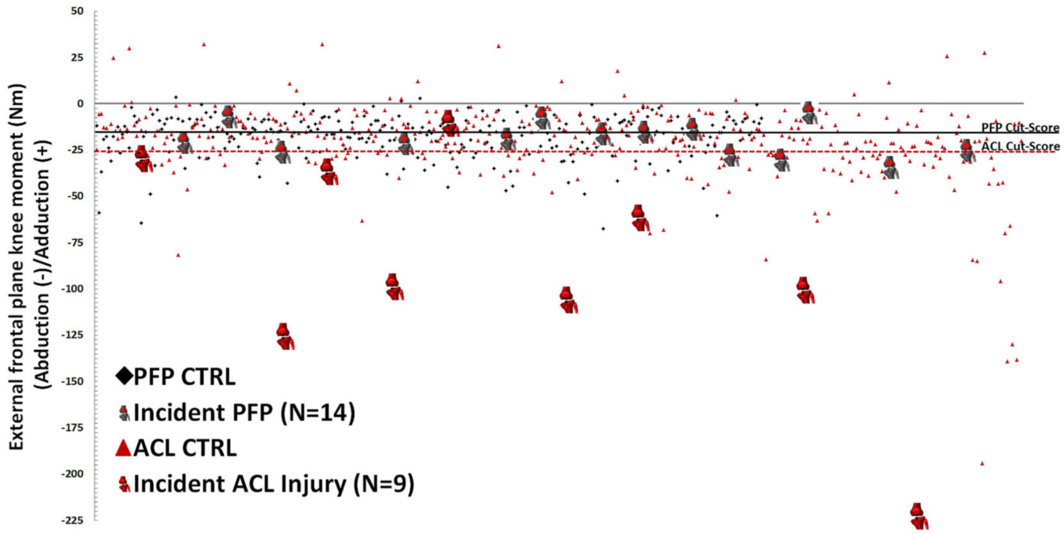

Figure 2.

Relative cut-off score for increased ACL and PFP injury risk. The highlighted red patella (grey knee) indicates the participants who developed PFP following screening. The red knee represents those participants who went on to ACL injury following screening. ACL, anterior cruciate ligament; CTRL, control; PFP, patellofemoral pain.

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Table 1

Cohort descriptive demographics and anthropometrics

		95% CI for mean	
Mean		**Lower bound**	**Upper bound**
Height (cm)			
ACL	164.4	163.6	165.3
PFP	160.1	158.7	161.4
Total	162.6	161.8	163.4
Mass (kg)			
ACL	59.2	58.1	60.3
PFP	54.3	52.3	56.2
Total	57.2	56.1	58.2
Age (years)			
ACL	16.1	15.9	16.3
PFP	13.3	13.1	13.6
Total	15.0	14.7	15.2

ACL, anterior cruciate ligament; PFP, patellofemoral pain.