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Altered hip control during a standing knee lift test is associated with increased risk of knee injuries

Running title: Hip control and knee injury risk

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ABSTRACT

Few prospective studies have investigated hip and pelvic control as a risk factor for lower extremity (LE) injuries. The purpose of this study was to investigate whether deficits in hip and lumbopelvic control during standing knee lift test are associated with increased risk of acute knee and LE injuries in youth team sports. At baseline, 258 basketball and floorball players (aged 12–21 y.) participated in a standing knee lift test using 3-dimensional motion analysis. Two trials per leg were recorded from each participant. Peak sagittal plane pelvic tilt and frontal plane pelvic drop/hike were measured. Both continuous and categorical variables were analysed. New non-contact LE injuries, and match and training exposure, were recorded for 12 months. Seventy acute LE injuries were registered. Of these, 17 were knee injuries (eight ACL ruptures) and 35 ankle injuries. Risk factor analyses showed that increased contralateral pelvic hike was significantly associated with knee injury risk when using categorical variable (HR for high versus low group 4.07; 95% CI 1.32–12.6). Furthermore, significant association was found between high lateral pelvic hike angles and ACL injury risk in female players (HR for high versus low group 9.10; 95% CI 1.10–75.2). Poor combined sensitivity and specificity of the test was observed. In conclusion, increased contralateral pelvic hike is associated with non-contact knee injury risk among young team sport players as well as non-contact ACL injuries among female players. More research to determine the role of pelvic control as a risk factor for knee injuries is needed.

Keywords: team sports; knee injuries; anterior cruciate ligament; biomechanics; screening

INTRODUCTION

Participation in team sports has become increasingly popular among young people around the world. Fast-paced pivoting and jumping sports, such as basketball and floorball, have a high incidence of lower extremity (LE) injuries, ankle and knee ligament injuries in particular[1,2]. Increased risk of recurrence, functional deficits, and osteoarthritis as well as prolonged absence from sport participation are devastating outcomes of these injuries[3,4]. Understanding factors that predispose athletes to injuries is an essential part of effective injury prevention[5].

To evaluate individual's risk of sustaining non-contact LE injuries, different tests to screen athletes' movement control have been developed. Both two- and three-dimensional motion analysis methods have been utilized to assess tasks such as vertical drop jump[6-8], single-leg drop jump[9] and single-leg squat[10,11]. Already, several biomechanical variables have been studied and linked to injury risk. Knee valgus loading[8], high vertical ground reaction force as well as limited knee and hip flexion[6,12] during a vertical drop jump task have been associated with ACL injury risk in young female athletes. A recent study suggested association between excessive knee valgus during a single-leg squat and a risk of LE injuries as well as ankle injuries[13]. Furthermore, a combination of knee valgus and lateral trunk motion during a single-leg drop jump has been suggested being associated with increased risk of non-contact knee injuries[9]. Nevertheless, prospective evidence gathered from these investigations is still limited and partly conflicting[7,14] highlighting the need for additional studies with larger study populations.

Whereas previous risk factor studies have focused on biomechanics of lower extremity, recent investigations have begun to focus more on proximal control of the knee and lower extremity[15,16]. The hip has been suggested to have a prominent role as a stabilizer of the pelvis, trunk and knee[17]. Prospective studies investigating trunk and core control have found significant associations between decreased trunk control and LE injuries.[15,18,19] However, only one risk factor study has investigated directly the deviation of the pelvis[20]. This study showed that decreased anterior-posterior control of the pelvis among baseball pitchers is related to long time-loss due to injuries but did not differentiate between injured body parts[20]. Furthermore, impaired hip strength has been suggested to increase the risk of ankle injuries[21], but prospective studies are scarce and results have been partly conflicting[22]. More studies are needed to determine the role of hip and pelvic control to the risk of LE injuries, especially to the knee and ankle.

A commonly used clinical test to assess hip and pelvic control was described by Friedrich Trendelenburg[23]. The Trendelenburgs's test was developed to assess hip abductor weakness during single-leg stance on patient populations. Although the test and many of its modifications[24-26] have been widely used in clinical practice, little research exists on pelvic control as a risk factor for lower extremity injuries.

The primary purpose of the present study was to investigate whether deficits in hip and lumbopelvic control during a standing knee lift test (a modified version of the Trendelenburg's test) are associated with increased risk of acute non-contact knee injuries in youth team sports. The secondary purpose was to examine the relationship between test outcomes and other LE injuries. We hypothesized that players with decreased hip and lumbopelvic control are more prone to injuries compared with players who have a good control.

MATERIALS AND METHODS

This investigation is a 12-month prospective cohort study, and is a part of a large study investigating risk factors of LE injuries in youth team sports[27]. The study has been conducted in accordance with the Declaration of Helsinki, and was approved by Ethics Committee of the Pirkanmaa Hospital District, Tampere, Finland (ETL-code R10169).

Participants

Participants were recruited from six basketball and floorball clubs of the Tampere region, Finland. We invited male and female players from the two highest junior league levels to participate in a baseline screening tests as a part of a prospective cohort study investigating risk factors for sports injuries. Screening tests took place in April 2013 and included a set of physical tests that are described in detail elsewhere[27]. Players who were junior-aged (≤21 years), official members of the participating teams, and had no current acute injury affecting the baseline test participation were eligible for participation. Prior to participation in the study, players signed a written informed consent (including parental consent for players <18 years).

A total of 319 players agreed to participate in the study (Figure 1). Players who did not participate in the baseline standing knee lift test (n=49) and the injury registration (n=8) were excluded. In addition, four players were excluded due to having an ongoing acute injury at baseline. The remaining 258 players successfully completed the standing knee lift test and were followed prospectively for new LE injuries as well as match/training exposure through April 2014 (12 months). Before the performance test, players completed a baseline questionnaire covering information on personal data, sports participation and previous sports injuries.

Test protocol

At baseline, players performed a standing knee lift test in our 3D motion analysis laboratory. The test was a modified version of the Trendelenburg test to assess stance leg hip and lumbopelvic control[23]. This test was chosen because it is commonly used clinical test in Finland. To our knowledge, reliability and repeatability of the test among athletes have not been demonstrated. Prior the test, height and weight, as well as knee and ankle joint widths were measured.

Twenty-two reflective markers were placed over anatomical landmarks on the lower extremities and torso according to the Plug-In Gait marker set (Vicon Nexus v1.7; Oxford Metrics, Oxford, UK) (on the shoe over the second metatarsal head and over the posterior calcaneus, lateral malleolus, lateral shank, lateral knee, lateral thigh, anterior superior iliac spine, posterior superior iliac spine, xiphoid process of the sternum, jugular notch where the clavicles meet the sternum, spinous process of the 10th thoracic vertebra, and spinous process of the 7th cervical vertebra). All marker positions were carefully defined, and one physiotherapist placed markers on all players.

Players started the test by standing with 20 cm stance (a wooden block between feet, feet directing forward), one leg on each separate force plates (AMTI BP6001200; AMTI, Watertown, MA). First, we instructed players to lift a dominant leg twice by flexing hip and knee (approximately to the horizontal level) and to keep their knee horizontally for few seconds. Then same two lifts were performed with a non-dominant leg. We instructed players to perform knee lift in the controlled manner and to keep arms at their sides. Dominant leg was defined as the preferred leg to kick a ball.

Motion data collection

Eight high-speed cameras (Vicon T40, Vicon) and two force platforms (AMTI BP6001200; AMTI, Watertown, MA) were used to record marker positions and ground reaction force data synchronously at 300 and 1500 Hz, respectively. A static calibration trial was completed prior to task to determine the anatomical segment coordinate systems. Marker trajectories were identified with the Vicon Nexus software (Vicon Nexus v1.7; Oxford Metrics). Both movement and ground reaction force were filtered using a fourth-order Butterworth filter with cutoff frequencies of 15 Hz.

For each participant, we calculated frontal and sagittal plane motions of the pelvis (Figure 2). The predefined frontal plane variables were peak contralateral pelvic hike angle and peak contralateral pelvic drop angle (positive value corresponded to contralateral pelvic hike and negative value to contralateral pelvic drop). The selected sagittal plane variables were peak anterior pelvic tilt angle and peak posterior pelvic tilt angle (positive value corresponded to anterior and negative value to posterior pelvic tilt).

Pelvic orientations were calculated from the 3D marker trajectories using a custom Python (2.7.13) script and an open-source Python wrapping of Biomechanical ToolKit platform (BTK 0.3) for reading and modifying motion capture and force plate acquisitions. The script utilized standard open-source Python libraries for scientific computing (NumPy 1.15.4), data analysis (pandas 0.19.2), and data visualization (Matplotlib 2.0.0). Knee lift performances were initially detected from the trial files by using the vertical trajectories of the heel and toe markers and 1000 ms as a threshold time for the minimum duration of the knee lift. After detecting knee lifts, the exact timings (motion capture frames) of the foot off and foot strike events were determined from the synchronously recorded analog force plate signals using 25N as the threshold value for each event. Validity of the extracted knee lift trials were inspected visually and erroneous or incomplete recordings were removed prior to analysis. Finally, the peak values for pelvic drop/hike as well as anterior/posterior tilt were determined for each knee lift according to the plug-in-gait model output specification for pelvic angles.

Injury and exposure registration

During the 1-year follow-up, a study physician contacted the teams once a week to check possible new injuries. After each reported injury the study physician interviewed the injured player over the phone using a structured questionnaire. Only noncontact (i.e. no direct contact or strike to the involved body part) acute LE injuries were included in the current analysis.

The definition of a new ACL injury was an MRI-confirmed ACL rupture that occurred during a match or scheduled team training (only noncontact ACL injuries were included). A previous ACL injury was defined as an ACL injury of the ipsilateral or contralateral knee, of which the player was fully recovered from and had returned to sport before entering the study.

We instructed the coaches to record player participation in team practices and matches using a team diary. We collected exposure time from the coaches on a monthly basis.

Statistical methods

Descriptive data are presented as means with standard deviation. Independent samples t-tests was used to compare group differences. Cox mixed-effects models with new non-contact knee, ACL, lower extremity and ankle injury as outcome and the leg as the unit of analysis were generated. The monthly exposure time (i.e. training and playing hours) from the start of the follow-up until the time of first injury or the end of the follow-up was included to the models.

The mean of two knee lift trials per each side was used for each biomechanical variable. In addition, to consider the possibly non-linear relationship between biomechanical factors and the risk of injury, categorical variables were formed based on the continuous variables utilizing the median of the cohort. The biomechanical variables were categorized into two groups: low group (values less than median value) and high group (values larger than median). Decision for using two groups was done based on the relatively low number of injury cases.

Adjustment factors used in the regression models were selected based on their possible association with the injury outcome. First, potential adjustment factors (sex, age, height, body mass, sport, dominant leg, participation in adult league level matches, and previous injury) were included in a regression model. Nonsignificant (P>0.2) variables were removed one-by-one. If several adjustment factors had a P-value less than 0.2, the variables with lowest P-values were included in the final models following the restriction of ten events per one variable[28]. All ACL injuries in our study occurred in female athletes. Hence, ACL injury risk factors were analysed by including only female athletes. All models included sports club and leg as random effects. The regression analysis was conducted in R software (v 3.1.2; R Foundation for Statistical Computing). All other analyses were conducted in SPSS (v 24; SPSS Inc.).

A receiver operating characteristic (ROC) curve analysis was calculated to investigate the combined sensitivity and specificity of the significant test variables. The area under the curve was interpreted as excellent (0.9–1.0), good (0.80–0.89), fair (0.70–0.79), poor (0.60–0.69), and fail (0.50–0.59)[29].

RESULTS

Player and injury characteristics

Complete data for the baseline standing knee lift test as well as prospective registration of injury and athlete exposure were obtained from 258 players (128 basketball and 130 floorball players) (Table 1). Of these, 32 players (12 %) dropped out during the study (12 basketball and 20 floorball players) due to reasons given in Figure 1. The data from these players were still included from the time they participated. Mean age of the players at the time they entered the study was 16.0 (median 16; SD 1.9) years.

The total player exposure was 61 492 hours during the 12-month study period. Altogether 133 injuries (2.2 injuries per 1 000 player-hours) were registered, of which 70 were non-contact lower extremity injuries (1.1 injuries per 1 000 player-hours). Ten players had more than one non-contact LE injury, and six of them had multiple injuries of the same leg. Hence, in the regression analysis the number of non-contact LE injuries was 62. Most of the non-contact LE injuries involved the ankle (35 injuries). Seventeen non-contact knee injuries were registered and 8 of them were ACL ruptures. All ACL injuries occurred in female players (2 basketball and 6 floorball players).

Association between biomechanical variables and injury risk

Unadjusted group comparisons revealed no significant differences in biomechanical test results between injured and uninjured players (Table 2). Notably, actual pelvic drop (contralateral ASIS dropping below the horizontal line) was observed only in 79 (15 %) out of 516 tested legs. Hence, the mean value of pelvic drop was positive (range -3.5 to 8.9 degrees) indicating that most of the players demonstrated a pelvic hike rather than drop.

In the regression models using continuous variables (Table 3), none of the investigated biomechanical factors were significantly associated with knee injuries, although a close to significant association was found between increased pelvic hike and knee injuries (adjusted HR 1.12; 95 % CI 1.00–1.27, *P*=0.055). In addition, increased pelvic hike and decreased pelvic drop were associated with ACL injury risk in unadjusted, but not in the adjusted models. In categorical variables, players displaying high lateral pelvic hike angles were at increased risk of knee injuries (adjusted HR for high versus low group 4.07; 95% CI 1.32–12.6, *P*=0.015). Furthermore, significant association was found between high pelvic hike angles and ACL injury risk in female players (adjusted HR for high versus low group 9.10; 95% CI 1.10–75.2, *P*=0.040). No potential risk factors for all LE injuries or ankle injuries were found (Table 4).

The frequency distribution of lateral pelvic hike angles between injured and uninjured players is presented in Figures 3 and 4. The ROC curve analysis for the pelvic hike angles and ACL injuries showed an area under the curve of 0.68, which indicates poor combined sensitivity and specificity of the test.

DISCUSSION

This study showed that increased contralateral pelvic hike during a standing knee lift test is associated with risk of sustaining acute non-contact knee injury among youth team sport players. Furthermore, we observed a significant association between excessive lateral pelvic hike and ACL injury risk among female players. We found no association between the measures of anterior-posterior tilt of the pelvis and the risk of non-contact LE injuries or ankle injuries.

Decreased hip control has been suggested to play a role in the risk of knee injuries. During landing and cutting movements, insufficient strength or recruitment of hip abductors and rotator muscles, especially in combination with lateral trunk motion, can create abduction loads to the knee and increase the knee injury risk[17]. In the current study, we found that players who demonstrated increased frontal plane pelvic movement towards pelvic hike, were at increased risk of sustaining a knee injury during the next 12 months. This finding is novel and somewhat surprising, because previous studies have linked opposite movement, contralateral pelvic drop on injuries such as running related medial tibial stress syndrome[30] and patellofemoral pain[31]. Due to lack of previous studies using similar tests, we were unable to compare our results to any previous examinations. Pelvic hike can be a result of decreased hip abductor strength as the pelvic hike brings the stance leg hip joint closer to the ground reaction force vector (i.e. more medially towards the foot), thereby reducing the frontal plane moment arm to the hip joint. Possibly, this could also lead to a lateral tilt of the trunk as described previously[23]. Furthermore, altered movement control can be a result of previous injuries or pain[32], or anatomical[33,34] imbalances. For example, excessive pelvic hike towards the symptomatic side has been reported in individuals with femoroacetabular impingement syndrome during step-ascent[35] and squatting[32]. Although our findings need to be confirmed in future studies with larger populations, these results suggest that the inability to control pelvic movement can increase the knee injury risk and especially ACL injury risk in young female athletes.

In our study, most of the athletes displayed contralateral pelvic hike during the knee lift, whereas pelvic drop was observed only in 15 % of cases. Contralateral pelvic drop during a single leg stance has been regarded as a sign of severe hip abductor weakness on a patient population[23]. Hence, it is not surprising that such weakness was uncommon in healthy athletes. The lowest values in pelvic drop observed in our study among young athletes (approximately -3 degrees) are somewhat similar than previously reported among healthy adults (approximately -4 to -6 degrees) in studies examining consciously altered pelvic drop during single leg standing[36,37].

To our knowledge, the association between hip control during a standing knee lift test and future knee injuries has not been previously established among athletes in prospective study settings. Chaudhari and others[20] examined peak anterior-posterior deviation of the pelvis during a single-leg raise test very similar to the test we used. They found poor lumbopelvic control being related to a higher likelihood of missing 30 or more days due to an injury. In our study, when assessing all LE injuries regardless of their severity, we did not observe such association. A major difference, which might explain the different results, was that the outcomes in our study focused on lower extremity injuries, whereas Chaudrari et al. investigated all injuries including upper extremity and low-back injuries[20]. Although sagittal plane pelvic deviation was not found being a significant risk factor for lower extremity injuries, the relationship between excessive pelvic tilt and low back injuries should be investigated more thoroughly in future studies. Impaired hip strength has been suggested to also increase the risk of ankle injuries[21], but in our study, we did not observe association between pelvic control and ankle injury risk.

Trunk stability during high-speed athletic movements common in team sports is linked to the ability of the hip to control the trunk[17]. The effects of decreased trunk and core control on the risk of knee injuries has been demonstrated earlier. Zazulak et al.[15] investigated trunk displacement after sudden force release and found association between lateral trunk displacement and the risk of knee, ligament, and ACL injuries among female, but not male athletes. Furthermore, the same group showed that decreased core proprioception was a risk factor for knee injuries again among female, but not among male athletes[18]. Dingenen and others[19] conducted a preliminary analysis of the double- to single-leg stance task with eyes closed among female mixed team sport athletes and showed that athletes with a decreased postural stability were at increased risk for lower extremity injury. These studies suggest that poor trunk control is common especially among female athletes and can partly explain the increased incidence of ligament injuries among females.

Interestingly, we observed that all ACL injured female athletes in our study demonstrated excessive contralateral pelvic hike of 13 degrees or more during the pre-injury screening test. Although the relationship between pelvic hike and ACL injury risk was significant in regression analysis only in unadjusted model and in adjusted model when using categorical variable, presumably due to the lack of statistical power, it supports the theory that lumbopelvic movement control plays a role in knee injury risk[17].

Strengthening of hip muscles helps to maintain the level position of the pelvis and control excessive adduction of the femur[16]. Exercises focusing on segments proximal to the knee have been shown to be effective to reduce the risk of ACL injuries[38] and as of part of multicomponent training also other lower extremity and knee injuries[39]. Hence, focusing on good pelvic control and strengthening the hip abductors and external rotators is recommended in prevention of these injuries.

The standing knee-lift test used in the current study, was a modified version of the original Trendelenburg's test[23] and there are two important differences, including the hip angle in the lifted leg and length of the stance, due to which our results should not be directly compared to studies using the Trendelenburg's test. We instructed players to shift from two-legged stance position to one-leg stance (in the controlled manner) by lifting and flexing the hip and knee until the knee was approximately at the horizontal level, and to keep the position for a few seconds. As there is no data available regarding reliability and repeatability of the test, caution is advised when using the test in practice. Moreover, as the ROC curve analysis demonstrated poor combined sensitivity and specificity, the standing knee-lift test could not discriminate players who sustained a knee or ACL injury from those who did not, which limits the usefulness of the test.

Besides many compelling strengths, including prospective registration of injuries and exposure, three-dimensional motion analysis method, low drop-out rate and a one-year follow-up, some limitations exist. First, soft tissue movement artifact is a possible source of error when using marker-based motion analysis[40]. Furthermore, the test results are dependent on correct marker positioning. To ensure uniformity in marker placing, one physiotherapist was responsible for placing markers for all players. Pelvic landmarks (ASIS and PSIS) are usually easy to locate for an experienced physiotherapist and hence, we feel confident that marker placement has little effect on our results. Secondly, although a one-year follow-up, it is a relatively long period for recording common injuries, it might still be insufficient for specific injury types, such as ACL injuries. Thirdly, although we tested only players who at the time of inclusion were free from injury, there might have been players with symptoms that may have affected their ability to conduct this simple movement. However, it is known that athletes often train and compete despite of pain and injuries. Hence, their performance in the test probably reflected their normal condition quite well. It is also known that players with previous injuries have a much larger risk of sustaining new injuries. It is therefore likely that including these players could have resulted in even larger differences between players with and without a new injury in the current study. Finally, we tested players with lumbo-pelvic control test only at the beginning of the study year. Biomechanical risk factors are complex and can change during the follow-up period, especially with growing athletes.

CONCLUSIONS

Athletes with increased lateral pelvic hike during a standing knee lift test, appeared to have an increased risk of acute non-contact knee injury. Furthermore, increased pelvic hike was found to be a risk factor for ACL injuries among female athletes. These findings are novel and need to be confirmed in future studies. As the combined sensitivity and specificity was poor, the standing knee-lift test could not discriminate players who sustained a knee injury from those who did not.

PERSPECTIVE

In our study we found increased lateral pelvic hike being an indicator of an increased risk of acute non-contact knee injury. The standing knee-lift test might be useful to assess athlete’s weaknesses in the ability to stabilize the hip and lumbopelvic area. However, as the combined sensitivity and specificity of the test was poor, injury prediction was not established. Neuromuscular training including core and hip strengthening exercises has been shown effective to reduce the risk of non-contact lower extremity injuries[41-43] and should be implemented to all players in high-risk sports.

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Table 1. Demographic characteristics of the participants, mean (standard deviation).

	Basketball (n=128)			Floorball (n=130)		
	Boys (n=67)	Girls (n=61)	Total	Boys (n=80)	Girls (n=50)	Total
Age, y	15.2 (1.8)	14.5 (1.3)	14.8 (1.6)	16.9 (1.4)	17.3 (1.8)	17.1 (1.6)
Height, cm	179.3 (10.4)	168.5 (6.5)	174.2 (10.3)	177.4 (6.0)	167.1 (6.0)	173.4 (7.8)
Weight, kg	68.3 (13.9)	61.0 (8.7)	64.8 (12.2)	69.2 (8.6)	62.3 (7.7)	66.6 (8.9)
BMI, kg/m^2	21.1 (3.1)	21.5 (2.8)	21.3 (2.9)	22.0 (2.3)	22.3 (2.6)	22.1 (2.4)
Playing experience, y	6.8 (3.1)	6.7 (2.6)	6.8 (2.8)	8.9 (3.0)	7.3 (2.5)	8.3 (2.9)

Table 2. Unadjusted test results in injured and uninjured groups, mean (standard deviation).

	LE injury during follow-up			Knee injury during follow-up			ACL injury during follow-up†			Ankle injury during follow-up		
	Yes (n=62)	No (n=453)	*P* value	Yes (n=17)	No (n=498)	*P* value	Yes (n=8)	No (n=214)	*P* value	Yes (n=32)	No (n=483)	*P* value
Anterior pelvic tilt, peak (degree)	9.6 (4.3)	9.4 (4.2)	0.76	9.8 (4.9)	9.4 (4.2)	0.73	11.1 (4.6)	10.3 (4.0)	0.59	9.9 (4.0)	9.4 (4.2)	0.52
Posterior pelvic tilt, peak (degree)	-4.2 (5.8)	-4.5 (5.9)	0.69	-4.3 (5.6)	-4.5 (5.9)	0.90	-3.1 (6.0)	-3.7 (5.7)	0.75	-3.3 (5.6)	-4.6 (5.9)	0.24
Pelvic hike, peak (degree)*	14.3 (3.5)	13.9 (3.3)	0.46	15.2 (2.8)	13.9 (3.3)	0.12	15.8 (2.4)	13.9 (3.6)	0.13	13.7 (3.5)	14.0 (3.3)	0.62
Pelvic drop, peak (degree)*	2.1 (2.1)	2.0 (2.1)	0.76	2.3 (2.4)	2.1 (2.1)	0.60	3.1 (2.4)	1.7 (2.1)	0.08	1.8 (2.3)	2.1 (2.1)	0.48

n=number of legs. LE, lower extremity. ACL, anterior cruciate ligament. †only female players included in the analysis. *Positive value in pelvic obliquity corresponds to contralateral pelvic hike and negative value to contralateral pelvic drop.

Table 3. The association between biomechanical variables of the pelvis and the risk of knee and ACL injuries. Unadjusted and adjusted cox regression models with hazard ratios (95 % confidence intervals).

	Knee injuries (n=17)		**ACL injuries (n=8)**†	
	Unadjusted model	Adjusted model	Unadjusted model	Adjusted model
Continuous variables				
Anterior pelvic tilt, peak (degree)	1.02 (0.91–1.14)	**0.97 (0.86–1.09)**	1.03 (0.86–1.23)	**1.04 (0.89–1.22)**
Adjustment factors		sex, male 0.10 (0.03–0.37)		previous ACL injury 16.2 (3.10–84.5)
Posterior pelvic tilt, peak (degree)	0.99 (0.91–1.08)	**1.03 (0.95–1.13)**	0.99 (0.87–1.13)	**1.00 (0.87–1.14)**
Adjustment factors		sex, male 0.10 (0.03–0.36)		previous ACL injury 15.7 (3.01–81.8)
Pelvic hike, peak (degree)	1.12 (0.98–1.28)	**1.12 (1.00–1.27)**	1.22 (1.01–1.47)*	**1.19 (0.98–1.45)**
Adjustment factors		sex, male 0.10 (0.03–0.37)		previous ACL injury 12.9 (2.43–68.7)
Pelvic drop, peak (degree)	0.95 (0.75–1.19)	**0.89 (0.70–1.12)**	0.65 (0.44–0.95)*	**0.74 (0.53–1.04)**
Adjustment factors		sex, male 0.10 (0.03–0.36)		previous ACL injury 11.4 (1.93–67.4)
Categorical variables				
Anterior pelvic tilt (high)	1.41 (0.53–3.70)	**1.02 (0.38–2.70)**	1.51 (0.36–6.33)	**1.65 (0.39–7.03)**
Adjustment factors		sex, male 0.11 (0.03–0.39)		previous ACL injury 13.8 (1.61–117.5)
Posterior pelvic tilt (high)	0.53 (0.20–1.44)	**0.72 (0.27–1.98)**	0.37 (0.55–13.6)	**0.33 (0.07–1.67)**
Adjustment factors		sex, male 0.11 (0.03–0.41)		previous ACL injury 15.4 (1.78–133.2)

Pelvic hike (high)	3.55 (1.16–10.9)*	**4.07 (1.32–12.6)***	9.44 (1.15–77.6)*	**9.10 (1.10–75.2)***
Adjustment factors		sex, male 0.10 (0.03–0.35)		previous ACL injury 10.3 (1.10–96.2)
Pelvic drop (high)	0.67 (0.26–1.77)	**0.66 (0.25–1.73)**	0.25 (0.05–1.26)	**0.17 (0.03–1.02)**
Adjustment factors		sex, male 0.11 (0.03–0.39)		previous ACL injury 30.7 (2.68–350.9)

ACL, anterior cruciate ligament. *significant association (*P* < 0.05); †only female players included in the analysis.

Table 4. The association between biomechanical variables of the pelvis and the risk of lower extremity and ankle injuries. Unadjusted and adjusted cox regression models with hazard ratios (95 % confidence intervals).

	LE injuries (n=62)		**Ankle injuries (n=32)**	
	Unadjusted model	Adjusted model	Unadjusted model	Adjusted model
Continuous variables				
Anterior pelvic tilt, peak (degree)	1.01 (0.95–1.07)	**0.97 (0.91–1.03)**	1.03 (0.94–1.12)	**0.99 (0.90–1.09)**
Adjustment factors		height 0.95 (0.92–0.98) league level 1.89 (1.04–3.41) previous injury 1.72 (1.00–2.96) dominant leg 1.80 (1.06–3.05)		height 0.94 (0.90–0.98) dominant leg 2.47 (1.14–5.35)
Posterior pelvic tilt, peak (degree)	0.99 (0.95–1.03)	**1.02 (0.97–1.06)**	0.96 (0.90–1.02)	**0.98 (0.91–1.05)**
Adjustment factors		height 0.95 (0.92–0.98) league level 1.94 (1.07–3.54) previous injury 1.68 (0.98–2.89)		height 0.94 (0.90–0.98) dominant leg 2.45 (1.13–5.30)

		dominant leg 1.80 (1.06–3.05)		
Pelvic hike, peak (degree)	1.03 (0.96–1.11)	**1.02 (0.95–1.09)**	0.97 (0.88–1.08)	**0.97 (0.87–1.07)**
Adjustment factors		height 0.95 (0.93–0.98)		height 0.94 (0.90–0.98)
		league level 1.88 (1.03–3.41)		dominant leg 2.44 (1.12–5.28)
		previous injury 1.70 (0.99–2.92)		
		dominant leg 1.79 (1.05–3.05)		
Pelvic drop, peak (degree)	0.99 (0.88–1.13)	**0.96 (0.48–1.91)**	1.08 (0.91–1.29)	**1.04 (0.87–1.25)**
Adjustment factors		height 0.95 (0.93–0.98)		height 0.94 (0.90–0.98)
		league level 1.90 (1.05–3.45)		dominant leg 2.41 (1.11–5.25)
		previous injury 1.67 (0.97–2.88)		
		dominant leg 1.84 (1.08–3.14)		
Categorical variables				
Anterior pelvic tilt (high)	1.20 (0.73–1.98)	**0.83 (0.49–1.40)**	1.20 (0.73–1.98)	**0.89 (0.43–1.84)**
Adjustment factors		height 0.95 (0.92–0.98)		height 0.94 (0.90–0.98)
		league level 1.90 (1.05–3.44)		dominant leg 2.48 (1.15–5.38)
		previous injury 1.70 (0.99–2.93)		
		dominant leg 1.81 (1.06–3.07)		
Posterior pelvic tilt (high)	0.63 (0.38–1.04)	**0.81 (0.48–1.37)**	0.63 (0.38–1.04)	**0.58 (0.28–1.21)**
Adjustment factors		height 0.96 (0.93–0.98)		height 0.94 (0.90–0.99)
		league level 1.85(1.01–3.36)		dominant leg 2.42 (1.12–5.24)
		previous injury 1.67 (0.97–2.87)		

		dominant leg 1.80 (1.06–3.05)		
Pelvic hike (high)	1.11 (0.67–1.83)	**1.05 (0.63–1.74)**	0.70 (0.34–1.42)	**0.65 (0.32–1.34)**
Adjustment factors		height 0.95 (0.93–0.98)		height 0.94 (0.90–0.98)
		league level 1.89 (1.04–3.42)		dominant leg 2.44 (1.13–5.28)
		previous injury 1.68 (0.98–2.90)		
		dominant leg 1.80 (1.06–3.06)		
Pelvic drop (high)	0.64 (0.38–1.07)	**0.61 (0.37–1.02)**	0.77 (0.38–1.55)	**0.68 (0.33–1.38)**
Adjustment factors		height 0.95 (0.93–0.98)		height 0.94 (0.90–0.98)
		league level 1.89 (1.04–3.42)		dominant leg 2.60 (1.19–5.66)
		previous injury 1.66 (0.96–2.86)		
		dominant leg 1.91 (1.12–3.25)		

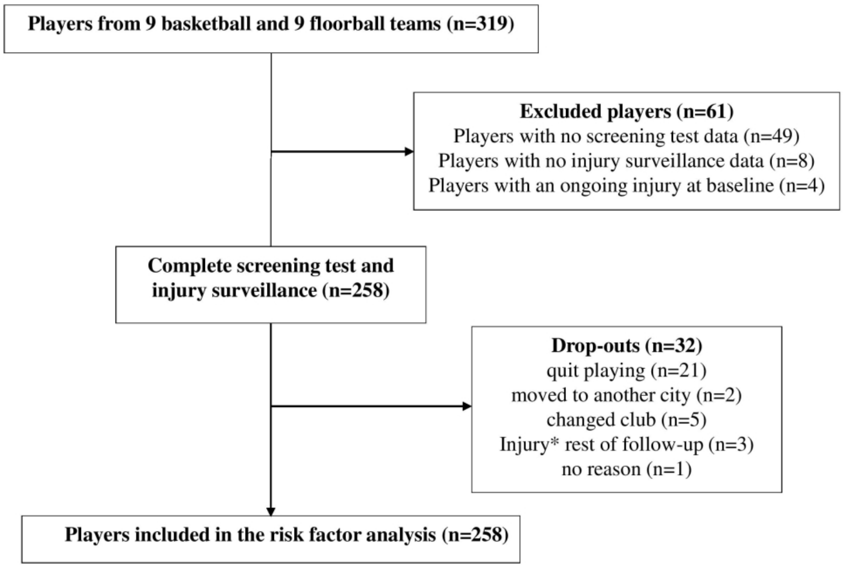
LE, lower extremity.

Figure 1. Flow of participants. The data from drop-outs are included from the time they participated. *Injury other than acute non-contact lower extremity injury.

Figure 2. Frontal and sagittal plane variables of pelvic motions. Modified from Lewis et al.[34]

Figure 3. Frequency distribution of lateral pelvic hike for players with and without a new knee injury. The dashed line represents the median of the cohort.

Figure 4. Frequency distribution of lateral pelvic hike for female players with and without a new anterior cruciate ligament (ACL) injury. The dashed line represents the median of the female cohort.



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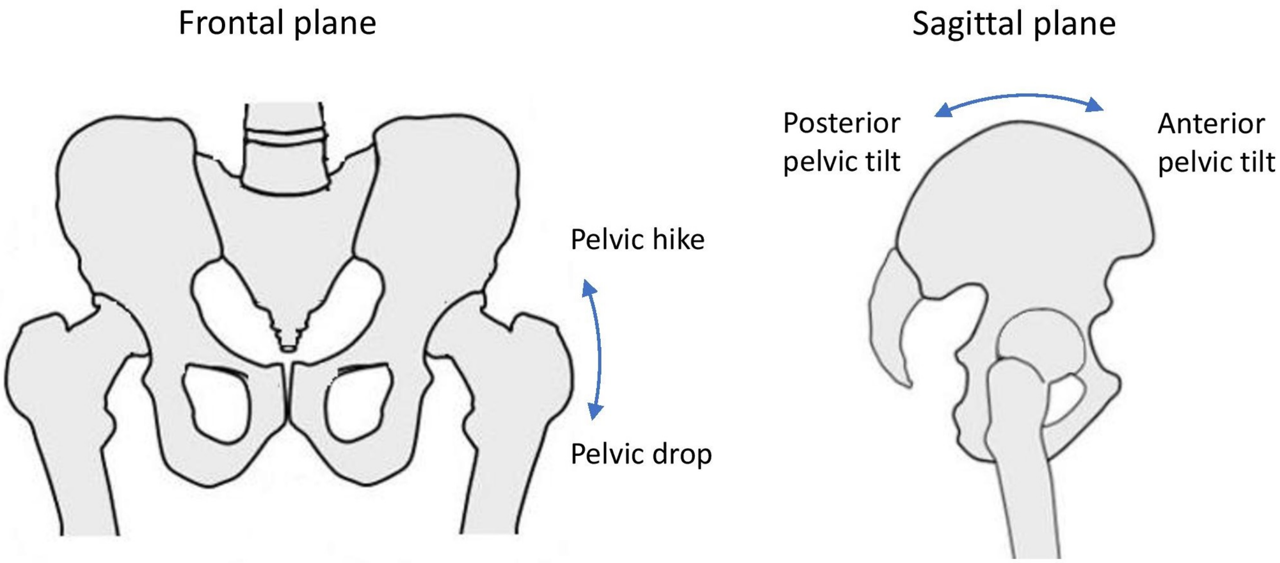

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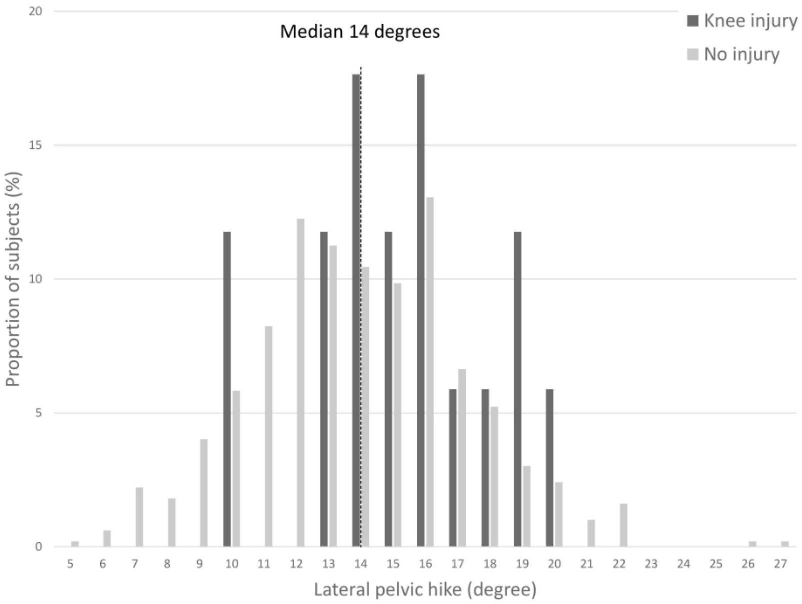

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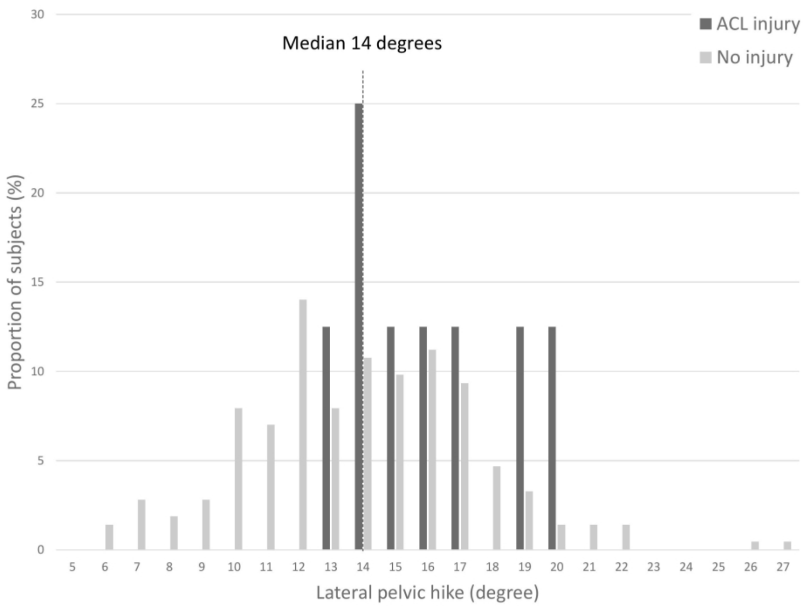

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