Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K.-M.,
     Myklebust, G. ... Bahr, R. (2016). 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. *American Journal
     of Sports Medicine, 44*, 874-883.

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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

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Background: The evidence linking knee kinematics and kinetics during a vertical drop jump (VDJ) to anterior cruciate ligament (ACL) injury risk is restricted to a single small sample. Still, the VDJ test continues to be advocated for clinical screening purposes.

Purpose: To test whether 5 selected kinematic and kinetic variables were associated with future ACL injuries in a large cohort of Norwegian female elite soccer and handball players. Furthermore, the authors wanted to assess whether the VDJ test can be recommended as a screening test to identify players with increased risk.

Study design: Cohort study; Level of evidence, 2.

Methods: Elite female soccer and handball players participated in preseason screening tests from 2007 through 2014. The tests included marker-based 3-dimensional motion analysis of a drop-jump landing. The authors followed a predefined statistical protocol in which they included the following candidate risk factors in 5 separate logistic regression analyses, with new ACL injury as the outcome: (1) knee valgus angle at initial contact, (2) peak knee abduction moment, (3) peak knee flexion angle, (4) peak vertical ground-reaction force, and (5) medial knee displacement.

Results: A total of 782 players were tested (age, 21 ± 4 years; height, 170 ± 7 cm; body mass, 67 ± 8 kg), of which 710 were included in the analyses. The authors registered 42 new noncontact ACL injuries, including 12 in previously ACL-injured players. Previous ACL injury (relative risk, 3.8; 95% CI, 2.1-7.1) and medial knee displacement (odds ratio, 1.40; 1.12-1.74 per 1-SD change) were associated with increased risk for injury. However, there was an association with medial knee

displacement among the 643 players with no history of previous injury. A receiver operating characteristic curve analysis of medial knee displacement showed an area under the curve of 0.6, indicating a poor-to-failed combined sensitivity and specificity of the test, even when including previously injured players.

Conclusion: Of the 5 risk factors considered, medial knee displacement was the only factor associated with increased risk for ACL. However, receiver operating characteristic curve analysis indicated a poor combined sensitivity and specificity when medial knee displacement was used as a screening test for predicting ACL injury. For players with no previous injury, none of the VDJ variables were associated with increased injury risk.

Clinical Relevance: VDJ tests cannot predict ACL injuries in female elite soccer and handball players.

Keywords: female; handball; soccer; football; anterior cruciate ligament; biomechanics; screening; vertical drop jump

Anterior cruciate ligament (ACL) injuries represent a significant concern in sports because of the serious consequences for the injured athlete, with time lost from sport and decreased performance. The long-term consequences may be even more severe, with increased risk of early osteoarthritis, reduced knee function, and pain.[32,42,46,64] A high incidence of ACL injury has been reported in pivoting sports such as soccer (football), basketball, and handball, and the incidence is 3 to 5 times higher among women than men.[3,40,41,51,66]

However, 50% to 65% of noncontact ACL injuries in team sports can be prevented through exercise programs focusing on neuromuscular control, balance, strength, and technique.[21,39,63] Still, we do not know to what extent each of these program components contributes to the overall effect[63,64] nor do we know if and how programs can be tailored to the at-risk athlete. Also, implementation, adoption, and maintenance of programs in real life remain a challenge, as they may be perceived as time-consuming.[59]

ACL injuries are multifactorial in nature[54,56,55,57] and motion patterns are believed to play a key role. This assumption is partly based on the effect seen from injury prevention programs focusing on lower limb alignment and soft landings[21,39,63] and also from video analyses of actual ACL injury situations, suggesting that poor frontal plane knee control is a key feature of the mechanism of injury[9,10,15,25,26,31,47 9,10,15,25,26,31,48].

Hewett et al[23] were the first to suggest that a vertical drop-jump (VDJ) test could be used to screen for ACL injury risk. They tested this hypothesis in a 1-season prospective cohort study on 205 female athletes and found that the 9 athletes (7 during soccer and 2 during basketball) with a confirmed ACL injury displayed greater knee abduction angles and moments, higher ground-reaction forces, and shorter stance times, concluding that knee motion and knee loading during a VDJ task are predictors of ACL injury risk in female athletes. However, this finding has not been replicated by others. In fact, Smith et al[57] screened 5047 male and female high school and college athletes using a VDJ landing task, albeit with frontal and sagittal video analyses, and could not identify any factors related to lower limb and trunk motion that could be used to separate the 28 athletes suffering an ACL injury from 64 matched controls.

Nevertheless, even if the evidence linking knee kinematics and kinetics during a VDJ test to ACL injury risk is restricted to a single small sample[23,23] the test continues to be advocated for clinical screening purposes.[16,36,38,44,45]

The aim of this study was therefore to test whether 5 carefully selected kinematic and kinetic variables were associated with future ACL injuries in a large cohort of Norwegian female elite

soccer and handball players. Furthermore, we wanted to assess whether the VDJ test can be recommended as a screening test to identify players with increased injury risk. We hypothesized that greater knee valgus angles at initial contact, greater peak knee abduction moments, lower peak knee flexion angles, higher peak vertical ground-reaction forces (vGRFs), and greater medial knee displacement during the contact phase would be associated with increased risk for sustaining an ACL injury.

METHODS

Study Design and Participants

This prospective cohort study started in 2007, when we invited all teams in the Norwegian female handball premier league to a comprehensive preseason baseline screening examination, including a VDJ test. Players with a first-team contract who were expected to play in the premier league during the 2007 season were eligible for participation. From 2008 through 2013, new teams advancing to the premier league and new players from included teams were invited for preseason tests. From 2009, we also included soccer players from the female premier league. A total of 372 handball players and 338 soccer players were included in the cohort. The Regional Committee for Medical Research Ethics, the South-Eastern Norway Regional Health Authority, and the Norwegian Social Science Data Services, Norway, approved the study. Players signed a written informed consent form before inclusion (including parental consent for players aged <18 years).

Three-dimensional Motion Analysis

We instructed players to drop off of a 30-cm box and perform a maximal jump upon landing with their feet on 2 separate force platforms (LG6-4-1; Advanced Mechanical Technology Inc). They were allowed up to 3 practice trials, and a minimum of 3 valid trials were collected for each player. At least 2 testers observed the execution of the jump and verbally encouraged maximal jump effort. If submaximal effort was suspected or if the player jumped instead of dropped off the box (ie, increasing the vertical center-of-mass position at takeoff from the box), the player was asked to repeat the jump.

Players wore their own indoor shoes (handball shoes, indoor soccer shoes, or jogging shoes), shorts, and a sports bra. A 35-marker setup was used to describe full-body kinematics.[27] In addition, from 2008 to 2011, we used 2 markers (left and right iliac crest) in some subjects (ie, when the markers on the left and right anterior superior iliac spine were occluded). From 2012 and onward, we included the crest markers consistently for all players but used them only in cases where the anterior superior iliac spine markers were occluded.

All marker positions—the ones over anatomic landmarks as well as the ones placed on muscle bellies—were uniquely defined.[37] For every test session, 1 research assistant (physical therapist or medical student) was responsible for placing markers on all players to ensure consistency.

From 2007 to 2012, we used eight 240-Hz infrared cameras (ProReflex; Qualisys) to capture motion while we recorded ground-reaction forces using 2 force platforms collecting at 960 Hz. From 2012, we used an upgraded 16-camera 480-Hz camera system (Oqus 4; Qualisys). We calibrated the motion analysis system according to guidelines of the manufacturer and calculated and tracked marker trajectories using the Qualisys Track Manager.

We defined the contact phase as the period where the unfiltered vGRF exceeded 20 N. Marker trajectories and force data were filtered and interpolated with Woltring's[69] smoothing spline in the cubic mode, with a 15-Hz cutoff.[27]

We calculated the hip joint center using the method proposed by Bell et al,[5] with the anterior-posterior position of the hip joint defined by the anterior-posterior position of the marker over the greater trochanter. Furthermore, we defined the knee joint center according to Davis et al[12] and the ankle joint center according to Eng and Winter[17].[17] Total body mass and anatomic coordinate systems of the thigh and shank were determined from the static calibration trial. We defined the vertical axis in the direction from the distal to the proximal joint center, while the anteroposterior axis was defined perpendicular to the vertical axis with no mediolateral component. The third axis was the cross product of the vertical and anteroposterior axes. Consequently, all segments had neutral internal-external rotation in the static calibration trial. We obtained technical, dynamic thigh and shank segment coordinate systems using an optimization procedure involving singular value decomposition.[58]

We estimated inertia parameters based on 46 measures of segment heights, perimeters, and widths using a modified method by Yeadon[71],[72] with hand and foot parameters calculated with the method of Zatsiorsky and Seluyanov[72].[73] Body height was measured in the standing position with a right-angle tool and tape measure.

We calculated external hip and knee joint moments with inverse dynamics using recursive Newton-Euler equations of motion as described by Davis et al[12] and projected them onto the 3 rotational axes of the joint according to the joint coordinate system standard.[8,22,29,70]

We used the Grood and Suntay[22] convention for calculating joint angles from the marker-based motion analysis. We calculated medial knee position as the perpendicular distance between the knee joint center and the line joining the ankle and hip joint centers, projected on the frontal plane (Figure 1). We calculated medial knee position only when the knee joint center was medial to the hip-ankle line. Otherwise, medial knee position was set to zero. The difference between medial knee position at initial foot contact and the peak value was defined as the medial knee displacement. An advantage of this convention as compared with a pure knee separation measure is that we were able to assess knee control individually for the left and right legs. We ran all calculations using custom Matlab scripts (MathWorks Inc).

[FIGURE 1 ABOUT HERE]

Figure 1.

Medial knee position was measured in the frontal plane, as the perpendicular distance from the knee joint center to the line connecting the hip and ankle joint. The difference between the medial knee position at the initial foot contact and the peak value was defined as the medial knee displacement. ACL, anterior cruciate ligament.

Injury Registration

We recorded all complete ACL injuries among the tested players through March 2014, primarily through semiannual contact with the participating teams (manager, coach, medical staff). If any acute knee injuries occurring during regular team training or competition were reported, we contacted the injured player by phone to obtain detailed medical data and a description of the injury situation. All ACL injuries were verified by magnetic resonance imaging and/or arthroscopy.

Statistical Protocol

We followed a rigorous protocol with predefined procedures and variables of interest as described below. To ensure high statistical power, we decided to limit the number of primary variables (potential risk factors) to 5. We selected these variables based on a step-by-step approach. First, on the basis of a literature review, we concluded that factors related to frontal plane knee control and landing stiffness were most likely to be associated with injury risk. These studies included the prospective cohort study of Hewett et al,[23] intervention studies on injury prevention programs,[21,39,63] and studies on injury mechanisms[13,14,25,26,31,33,34,55,60,67,68] [13,14,25,26,31,33,34,56,61,68,69] **[*FOOTNOTE*]** Next, we investigated the correlations among all candidate risk factors to avoid including highly correlated factors, and we included only variables with good or excellent reliability. We interpreted the intraclass correlation coefficient (ICC) according to Fleiss[19] as poor (<0.40), fair (0.40-0.59), good (0.60-0.75), and excellent (>0.75).

Ultimately, we included the following candidate risk factors, measured during the stance phase of the vertical drop jump: (1) knee valgus angle at initial contact, (2) peak knee abduction moment, (3) peak knee flexion angle, (4) peak vGRF, and (5) medial knee displacement.

We chose knee valgus at initial contact and peak knee abduction moment as candidate factors based on Hewett et al,[23] who found these to be associated with injury. We also included medial knee displacement as a simple and robust measure of frontal plane knee control during the contact phase. Medial knee displacement, as defined here, is a similar measure to those previously reported from studies based on subjective assessment or 2-dimensional video analyses in VDJ screening tests[16,36,44,62] [16,36,45,63] We furthermore chose medial knee displacement rather than peak knee valgus angle, for example, as the peak angle had a strong correlation with knee valgus angle at initial contact ($r > 0.80$).

We chose peak knee flexion angle and peak vGRF as measures of landing stiffness. These variables displayed the highest intercorrelation among the 5 variables ($r = -0.59$).

Reliability of the Primary Variables

The short-term test-retest reliability of the potential risk factor variables is described by Mok et al. (unpublished). All the primary variables of the present study achieved good to excellent within- and between-session reliability. The medial knee displacement had a within-session ICC of 0.91, whereas the between-session ICC was 0.75. To examine long-term changes, we retested 107 players (mean ± SD age, 20.7 ± 3.3 years) 1 to 4 years after the first test session (mean ± SD, 2.2 ± 0.7 years). We calculated the mean difference, the method error (the SD of the difference divided by the square root of 2), and the $ICC_{3,1}$ with 95% CIs between test sessions 1 and 2.[7]

Statistical Models and Calculations

We generated 5 separate logistic regression models, 1 for each proposed risk factor. New ACL injury was the outcome, with the leg as the unit of analysis. Each of the 5 risk factor variables was based on the mean of 3 jump trials. All models included the same set of adjustment factors to compensate for factors that could influence injury risk: (1) sport, (2) dominant leg, (3) height, (4) body mass, and (5) previous ACL injury. We defined the dominant leg as the preferred leg when kicking a ball. We calculated standardized odds ratios (ORs) per 1-SD change with 95% CIs for each risk factor and adjustment factor.

We calculated receiver operating characteristic (ROC) curve to investigate the sensitivity and specificity characteristics of a test based on the medial displacement variable.[35] The test outcome is defined as excellent (0.90-1), good (0.80-0.89), fair (0.70-0.79), poor (0.60-0.69), and fail (0.50-0.59).

Relative risk (95% CI) for reinjuries was calculated as the rate of new injuries in previously injured divided by the rate of new injuries in noninjured players. Similarly, we calculated the relative risk of injuries in soccer players compared with handball players as the rate of new injuries among soccer players divided by the rate of new injuries among handball players.

We plotted the frequency diagram for the medial knee displacement variable in injured and uninjured knees dividing measurements into 0.5-cm intervals.

We compared relevant variables between players with and without new ACL injuries during the study period using the Student t test. STATA for Windows (v 12; STATA Corp) was used to run the statistical analyses and interpreted $P < .05$ as statistically significant. Data are presented as means with ±SDs or 95% CIs unless otherwise noted.

RESULTS

Player and Injury Characteristics

We tested 782 players in the VDJ test from August 2007 through February 2014. We chose not to process recordings that were suboptimal owing to missing markers or poor capture quality. Additionally, technical errors with the force plate recordings occurred in 1 test session, and data were lost in another session. One player withdrew from the testing because of an ankle sprain. This left us with 710 players eligible for analysis: 338 (48%) soccer and 372 (52%) handball players.

We recorded 53 new ACL injuries during the study period: 27 among soccer and 26 among handball players. Two players were injured twice during the observation period; their first injury was used as the index injury in the analyses. Seven players sustaining a contact injury and 2 with incomplete test data were excluded before the statistical analyses. This left 42 noncontact injuries available for analysis (Table 1): 24 from soccer and 18 from handball. In 1 case, technical problems with the force plate recording prevented us from calculating kinetics. ACL injury occurred 1.5 ± 1.3 years after the baseline test. The nondominant leg was injured in 26 cases (62%).

[FIGURE 2 ABOUT HERE]

Figure 2.

Flow diagram of the included/excluded players (top) and included/excluded injured players (bottom). ACL, anterior cruciate ligament.

TABLE 1

Player Characteristics in 4 Groups, Classified According to Their Past and Current History of ACL Injury[a]

	No Previous ACL Injury	Previous ACL Injury	All Subjects

Player Characteristics	New INJ (n = 30)	No New INJ (n = 613)	P	New INJ (n = 12)	No New INJ (n = 55)	P	New INJ (n = 42)	No New INJ (n = 668)	P
Age, y	19.9 ± 2.8	21.0 ± 3.9	.02[b]	22.7 ± 3.8	23.6 ± 4.1	.23	20.9 ± 3.3	21.2 ± 4.0	.45
Height, cm	168.0 ± 6.3	169.5 ± 6.4	.21	172.9 ± 7.4	171.0 ± 6.7	.29	169.4 ± 6.9	169.6 ± 6.5	.83
Body mass, kg	64.6 ± 7.8	66.3 ± 7.9	.26	72.2 ± 7.9	67.9 ± 7.8	.05	66.8 ± 8.4	66.4 ± 7.9	.76
Knee valgus at initial contact, deg	−2.2 ± 4.7	−1.7 ± 4.1	.51	−2.3 ± 5.6	−3.0 ± 3.9	.61	−2.2 ± 4.9	−1.8 ± 4.1	.51
Peak knee abduction moment, N·m	21.2 ± 12.2	20.9 ± 11.0	.91	23.9 ± 11.8	18.7 ± 9.1	.07	22.0 ± 12.0	20.7 ± 10.8	.47
Peak knee flexion, deg	92.2 ± 13.8	90.8 ± 14.9	.62	90.2 ± 15.8	91.6 ± 14.6	.80	91.6 ± 14.2	90.9 ± 14.8	.75
Peak vGRF, N	1341 ± 410	1373 ± 426	.69	1239 ± 297	1380 ± 466	.33	1311 ± 380	1373 ± 429	.36
Medial knee displacement, cm	2.5 ± 1.2	2.2 ± 1.3	.22	3.2 ± 1.6	2.1 ± 1.4	.02[b]	2.7 ± 1.4	2.2 ± 1.3	.02[b]

[a]Data are reported as mean ± SD. *P* values are shown for univariate comparisons between players with and without a new noncontact anterior cruciate ligament (ACL) injury. For players with new injuries, peak knee flexion, peak vertical ground-reaction force (vGRF), knee valgus at initial contact, peak knee abduction moment, and medial knee displacement are reported for the injured leg only. In the groups with no new injuries, the data represent the mean of the left and right legs, as there were no significant side-to-side differences. INJ, injury.

[b]$P < .05$ (Student *t* test).

Of the 710 players, 67 (9.4%) reported a history of ACL injury before testing. Of these, 12 (17.9%) suffered a new injury: 4 an ipsilateral reinjury and 8 an injury to the contralateral, healthy knee. The relative risk of a new ACL injury among the previously injured versus those with no previous injury was 3.8 (95% CI, 2.1-7.1).

The relative risk of ACL injury in soccer players versus handball players was 1.5 (95% CI, 0.8-2.7).

Univariate Risk Analysis

Table 1 depicts the characteristics of players classified according to their past and current history of ACL injury. Among players with no previous ACL injury, those who sustained an ACL injury were 1.1 years younger than uninjured players. Also, we observed greater medial knee displacement among those with new injury among all 710 subjects (mean, 0.5 cm; 95% CI, 0.07-0.93) and in the group of 67 previously injured players (mean, 1.0 cm; 95% CI, 0.01-2.10), while there was no difference in medial knee displacement among the 643 players with no history of previous injury.

Among the 42 injured players, we detected no side-to-side differences between the injured and uninjured legs in any of the 5 variables.

Multivariate Risk Analysis

The standardized ORs, corresponding to the increased risk associated with a 1-SD change in the variable, for each of the 5 separate logistic regression analyses are listed in Table 2. Medial knee displacement was the only factor associated with increased risk for injury (OR, 1.40; 95% CI, 1.12-

1.74). In a similar analysis including only players without a history of previous ACL injury (n = 643 players, n = 30 new injuries), the OR decreased to 1.25 (95% CI, 0.97-1.61).

TABLE 2
Standardized Odds Ratios (per 1-SD Change) for Each Risk Factor Based on 5 Separate Logistic Regression Analyses[a]

Model: Risk Factor	Adjustment Factors					
	Risk Factor	Sport	Dominant Leg	Body Mass	Height	Previous ACL Injury[b]
1: Valgus at initial contact	1.00	0.75	0.83	1.16	0.94	1.54
	(0.69, 1.45)	(0.49, 1.14)	(0.68, 1.02)	(0.78, 1.73)	(0.65, 1.38)	(1.25, 1.88)
2: Peak knee abduction moment	1.18	0.76	0.84	1.16	0.91	1.57
	(0.87, 1.60)	(0.51, 1.14)	(0.69, 1.03)	(0.73, 1.74)	(0.62, 1.34)	(1.28, 1.92)
3: Peak knee flexion	1.00	0.75	0.83	1.16	0.94	1.54
	(0.73, 1.36)	(0.50, 1.11)	(0.68, 1.02)	(0.78, 1.72)	(0.64, 1.39)	(1.26, 1.87)
4: vGRF	0.89	0.77	0.85	1.21	0.95	1.54
	(0.61, 1.29)	(0.52, 1.15)	(0.69, 1.04)	(0.81, 1.81)	(0.63, 1.43)	(1.27, 1.87)
5: Medial knee displacement	1.40[b]	0.73	0.83	1.17	0.90	1.54
	(1.12, 1.74)	(0.49, 1.08)	(0.68, 1.02)	(0.79, 1.74)	(0.61, 1.33)	(1.27, 1.87)

[a]Data in parentheses are 95% CIs. The analyses adjusted for the effect of height, mass, sport, dominant leg and previous anterior cruciate ligament (ACL) injury, as shown. vGRF, vertical ground-reaction force.

[b]For each cell in column, $P < .05$ (Z test).

VDJ Screening Test Characteristics for the Medial Knee Displacement Variable

As shown in Figure 3, there was substantial overlap in the frequency distribution of medial knee displacement between injured and noninjured players. An ROC curve analysis showed an area under the curve of 0.6, indicating a poor-to-failed combined sensitivity and specificity of the test.

[FIGURE 3 ABOUT HERE]

Figure 3.
Frequency diagram with Gaussian regression line of medial knee displacement (cm) in injured (top panel) and uninjured knees (lower panel).

Time Changes of the Primary Variables

There were no systematic changes in medial knee displacement and only small systematic changes in the remaining measurements taken 1 to 4 years apart (Table 3). For knee valgus at initial contact, peak knee flexion and peak vGRF, consistency was good (ICC range = 0.60-0.66), whereas consistency for medial knee displacement was fair (ICC = 0.54). Consistency for peak knee abduction moment was poor (ICC = 0.25).

TABLE 3

Test-Retest Characteristics of 107 Players (214 Legs)[a]

	Mean Session Difference	Method Error	ICC (95% CI)	P
Valgus at initial contact, deg	1.4	2.5	0.66 (0.53-0.75)	<.01[b]
Peak knee abduction moment, N·m	6.8	10.3	0.25 (0.10-0.39)	<.01[b]
Peak knee flexion, deg	2.7	8.1	0.66 (0.57-0.74)	<.01[b]
Peak vGRF, N	–80	260	0.60 (0.50-0.68)	<.01[b]
Medial knee displacement, cm	0.0	0.9	0.54 (0.44-0.63)	.98

[a]Mean session difference, SD of the difference, 95% limit of agreement, and intraclass correlation coefficient (ICC) with 95% CI from session 1 to session 2 are reported. vGRF, vertical ground-reaction force.

[b]$P < .05$ (t test).

DISCUSSION

Of the 5 factors suggested as predictors for ACL injury (knee valgus angle, knee abduction moment, vGRF, knee flexion angle, and medial knee displacement), only 1 factor was statistically associated with elevated ACL injury risk. Greater medial knee displacement during the contact phase increased injury risk by approximately 40% for a 1-SD (1.2 cm) increase in medial knee motion. The elevated risk associated with greater medial knee displacement in previously injured players supports studies suggesting that frontal plane kinematics is an important component in ACL injury causation[23,25,60].[23,26,61] However, it should be noted that the difference between cases and controls was small (mean, 0.5 cm). Therefore, it is not surprising that the ROC curve analysis revealed an area under the curve of only 0.6, documenting that the VDJ test cannot be used as a screening test to predict ACL injury.

The present study represents a major undertaking with >700 elite female handball and soccer players tested with 3-dimensional motion analysis over a 7-year period. These are high-risk populations, with 53 new ACL injuries registered among the 782 players tested during the study period. The statistical analyses were predefined with predictor variables carefully chosen per the literature. This rigorous statistical approach, in contrast to exploratory data mining, minimizes the chance for obtaining spurious statistical relationships.[24,65]

In contrast to the study of Hewett et al,[23] knee abduction moments and valgus angles at initial contact could not identify players with increased risk of future ACL injury. Although we investigated

only a limited number of potential risk factors, the measured variables are considered to be those most likely to play a role in ACL injury causation, based on the current literature. Although other biomechanical variables, such as knee internal rotation and anterior tibial translation, may be important, these variables are possible to measure only with high-end methods, such as fluoroscopy, and cannot currently be implemented in a mass screening of athletes.

We observed a 3.8-times-higher injury rate among players with previous injury, which is lower than what has been reported in other studies[18,48-50].[18,49-51] The higher injury rate may be related to the increased medial knee displacement observed among injured athletes with a history of previous injury (Table 1) but also a host of other factors[1,56].[1,57] In contrast to Hewett et al,[23] we did not detect side-to-side differences in any of the 5 candidate variables among the group of injured players. However, players with a history of previous injury clearly represent a high-risk group. More advanced testing with VDJ or other tasks are not needed to identify these. Such players should be targeted with preventive exercise programs on the basis of their injury history alone.

It is worth noting that not only the outcomes but also the subject characteristics are substantially different among the cohorts of the 3 risk factor studies available. Our group of well-trained adult (21 years on average) elite players is likely to have a better physique and skill level, as well as higher exposure to injury prevention training, compared with the high school cohort (16 years) of Hewett et al[23] and mixed high school–college cohort (18 years) of Smith et al.[57] It is possible that a VDJ test can identify high-risk players in groups of younger, less trained athletes, but this needs to be documented in large prospective cohort studies.

Substantial reductions in ACL injury rates have been observed in numerous intervention studies[21,39,63],[21,40,64] even national injury prevention programs[43].[44] Therefore, it is surprising that what appears to be key elements in the programs, such as "knee over toe" alignment and "soft landings," were not found to be associated with increased injury risk in the current study, except among those with a history of previous injury. One could speculate that the efforts made to reduce the ACL injury incidence in Norwegian handball for more than a decade have improved landing and cutting technique among all players,[7] thereby reducing inherent variability. Still, 39% of the players were evaluated as having poor landing technique in VDJs.[8] Furthermore, there were no differences in medial knee displacement between the handball and soccer cohorts, indicating that injury prevention training does not seem to have influenced landing technique substantially. Another possible reason may be that a VDJ task is not sufficiently challenging for unveiling poor frontal plane knee control, as suggested by Smith and coauthors.[57] A previous study reported 5-times-higher peak knee abduction moments in a handball-specific side-step cutting maneuver compared with VDJ[28].[27] Moreover, there was no correlation between the 2 measures, indicating that a drop jump cannot simulate the loading patterns of motions where ACL injuries are known to occur[25,31,47].[26,31,48] Consequently, it may be necessary to develop screening tests where the frontal plane loads are higher and movements more comparable with what is seen in injury situations, including 1-leg out-of-balance landings or cutting maneuvers. Also, an overhead target could alter the player jump performance and biomechanics.[20] We did not include an overhead target in the test, since we wanted to make the test as simple as possible.

Limitations

We used a logistic regression analysis rather than a Cox regression to investigate risk factors. We chose the logistic regression approach since the percentage of players with new injury included in the cohort was as low as 7.4%. The difference between a logistic regression and a survival analysis is insignificant when the proportion of injured players is <10%.[2]

Although this is the largest study to date, 42 injured players still represent a limited sample. Moreover, with this sample size, including 5 risk factors and 5 covariates in the model results in limited statistical power. Still, according to Bahr and Holme[4,4] this sample size is sufficient to detect moderate to strong associations. As can be seen from the 95% CIs, it is clear that none of the factors examined have strong associations with injury risk. In other words, increasing sample size would provide more precise ORs, yet they would still be clinically insignificant.

We ran 5 separate logistic regression analyses to investigate the effect of each of the 5 preselected variables in isolation (while adjusted for possible confounders). However, we also inputted all 5 primary variables, as well as the adjustment factors, into 1 combined model. In the new, combined model, results were almost identical. For instance, the medial knee motion standardized OR changed from 1.40 to 1.47.

We used the leg as the unit of analysis, through clustered regression models, ignoring the fact that repeated within-person observations were likely dependent. Such dependencies were, however, present only in the control group and therefore did not likely influence outcome.

Another potential limitation of such a long-term study is that the candidate risk factors may have changed during the course of the study (eg, through training or maturation), invalidating our baseline risk factor estimates. From questionnaire data, 38% of the players (in both soccer and handball) reported to have implemented preventive training as part of their routine during the season. However, we cannot be sure what or how much was done. Such training may have influenced jump-landing execution and thereby led to misclassification of players. In the current study, the time from test to injury was on average 1.5 years. In our long-term test-retest study (average, 2.1 years), there were only small systematic changes in risk factors. The method errors can be considered small, but the method error for knee flexion (8.1°) (see Table 3) indicated that the movement patterns have changed. Measurements of knee flexion angles through marker-based motion analysis systems are known to be reliable and accurate[6,52,53,61],[6,53,54,62] indicating that the observed variation is a result of VDJ technique changes. Mok et al (unpublished) also found similar results in a short-term test-retest study on the same cohort. However, if we take into consideration the relative large number of injured cases, the error in the calculated ORs is likely minimal.

We wanted to make the VDJ test as simple as possible to optimize its clinical applicability. In contrast, other protocols have standardized foot distance and jump length. In a study comparing VDJ with a minimal forward displacement and a drop jump with a forward displacement corresponding to 50% of the body height, a higher tibial shear force and knee abduction moment was found but with no differences in knee valgus or knee flexion.[11] In this study, the forward displacement of the center of mass was relatively consistent among the players and corresponded to approximately 30% of their body height (0.48 ± 0.13 m). The results of our protocol are therefore expected to be comparable with most other protocols, at least for knee valgus and knee flexion angles. A narrow stance may limit the range of medial knee displacement attributed to physical contact between the knees. However, this situation was observed in only 1.2% of the subjects, as evaluated by the distance between knee centers.

Another limitation is related to the fact that we relied on player interviews to classify injuries as contact or noncontact. Recall bias and the ability to interpret what happened in an injury situation may be problematic.[30] For this reason, we performed additional regression analyses where we included all injuries (also contact injuries), for both the primary analysis including all players and a secondary analysis where players with a history of previous injury were removed. However, the outcome remained the same, documenting that potential misclassification of the mechanism of injury does not change the results of this study.

CONCLUSION

In players with no previous injury, none of the VDJ variables were associated with increased injury risk. Therefore, the VDJ cannot be used as a screening test to predict ACL injuries in female elite soccer and handball players. Of the 5 risk factors considered, medial knee displacement was the only factor associated with increased risk for ACL injury. However, ROC analysis indicated a poor combined sensitivity and specificity when medial knee displacement was used as a screening test for predicting ACL injury.

ACKNOWLEDGMENT

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