Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury

A Prospective Study

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Background: Stiff landings with less knee flexion and high vertical ground-reaction forces have been shown to be associated with an increased risk of anterior cruciate ligament (ACL) injury. The literature on the association between other sagittal plane measures and the risk of ACL injuries with a prospective study design is lacking.

Purpose: To investigate the relationship between selected sagittal plane hip, knee, and ankle biomechanics and the risk of ACL injury in young female team-sport athletes.

Study Design: Case-control study; Level of evidence, 3.

Methods: A total of 171 female basketball and floorball athletes (age range, 12-21 years) participated in a vertical drop jump test using 3-dimensional motion analysis. All new ACL injuries, as well as match and training exposure data, were recorded for 1 to 3 years. Biomechanical variables, including hip and ankle flexion at initial contact (IC), hip and ankle ranges of motion (ROMs), and peak external knee and hip flexion moments, were selected for analysis. Cox regression models were used to calculate hazard ratios (HRs) with 95% CIs. The combined sensitivity and specificity of significant test variables were assessed using a receiver operating characteristic (ROC) curve analysis.

Results: A total of 15 noncontact ACL injuries were recorded during follow-up (0.2 injuries/1000 player-hours). Of the variables investigated, landing with less hip flexion ROM (HR for each 10° increase in hip ROM, 0.61 [95% CI, 0.38-0.99]; $P < .05$) and a greater knee flexion moment (HR for each 10-N·m increase in knee moment, 1.21 [95% CI, 1.04-1.40]; $P = .01$) was significantly associated with an increased risk of ACL injury. Hip flexion at IC, ankle flexion at IC, ankle flexion ROM, and peak external hip flexion moment were not significantly associated with the risk of ACL injury. ROC curve analysis for significant variables showed an area under the curve of 0.6, indicating a poor combined sensitivity and specificity of the test.

Conclusion: Landing with less hip flexion ROM and a greater peak external knee flexion moment was associated with an increased risk of ACL injury in young female team-sport players. Studies with larger populations are needed to confirm these findings and to determine the role of ankle flexion ROM as a risk factor for ACL injury. Increasing knee and hip flexion ROMs to produce soft landings might reduce knee loading and risk of ACL injury in young female athletes.

Keywords: anterior cruciate ligament; biomechanics; risk factors; female; team sports

An anterior cruciate ligament (ACL) injury is one of the most common and severe knee injuries among young athletes.[1,20] While there is strong evidence on the effectiveness of training interventions to reduce the risk of ACL injuries,[29] the incidence of such injuries, especially among young female athletes, has still grown.[20] Understanding the cause of ACL injuries is an essential part of effective injury prevention,[35] but it is so far incomplete.[30]

A few prospective studies have examined the biomechanical risk factors for ACL injuries.[12,16,18,26,31] Proposed biomechanical risk factors include knee valgus loading[12] and stiff landings with less peak knee flexion and high vertical ground-reaction forces.[12,18] However, the evidence gathered from these investigations is inconclusive,[30] and more

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prospective studies that include hip and ankle variables, in addition to knee variables, are needed.

There is a strong body of evidence showing that sagittal plane factors contribute to the ACL injury mechanism.[7,13,23,33,36] Higher lower extremity joint flexion during landing will likely lead to higher energy absorption in muscles and less energy transmission to passive elements of the knee.[1] Limited sagittal plane movement might also be associated with increased frontal plane loading.[28] Nevertheless, only one prospective study has investigated knee and hip flexion-extension moments.[12] Those authors reported no association between knee flexion moments and ACL injury risk; however, they did show significantly greater hip flexion moments in the ACL group compared with the uninjured group. Hashemi et al[9] proposed that a high external hip flexion moment might represent an important ACL loading mechanism. Furthermore, sagittal plane ankle kinematics may potentially also influence ACL injury risk through its effect on the magnitude of the ground-reaction force,[6] but this has not been thoroughly investigated in previous prospective studies.

This study was a hypothesis-driven, in-depth analysis based on previously published data on the biomechanical risk factors of ACL injury.[18] The purpose of this study was to investigate the relationship between selected sagittal plane hip, knee, and ankle biomechanics and the risk of ACL injury in young female team-sport athletes.

METHODS

Study Design

The current investigation extends earlier analyses on the biomechanical risk factors of ACL injuries[18] and is a part of the PROFITS (Predictors of Lower Extremity Injuries in Team Sports) study.[27] This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Pirkanmaa Hospital District (ETL code R10169).

Participants

Participants were recruited from 6 basketball and floorball clubs of the Tampere region in Finland. In each study year (2011, 2012, and 2013), players from the 2 highest junior league levels were invited to participate. Female players who were junior aged (≤21 years) and official members of the participating teams were eligible for participation. Players with previous ACL injuries were eligible to participate if they were fully recovered from their previous injury. Final participation was based on a written informed consent form from the player (including parental consent for players aged <18 years).

A total of 189 players agreed to participate. Of these, 174 successfully completed the vertical drop jump screening test and were observed prospectively for new ACL injuries through April 2014. Complete data for the baseline screening tests as well as the prospective registration of injury and match/training exposure were obtained from 171 players overall: 80 players started the study in 2011, 29 in 2012, and 62 in 2013. Three players were lost to follow-up.

Test Protocol

At baseline, each participant underwent a vertical drop jump test performed in a 3-dimensional motion analysis laboratory. Detailed information about the test protocol is described elsewhere.[18] Players were instructed to drop off a 30-cm box, land with one foot on each of the adjacent force platforms, and perform a maximal jump upon landing (BP6001200; AMTI). Data from 3 successful trials were collected from each participant.

Before the test, after a standardized warm-up (including 5 minutes of bicycling), 16 reflective markers were placed over anatomic landmarks on the lower extremities according to the Plug-in Gait marker set (Vicon Nexus v1.7; Oxford Metrics): 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, and posterior superior iliac spine. All marker positions were carefully defined. Two physical therapists were responsible for placing markers uniformly.

Motion Data Collection

Eight high-speed cameras (T40; Vicon Motion Systems) and 2 force platforms (BP6001200) were used to record marker positions and ground-reaction force data synchronously at 300 and 1500 Hz, respectively. A static calibration trial was completed before task to determine the anatomic segment coordinate systems. Marker trajectories were identified with Vicon Nexus v1.7 software. A fourth-order Butterworth filter with cutoff frequencies of 15 Hz was used to filter movement and ground-reaction forces.[15] The landing

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phase was defined as the period when the unfiltered ground-reaction force exceeded 20 N.

In the current investigation, selected sagittal plane variables during the contact phase (the period when the unfiltered ground-reaction force exceeded 20 N) of the vertical drop jump task were analyzed. The variables included hip and ankle flexion at initial contact (IC), hip and ankle flexion ranges of motion (ROMs), and peak external knee and hip flexion moments. Variables were analyzed using the Plug-in Gait model (Vicon Nexus v1.7). Hip and ankle flexion ROMs were calculated from the flexion at IC with the ground to the maximum flexion during the landing phase. The inverse dynamics approach according to the Plug-in Gait model was used to calculate knee and hip joint moments. We report external knee and hip flexion moments. An external knee flexion moment refers to the torque (generated by the ground-reaction force and its moment arm) that tends to flex the knee. If an external knee flexion moment is reported, this is counterbalanced by an internal knee extension moment, generated by the quadriceps.

Injury and Exposure Registration

When entering the study, each player filled out a baseline questionnaire regarding information such as demographics, injury history, and playing experience. During the prospective follow-up, 5 study physicians were responsible for collecting the injury data. The teams were contacted once a week to check for possible new injuries. Each injured player was interviewed by telephone by a study physician using a structured questionnaire. In the current analysis, new ACL injuries that occurred during a match or scheduled team training were included. Only magnetic resonance imaging–confirmed noncontact ACL injuries (ie, no direct contact or strike to the involved knee) were included. The coaches recorded player participation in team training and matches using a team diary. Player attendance in a training session (yes/no), duration of a training session (h), and attendance in each period of a game (yes/no) were recorded for each player.

Statistical Analysis

Descriptive data are presented as the mean ± SD. An independent-samples *t* test was used to compare group differences for normally distributed variables. The Mann-Whitney *U* test was used for nonnormally distributed variables. The injury incidence was calculated as the number of injuries per 1000 player-hours and was reported with 95% CIs.

Six separate Cox mixed-effects models[34] with a new noncontact ACL injury as the outcome and the leg as a unit of analysis were generated. The monthly exposure time from the start of follow-up until the first ACL injury or the end of follow-up was included in the models. The mean of 3 jump trials was used for each biomechanical variable. Each model included a similar set of predefined adjustment factors that might influence the risk of injuries: age, height, weight, sport, dominant leg, playing at adult level, and previous ACL injury (ACL injury of the ipsilateral or contralateral leg). Sports club and leg were included as random effects. The dominant leg was defined as the preferred leg when kicking a ball.

Cox hazard ratios (HRs) with 95% CIs were calculated. For improved interpretation, HRs were adjusted for a 10-unit change. Variables that had a *P* value <.05 were considered significant. Statistical analyses were conducted in SPSS for Windows (v20.0.0; SPSS), except the regression analysis, which was conducted in R (v3.1.2; R Foundation for Statistical Computing).

The combined sensitivity and specificity of significant test variables were assessed by using a receiver operating characteristic (ROC) curve analysis. The test outcome was defined as excellent (0.90-1.00), good (0.80-0.89), fair (0.70-0.79), poor (0.60-0.69), and fail (0.50-0.59).

TABLE 1
Baseline Characteristics of Participants[a]

	Basketball (n = 96)	Floorball (n = 75)	*P* Value
Age, y	14.6 ± 1.6	16.5 ± 1.8	<.01
Height, cm	168.6 ± 6.5	166.6 ± 5.6	.04
Weight, kg	60.6 ± 9.1	61.0 ± 6.6	.74
Body mass index, kg/m^2	21.3 ± 2.7	22.0 ± 2.0	.06
Playing experience, y	6.4. ± 2.5	6.2 ± 2.5	.59

[a]Data are presented as mean ± SD.

TABLE 2
Incidence of Anterior Cruciate Ligament Injuries in Training and Matches[a]

	Basketball	Floorball	Total
Training injuries	—	0.1 (0.0-0.3)	0.1 (0.0-0.2)
Match injuries	3.4 (0.0-7.2)	4.1 (0.8-7.3)	3.8 (1.3-6.3)

[a]Data are presented as No./1000 hours of exposure (95% CI).

RESULTS

Baseline and Injury Characteristics

The final sample with complete data for the baseline vertical drop jump test as well as injury and exposure surveillance comprised a total of 171 players (96 basketball and 75 floorball players). The basketball players were significantly younger and taller compared with the floorball players (Table 1).

In all, 17 new ACL injuries were registered, of which 15 were noncontact injuries and were included in the present analysis. Three basketball players and 11 floorball players were injured. One athlete sustained 2 separate ACL injuries (different legs). The overall ACL injury incidence was 0.2 injuries per 1000 player-hours (95% CI, 0.1-0.4) (Table 2).

TABLE 3
Knee, Hip, and Ankle Biomechanics[a]

	ACL-Injured Knees (n = 15)	Uninjured Knees (n = 327)	*P* Value
Angles, deg			
Hip flexion at IC	45.4 ± 10.7	43.5 ± 9.2	.43
Hip flexion ROM	21.4 ± 13.2	24.6 ± 12.2	.22
Ankle flexion at IC[b]	7.4 ± 8.4	9.8 ± 9.6	.26
Ankle flexion ROM	47.2 ± 12.5	51.8 ± 9.1	.16
External moments, N·m			
Peak knee flexion	134.7 ± 42.4	122.9 ± 40.0	.24
Peak hip flexion	214.0 ± 68.0	192.5 ± 57.7	.24

[a]Data are presented as mean ± SD. ACL, anterior cruciate ligament; IC, initial contact; ROM, range of motion.
[b]Positive values refer to ankle plantar flexion.

Sagittal Plane Biomechanics and the Risk of ACL Injury

Unadjusted group comparisons revealed no significant differences between injured and uninjured knees regarding the selected sagittal plane variables (Table 3). Of the sagittal plane joint angles investigated (hip and ankle), only hip flexion ROM was significantly associated with a new ACL injury (Table 4). Landing with less hip flexion was associated with an increased risk of ACL injury (HR for each 10° increase in hip ROM, 0.61 [95% CI, 0.38-0.99]; $P < .05$). No significant association was observed between hip flexion at IC (HR for each 10° increase in hip flexion, 1.11 [95% CI, 0.95-1.07]; $P = .73$), ankle flexion at IC (HR for each 10° increase in ankle (plantar) flexion, 0.67 [95% CI, 0.38-1.18]; $P = .17$), or ankle flexion ROM (HR for each 10° increase in ankle ROM, 0.62 [95% CI, 0.37-1.05]; $P = .07$) and ACL injury.

Peak external knee flexion moment (quadriceps moment) was significantly associated with ACL injury risk (HR for each 10-N·m increase in knee moment, 1.21 [95% CI, 1.04-1.40]; $P = .01$). Peak external hip flexion moment (HR for each 10-N·m increase in hip moment, 1.08 [95% CI, 0.98-1.18]; $P = .14$) was not associated with ACL injury risk. ROC curve analysis for both hip flexion ROM and peak external knee flexion moment showed an area under the curve of 0.6, indicating a poor combined sensitivity and specificity of the test.

DISCUSSION

This in-depth analysis was carried out to expand on our previous findings on sagittal plane biomechanics and ACL injury risk.[18] In the current study, we included variables that have not been thoroughly investigated in previous risk factor studies. The findings of this study showed that limited hip flexion ROM and greater knee flexion-extension moments are associated with an increased risk of ACL injury in young female basketball and floorball players. In this study, participants who landed with less hip flexion and higher peak external knee flexion moments were at an increased risk of ACL injury compared with players with more hip flexion ROM and lower knee moments, thereby supporting the current body of evidence that sagittal plane hip and knee kinetics and kinematics have an influence on ACL injury risk.

Many have emphasized the critical role of the hip in proximal control of the knee joint during closed kinetic chain maneuvers.[10,11,22] Excessive hip motion in the frontal or transverse plane, in particular, has been suggested to contribute to valgus movement and loading of the knee joint.[11] Sagittal plane hip kinetics and kinematics, however, are less often considered as contributors of ACL loading.[9]

In our previous study,[18] we showed that decreased peak knee flexion and increased vertical ground-reaction forces are factors associated with a higher risk of ACL injury. Thus, the current finding that less hip flexion also increases ACL injury risk is expected. Increasing knee and hip flexion during jump landings has been a part of many successful intervention programs.[19,25,32] Such modifications are associated with reduced ground-reaction forces as well as external knee flexion and internal quadriceps moments[8,22] and thus might reduce the risk of injuries.

In our study, landing with a high peak external knee flexion moment was associated with an increased risk of ACL injury, suggesting that athletes who suffered ACL injuries likely had increased quadriceps forces. In our previous study,[18] we additionally found that these players also had less knee flexion. This finding is in line with several previous studies implicating that the quadriceps are able to produce significant ACL loading, especially at low knee flexion angles.[3,4,7,21,37]

According to the hypothesis of Hashemi et al,[9] an increased internal hip extension moment may generate a mismatch between hip and knee flexion and thereby increase ACL loading. Although we found no significant association between peak external hip flexion moments and ACL injury risk, there was a trend for injured athletes having greater peak external hip flexion moments. The unadjusted group mean difference for the peak external hip flexion moment was 11% greater for the injured compared with the uninjured athletes, but this was similar to the difference in the peak external knee flexion moment (10%). Therefore, although we observed higher hip stiffness in athletes with a new injury, there did not seem to be such a mismatch in the vertical drop jumps compared with uninjured athletes.

Limited ankle ROM during landing might lead to lower absorption of ground-reaction forces that will subsequently be transmitted to the knee.[6] Boden et al[6] reported in a case-control video study that ACL-injured athletes landed with reduced ankle plantar flexion at IC and with less ankle ROM compared with uninjured controls. In a prospective study by Padua et al[26] using the Landing Error Scoring System, ankle plantar flexion scores did not differ between the ACL-injured and uninjured groups. Similarly, no significant association between ankle kinematics and ACL injury risk was found in our study. However, there was a nonsignificant trend that the ACL-injured athletes landed with smaller ankle plantar flexion at IC and with reduced

TABLE 4
Regression Models[a]

Model	Risk Factor[b]	Adjustment Factor: Age	Height	Weight	Dominant Leg	Sport	Previous ACL Injury	Playing at Adult Level
Hip flexion at IC, deg	1.11 (0.95-1.07)	1.10 (0.80-1.51)	0.86 (0.76-0.97)	1.08 (0.99-1.17)	Yes: 0.67 (0.23-1.91) No: 1.00	Floorball: 0.38 (0.03-5.41) Basketball: 1.00	1.55 (0.28-8.60)	Yes: 4.57 (1.07-19.50) No: 1.00
Hip flexion ROM, deg	0.61 (0.38-0.99)	1.17 (0.86-1.59)	0.84 (0.74-0.95)	1.08 (0.99-1.18)	Yes: 0.59 (0.20-1.71) No: 1.00	Floorball: 0.38 (0.03-5.61) Basketball: 1.00	2.89 (0.45-18.47)	Yes: 4.66 (1.18-18.43) No: 1.00
Ankle (plantar) flexion at IC, deg	0.67 (0.38-1.18)	1.09 (0.79-1.49)	0.87 (0.77-0.98)	1.06 (0.98-1.16)	Yes: 0.59 (0.20-1.77) No: 1.00	Floorball: 0.45 (0.03-6.22) Basketball: 1.00	1.24 (0.22-6.98)	Yes: 5.12 (1.20-21.86) No: 1.00
Ankle flexion ROM, deg	0.62 (0.37-1.05)	1.10 (0.80-1.52)	0.86 (0.76-0.97)	1.07 (0.98-1.16)	Yes: 0.45 (0.14-1.51) No: 1.00	Floorball: 0.43 (0.03-5.96) Basketball: 1.00	1.15 (0.20-6.73)	Yes: 4.70 (1.13-19.66) No: 1.00
Peak external knee flexion moment, N·m	1.21 (1.04-1.40)	1.18 (0.83-1.68)	0.83 (0.73-0.94)	1.05 (0.95-1.15)	Yes: 0.48 (0.16-1.50) No: 1.00	Floorball: 0.62 (0.04-8.98) Basketball: 1.00	1.54 (0.26-9.34)	Yes: 2.80 (1.63-12.42) No: 1.00
Peak external hip flexion moment, N·m	1.08 (0.98-1.18)	1.08 (0.77-1.52)	0.85 (0.74-0.96)	1.06 (0.97-1.16)	Yes: 0.54 (0.18-1.68) No: 1.00	Floorball: 0.32 (0.02-5.29) Basketball: 1.00	1.60 (0.28-9.10)	Yes: 4.64 (1.11-19.39) No: 1.00

[a]Data are presented as hazard ratio (95% CI). ACL, anterior cruciate ligament; IC, initial contact; ROM, range of motion.
[b]Hazard ratio for 10-unit change.

ankle flexion ROM than the uninjured athletes. The lack of significance could be caused by limited statistical power. Modifying landing strategies with forefoot landings has been shown to be associated with lower ACL loading[14] and does not impair performance.[25] Hence, the role of ankle ROM should be thoroughly investigated in future studies with larger sample sizes.

This study focused on investigating biomechanical factors. However, it is important to bear in mind that certainly other possible ACL injury risk factors exist.[1] Interestingly, playing at the adult league level seemed to have an important role in all of the investigated risk factor models. Junior-aged players who participated in adult league matches were at an increased risk of ACL injury compared with players competing at the junior level only (HR, 2.8-5.1). Although this finding needs further investigation, attention should be paid to determine when a young athlete is ready to participate in adult matches. At the adult level, the physical demands and workloads can be considerably higher than at the junior level.

Injury prediction is a challenging issue,[5] and currently, there is no screening test capable of predicting ACL injury with sufficient accuracy.[2] Neither of the landing variables investigated in the current study or our previous study[18] appeared to be strong predictors of injuries, although there were statistically significant associations (ROC area under the curve, 0.6). Furthermore, it is not known if sagittal plane hip and knee kinetics and kinematics have significant associations with ACL injury risk in other tasks such as cutting and changing directions.

This investigation has several strengths, including the relatively long duration, prospectively collected injury and exposure data, low dropout rate, and use of high-quality data collection and analysis methods. Nevertheless, this study has limitations. The statistical power was limited because of the small number of injuries during the 3 years of follow-up. Thus, less than strong risk factors might not have been detected. In addition, it was not reasonable to conduct a multivariate analysis with different combinations of biomechanical factors with this sample size. Moreover, the accuracy of marker-based motion analyses is limited by marker placement precision[24] and soft tissue movement artifacts.[17] To avoid potential inconsistencies in marker placement, all marker places were carefully defined, and 2 physical therapists were trained to place markers uniformly. Another limitation concerns the time interval between the test and 3-year follow-up. Young athletes might have changed their performance over the course of the study as they matured, gained strength, or became better at jumping and landing.

In conclusion, a landing strategy that includes limited hip flexion ROM and high peak external knee flexion moments may increase the risk of ACL injury in young female team-sport players. Hence, increasing knee and hip flexion ROMs to produce soft landings might reduce knee loading and ACL injury risk.

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REFERENCES

1. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players, part 1: mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(7):705-729.

2. Bahr R. Why screening tests to predict injury do not work—and probably never will . . .: a critical review. *Br J Sports Med*. 2016;50(13):776-780.
3. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech*. 1998;31(6):519-525.
4. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med*. 1995;23(1):24-34.
5. Bittencourt NF, Meeuwisse WH, Mendonca LD, Nettel-Aguirre A, Ocarino JM, Fonseca ST. Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition. Narrative review and new concept. *Br J Sports Med*. 2016;50(21):1309-1314.
6. Boden BP, Torg JS, Knowles SB, Hewett TE. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med*. 2009;37(2):252-259.
7. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32(2):477-483.
8. Favre J, Clancy C, Dowling AV, Andriacchi TP. Modification of knee flexion angle has patient-specific effects on anterior cruciate ligament injury risk factors during jump landing. *Am J Sports Med*. 2016;44(6):1540-1546.
9. Hashemi J, Breighner R, Chandrashekar N, et al. Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. *J Biomech*. 2011;44(4):577-585.
10. Hewett TE, Ford KR, Xu YY, Khoury J, Myer GD. Effectiveness of neuromuscular training based on the neuromuscular risk profile. *Am J Sports Med*. 2017;45(9):2142-2147.
11. Hewett TE, Myer GD. The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exerc Sport Sci Rev*. 2011;39(4):161-166.
12. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501.
13. Koga H, Bahr R, Myklebust G, Engebretsen L, Grund T, Krosshaug T. Estimating anterior tibial translation from model-based image-matching of a noncontact anterior cruciate ligament injury in professional football: a case report. *Clin J Sport Med*. 2011;21(3):271-274.
14. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *Br J Sports Med*. 2014;48(9):779-783.
15. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45(4):666-671.
16. Krosshaug T, Steffen K, Kristianslund E, et al. The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: a prospective cohort study of 710 athletes. *Am J Sports Med*. 2016;44(4):874-883.
17. Leardini A, Chiari L, Croce UD, Cappozzo A. Human movement analysis using stereophotogrammetry, part 3: soft tissue artifact assessment and compensation. *Gait Posture*. 2005;21(2):212-225.
18. Leppänen M, Pasanen K, Kujala UM, et al. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med*. 2017;45(2):386-393.
19. Longo UG, Loppini M, Berton A, Marinozzi A, Maffulli N, Denaro V. The FIFA 11+ program is effective in preventing injuries in elite male basketball players: a cluster randomized controlled trial. *Am J Sports Med*. 2012;40(5):996-1005.
20. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med*. 2014;42(10):2363-2370.
21. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GAM, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13(6):930-935.
22. Mendiguchia J, Ford KR, Quatman CE, Alentorn-Geli E, Hewett TE. Sex differences in proximal control of the knee joint. *Sports Med*. 2011;41(7):541-557.
23. Meyer EG, Haut RC. Anterior cruciate ligament injury induced by internal tibial torsion or tibiofemoral compression. *J Biomech*. 2008;41(16):3377-3383.
24. Mok KM, Kristianslund E, Krosshaug T. The effect of thigh marker placement on knee valgus angles in vertical drop jumps and sidestep cutting. *J Appl Biomech*. 2015;31(4):269-274.
25. Myers CA, Hawkins D. Alterations to movement mechanics can greatly reduce anterior cruciate ligament loading without reducing performance. *J Biomech*. 2010;43(14):2657-2664.
26. Padua DA, DiStefano LJ, Beutler AI, De La Motte SJ, DiStefano MJ, Marshall SW. The landing error scoring system as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *J Athl Train*. 2015;50(6):589-595.
27. Pasanen K, Rossi MT, Parkkari J, et al. Predictors of lower extremity injuries in team sports (profits-study): a study protocol. *BMJ Open Sport Exerc Med*. 2015;1(1):e000076.
28. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech (Bristol, Avon)*. 2010;25(2):142-146.
29. Sadoghi P, von Keudell A, Vavken P. Effectiveness of anterior cruciate ligament injury prevention training programs. *J Bone Joint Surg Am*. 2012;94(9):769-776.
30. Sharir R, Rafeeuddin R, Staes F, et al. Mapping current research trends on anterior cruciate ligament injury risk against the existing evidence: in vivo biomechanical risk factors. *Clin Biomech (Bristol, Avon)*. 2016;37:34-43.
31. Smith HC, Johnson RJ, Shultz SJ, et al. A prospective evaluation of the landing error scoring system (less) as a screening tool for anterior cruciate ligament injury risk. *Am J Sports Med*. 2012;40(3):521-526.
32. Soligard T, Myklebust G, Steffen K, et al. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *BMJ*. 2008;337:a2469.
33. Speer KP, Spritzer CE, Bassett FH 3rd, Feagin JA Jr, Garrett WE Jr. Osseous injury associated with acute tears of the anterior cruciate ligament. *Am J Sports Med*. 1992;20(4):382-389.
34. Therneau T. *Mixed Effects Cox Models*. Rochester, Minnesota: Mayo Clinic; 2015.
35. van Mechelen W, Hlobil H, Kemper HCG. Incidence, severity, aetiology and prevention of sports injuries. *Sports Med*. 1992;14(2):82-99.
36. Weinhandl JT, Earl-Boehm JE, Ebersole KT, Huddleston WE, Armstrong BSR, O'Connor KM. Reduced hamstring strength increases anterior cruciate ligament loading during anticipated sidestep cutting. *Clin Biomech (Bristol, Avon)*. 2014;29(7):752-759.
37. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med*. 2007;41(suppl 1):i47-i51.