Strength and Biomechanical Risk Factors for Noncontact ACL Injury in Elite Female Footballers: A Prospective Study

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ABSTRACT

COLLINGS, T. J., L. E. DIAMOND, R. S. BARRETT, R. G. TIMMINS, J. T. HICKEY, W. S. DU MOULIN, M. D. WILLIAMS, K. A. BEERWORTH, and M. N. BOURNE. Strength and Biomechanical Risk Factors for Noncontact ACL Injury in Elite Female Footballers: A Prospective Study. *Med. Sci. Sports Exerc.*, Vol. 54, No. 8, pp. 1242–1251, 2022. **Purpose:** This study aimed to determine if a preseason field-based test battery was prospectively associated with noncontact anterior cruciate ligament (ACL) injury in elite female footballers. **Methods:** In total, 322 elite senior and junior female Australian Rules Football and soccer players had their isometric hip adductor and abductor strength, eccentric knee flexor strength, countermovement jump (CMJ) kinetics, and single-leg hop kinematics assessed during the 2019 preseason. Demographic and injury history details were also collected. Footballers were subsequently followed for 18 months for ACL injury. **Results:** Fifteen noncontact ACL injuries occurred during the follow-up period. Prior ACL injury (odds ratio [OR], 9.68; 95% confidence interval (95% CI), 2.67–31.46), a lower isometric hip adductor to abductor strength ratio (OR, 1.98; 95% CI, 1.09–3.61), greater CMJ peak take-off force (OR, 1.74; 95% CI, 1.09–3.61), and greater single-leg triple vertical hop average dynamic knee valgus (OR, 1.97; 95% CI, 1.06–3.63) and ipsilateral trunk flexion (OR, 1.60; 95% CI, 1.01–2.55) were independently associated with an increased risk of subsequent ACL injury. A multivariable prediction model consisting of CMJ peak take-off force, dynamic knee valgus, and ACL injury history that was internally validated classified ACL injured from uninjured footballers with 78% total accuracy. Between-leg asymmetry in lower limb strength and CMJ kinetics were not associated with subsequent ACL injury risk. **Conclusions:** Preseason field-based measures of lower limb muscle strength and biomechanics were associated with future noncontact ACL injury in elite female footballers. These risk factors can be used to guide ACL injury screening practices and inform the design of targeted injury prevention training in elite female footballers. **Key Words:** ACL, INJURY PREVENTION, REHABILITATION, FEMALE ATHLETE, STRENGTH, BIOMECHANICS

Anterior cruciate ligament (ACL) ruptures are among the most catastrophic injuries in soccer and Australian Rules Football and occur 3–6 times more frequently in female than male footballers (1,2). Even after ACL reconstructive surgery, two-thirds of female footballers fail to return to the same level of competition, and one in three go on to sustain a second ACL injury (3). The treatment and surgery costs associated with ACL injury, combined with the potential for early-onset knee osteoarthritis, generate a large health care–related financial burden (4). Therefore, efforts to prevent ACL injury in female footballers are imperative.

In soccer and Australian Rules Football, ACL injuries most commonly occur because of a noncontact mechanism when changing direction, decelerating, or landing on a single-leg (5,6). Prior ACL injury is the most consistently identified risk factor for subsequent ACL injury (7). Biomechanical factors suggested to be associated with increased risk of an index ACL injury include greater knee valgus angles, moments and peak vertical ground reaction force during double-leg drop vertical jumps

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(8,9), two-dimensional frontal plane knee valgus and trunk lateral flexion during single-leg drop vertical jumps (10), and hip flexion and knee internal rotation angles at initial contact during sidestepping (11). However, mixed evidence regarding risk factors such as knee valgus exist (12,13), and until recently, automated methods of determining kinematics have been difficult to obtain outside of the laboratory. Between-leg asymmetry in jumping kinetics is also used as a tool to monitor ACL rehabilitation (14), yet it is unknown whether asymmetries are associated with increased ACL injury risk.

Lower limb muscle strength may mediate biomechanics associated with ACL injury risk. For example, hip muscle weakness (in all planes) is associated with greater dynamic knee valgus during single-leg landing in females (15), which may increase ACL strain (16). Furthermore, the hip abductors and hamstrings may be important for opposing ACL loads during side-step cutting by applying a knee varus moment, or posterior shear force to the knee, respectively (17). In theory, hamstrings and hip muscle weakness, or asymmetry between legs, may expose a player to a greater risk of ACL injury, although this has never been explored in elite female footballers (18).

An improved understanding of risk factors for ACL injury in female football is needed to identify at-risk players and inform the design of targeted injury prevention strategies. To date, limited research has examined female-only cohorts, and no studies have been conducted in female Australian soccer players or Australian Rules footballers, despite the latter having the highest rates of ACL injury in the world (2). Previous research has also been limited by univariable approaches to injury risk profiling, which may not capture the complex, multifactorial nature of sport injuries (19,20). Measuring several physical characteristics, including strength and biomechanics, may provide a better estimation of injury risk than a single test (19,20). Furthermore, for any test to be widely adopted, it is important that equipment is quick and easy to use, inexpensive, and able to be used in a wide range of settings. As such, field-based testing devices may provide suitable substitutes to traditional laboratory measures, which remain inaccessible for many teams.

The primary aim of this study was to determine if a preseason, field-based test battery consisting of hip strength, knee flexor strength, jump-landing kinetics, and hop kinematics was associated with future noncontact ACL injury in elite female footballers. A secondary aim was to determine the ability of multivariable prediction models to estimate ACL injury risk.

METHODS

Participants and study design. This prospective cohort study was conducted from 2019 to 2021. Data were collected from 322 elite senior and junior Australian Rules Football and soccer players. Senior players were recruited via established contacts at clubs located in Queensland, New South Wales, and Victoria. Junior players were recruited at an under-17 state-representative tournament involving the best players from around Australia. Of the 21 teams invited to participate, 1 declined, and 1 was unable to fit the testing schedule. All players within the training squad were invited to participate in the study. Players were excluded from the testing at the discretion of team medical staff if they were absent or had an injury or illness that precluded them from performing maximal intensity exercise. This study was approved by the University's human research ethics committee (reference number: 2019/423), and all players provided written informed consent before data collection. The parents/guardians of players under 18 yr of age also provided written informed consent.

At the beginning of their preseason (between November and December 2019), players completed a questionnaire detailing their demographics, injury history (including any lower limb injuries over the prior 12 months and lifetime history of ACL or other knee injuries), current hormonal contraceptive medication use, and the Knee injury and Osteoarthritis Outcome Score (KOOS) "pain" and "sport and recreation" (sport/rec) subscales. Subsequently, players underwent assessments of 1) isometric hip adductor and abductor strength, 2) eccentric knee flexor strength during the Nordic hamstring exercise (NHE), 3) bilateral countermovement jump (CMJ) kinetics, and 4) single-leg triple vertical hop kinematics. Each test was performed by 2–3 trained and well-practiced researchers. Details of any prospective ACL injuries sustained in the subsequent 18 months were reported to the research team. This study was designed and conducted in coordination with team medical staff and the sporting national governing bodies. The screening battery was purposefully designed to take <10 min per player, as established during pilot testing, and utilized equipment/tests that were routinely used by the included teams. Data and study findings were shared with all participating teams to guide future practice.

Hip adductor and abductor strength. Isometric hip adductor and abductor strength were measured for the left and right legs independently during bilateral contractions using uniaxial load cells (sampling rate of 50 Hz) attached to a rigid frame (ForceFrame; Vald Performance, Brisbane, Australia; Fig. 1A). Players were tested in a supine position, with the hip in neutral and the knee fully extended, and the load cells aligned with the ankle malleoli (21). Players performed three maximal effort trials of approximately 5-s isometric contractions, alternating between hip abduction and adduction with 5- to 10-s rest in between efforts. Similar testing protocols with the same device have shown excellent reliability (intraclass correlation coefficient (ICC) = 0.94) (22). The maximum force produced during three trials was used in the analysis. In addition, the ratio of hip adductor to hip abductor force for each leg was calculated (ADD:ABD force ratio).

Eccentric knee flexor strength. Eccentric knee flexor strength was measured from the left and right legs independently during the NHE using two uniaxial load cells (sampling rate of 50 Hz) attached immediately superior to the ankle malleoli (NordBord; Vald Performance; Fig. 1B). From a kneeling position, players were instructed to lower themselves to the ground as slowly as possible while keeping the trunk and hips in a neutral position. Players performed three maximal effort trials separated

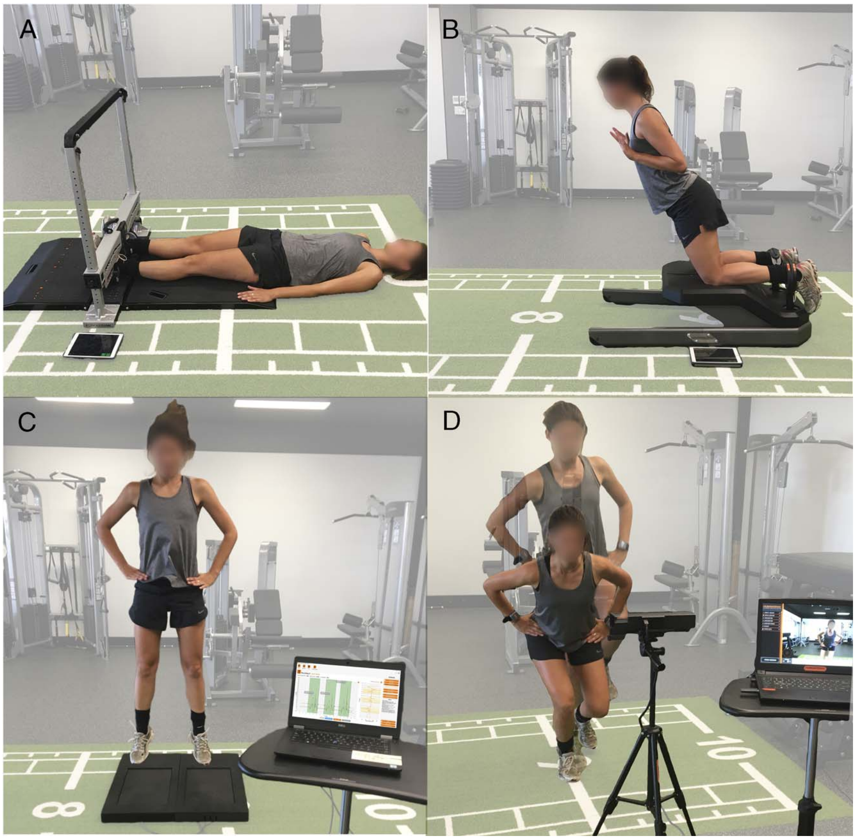


FIGURE 1—Demonstration of the strength and biomechanics field-based testing battery. A, Isometric hip adductor and abductor strength. B, Eccentric knee flexor strength during the NHE. C, Bilateral CMJ on portable force plates. D, Single-leg triple vertical hop kinematics using a markerless motion capture system.

by 5–10 s of rest. Similar testing protocols with a similar device have shown moderate-to-high reliability (ICC = 0.83 for left and 0.90 for right leg) (23). The maximum force produced during three trials was used in the analysis. To remove the relationship between force and body weight (BW) in the current cohort ($r = 0.58$), eccentric knee flexor strength was also reported allometrically scaled ($N{\cdot}kg^{-k}$, where k was 0.68) (24).

CMJ-landing kinetics. Bilateral CMJs were performed on dual-force plates that independently recorded left and right vertical ground reaction forces at 1000 Hz (ForceDecks, FDLite; Vald Performance; Fig. 1C). Players were instructed to jump as high as possible, using a countermovement to a self-selected depth, and to keep their hands on their hips throughout jumping and landing. Players performed three maximal effort trials separated by 5–10 s of rest. Peak forces and impulses measured using similar protocols and the same device have demonstrated excellent reliability (ICC > 0.90) (25). Data were extracted using ForceDecks software (version 2.0.7). Variables were selected based on previous research in athletes with ACL reconstructions (14) and included peak take-off force (concentric phase), take-off impulse (total eccentric + concentric phase), rate of force development (RFD; eccentric phase), peak landing force, and landing RFD. Other variables were excluded because they were highly correlated with the selected variables and offered little independent information (see Figure, Supplemental Digital Content 1, showing correlation matrix, http://links.lww.com/MSS/C544). All CMJ variables were normalized to BW in newtons.

Single-leg triple vertical hop landing kinematics. Single-leg hopping kinematics were recorded during a novel "single-leg triple vertical hop" task using a three-dimensional markerless motion capture system (HumanTrak; Vald Performance; Fig. 1D), consisting of a Kinect camera (v2; Microsoft, Redmond, WA) and Microsoft artificial intelligence to track joint trajectories. The single-leg triple vertical hop test involved three consecutive single-leg vertical jumps for maximal height in a continuous motion. Players were instructed to jump as high as they could with every jump while minimizing ground contact time. Players completed three trials for the left leg, followed by three trials for the right leg (i.e., nine hops per leg). All trials were analyzed by taking the mean of the nine landings. The single-leg triple vertical hop was designed to require high levels of exertion while challenging single-leg knee and trunk control. Kinematics were extracted (using R Studio, version 4.0.5, Boston, MA) from the landing phase defined as the phase between estimated ground contact (center of mass below standing height) and the lowest position of the center of mass. Variables selected for analysis were based on previous ACL risk factor studies in female athletes (9,10) and included average knee flexion, two-dimensional dynamic knee valgus, trunk flexion, and trunk ipsilateral flexion angles during landing. Measurement validity compared with a gold standard

TABLE 1. Number of players and ACL injury characteristics by sport cohort.

	Australian Rules Football (AFLW)	Senior Soccer (W-League)	Junior Soccer (Under-17 State)	Total
Total players	153	62	107	322
Completed follow-up	149 (97%)	44 (69%)	84 (79%)	277 (86%)
ACL injury group	12	1	2	15
Dominant leg	2 (17%)	1 (100%)	2 (100%)	5 (33%)
Nondominant leg	10 (83%)	0 (0%)	0 (0%)	10 (67%)
Index injury	8 (67%)	1 (100%)	1 (50%)	10 (67%)
Reinjury (same side)	1 (8%)	0 (0%)	0 (0%)	1 (7%)
Contralateral injury	3 (25%)	0 (0%)	1 (50%)	4 (27%)
Change of direction	9 (75%)	1 (100%)	2 (100%)	12 (80%)
Tackling	2 (17%)	0 (0%)	0 (0%)	2 (13%)
Landing from a jump	1 (8%)	0 (0%)	0 (0%)	1 (7%)
Match	8 (67%)	1 (100%)	1 (50%)	10 (67%)
Training	4 (33%)	0 (0%)	1 (50%)	5 (33%)

Six junior soccer players were also playing for a W-League team and are counted only in the junior soccer group. Data are total number (percentage relative to column total).
AFLW, Australian Football League Women's; W-League, National Australian Women's Soccer League.

three-dimensional motion capture system (Vicon, Oxford, United Kingdom) ranged from 2° to 9° (root mean square error), and reliability was moderate to good (ICC = 0.58–0.87) for all examined variables (see Report, Supplemental Digital Content 2, for HumanTrak validity and reliability study, http://links.lww.com/MSS/C545).

Between-leg asymmetry. Directional between-leg asymmetry (%) was calculated for lower limb strength and CMJ variables using the equation (leg maximum − leg minimum)/(leg maximum) × 100 and made positive when the injured leg (or right leg for uninjured players) was greater than the uninjured leg (or left leg for uninjured players). Nondirectional asymmetry was also analyzed by taking the absolute value of the directional between-leg asymmetry measure (i.e., making all values positive).

ACL injury reporting. All ACL injuries were reported to the researchers during the subsequent 18 months, which included two professional league playing seasons (2019/2020 and 2020/2021) and one regular season/COVID-19 break (2020). No partial ACL ruptures occurred during the follow-up; therefore, only total ruptures of the ACL (both index and recurrent injuries) due to a noncontact injury mechanism were included in the analysis. For players competing in a national professional league, ACL injuries were recorded by team medical staff using a standardized form that included injury diagnosis, time loss, mechanism of injury, and place of injury. For under-17 soccer players who did not have regular team medical staff, ACL injuries and related questions were self-reported by players via text message or email at the end of each season.

Statistical analysis. Statistical analysis was performed using R Studio (version 4.0.5; see Table, Supplemental Digital Content 3, for a list of packages used, http://links.lww.com/MSS/C546). The number of players and ACL injury characteristics were summarized by sport cohort using frequencies (*n*) and proportions (%) (Table 1). Group data for players who sustained a subsequent ACL injury ("ACL injured") and those who did not ("uninjured") were summarized with descriptive statistics (Table 2) and compared using Glass's delta effect sizes and independent two-tailed *t*-tests for normally distributed variables, and Wilcoxon effect sizes (*r*) and Wilcoxon rank sum tests for nonparametric variables. Categorical variables were compared between groups using Fisher's exact test. Statistical significance was set at $P < 0.05$. Glass's delta effect sizes can generally be interpreted as small (<0.3), moderate (0.3–0.5), or large (>0.5).

Incomplete data differed by 0%–19% per variable mainly because of availability of equipment at testing sessions (see Figure, Supplemental Digital Content 4, showing missing data count, http://links.lww.com/MSS/C547). Therefore, data were considered missing at random, and for subsequent analysis, these data were handled using multiple imputation ($m = 20$)

TABLE 2. Group comparison of players who sustained an ACL injury (ACL injured leg) and players who did not (average of legs) during the 18-month follow up period.

	ACL Injured Players ($n \leq 15$)	Uninjured Players ($n \leq 262$)	Effect Size	*P*
Demographic				
Age (yr)^a	20.1 (3.8)	20.4 (9.7)	0.02	0.682
Height (m)	1.77 (0.06)	1.78 (0.07)	0.09	0.781
Mass (kg)	67.8 (10.9)	65.6 (8.7)	0.20	0.351
Playing experience (yr)	8.1 (2.7)	8.4 (5.1)	0.11	0.819
Contraceptive use, *n* (%)	2 (13%)	55 (21%)		0.743
Injury history^b				
Prior ACL injury, *n* (%)	5 (33%)	13 (5%)		**0.001**
Prior knee (any) injury, *n* (%)	2 (13%)	16 (6%)		0.253
Prior hamstring injury, *n* (%)	2 (13%)	20 (8%)		0.338
Prior hip/groin injury, *n* (%)	1 (7%)	15 (6%)		0.600
KOOS before injury				
Pain^a	100 (9.7)	100 (0)	0.12	**0.046**
Sport/Rec^a	100 (5)	100 (0)	0.08	0.201
Strength				
Isometric hip adductor force (N)	135 (26)	145 (27)	0.41	0.149
Isometric hip abductor force (N)	147 (26)	145 (24)	0.11	0.658
Isometric hip ADD:ABD force ratio	0.93 (0.17)	1.01 (0.14)	0.51	**0.022**
Eccentric knee flexor force (N)	293 (35)	277 (55)	0.46	0.302
Eccentric knee flexor force allometrically scaled (N·kg^{-k})	16.4 (2.1)	15.8 (2.8)	0.28	0.458
CMJ kinetics				
Peak take-off force (BW)	1.23 (0.11)	1.15 (0.13)	0.75	**0.013**
Take-off positive impulse (BW·s)	0.37 (0.04)	0.39 (0.05)	0.44	0.174
Take-off eccentric RFD (BW·s^{-1})^a	4.2 (2.5)	3.3 (2.5)	0.11	0.083
Peak landing force (BW)^a	2.22 (0.79)	2.31 (0.64)	0.01	0.876
Landing RFD (BW·s^{-1})^a	38.9 (25.7)	39.9 (26.5)	0.02	0.759
Hop kinematics (average angle)				
Knee flexion angle (°)	40.7 (9)	43.4 (9.9)	0.30	0.310
Dynamic knee valgus (+°)/varus (−°)	1.5 (5.8)	−2.6 (7.2)	0.71	**0.030**
Trunk flexion angle (°)	18.1 (5.3)	17.5 (5.8)	0.11	0.702
Ipsilateral trunk flexion (°)	9.1 (4.2)	7.8 (2.3)	0.31	**0.046**

Bold indicates statistically significant, $P < 0.05$.
The amount of missing data differs for each variable (see Supplemental Digital Content 4, http://links.lww.com/MSS/C547). Unless indicated, data presented as mean (SD), Glass's delta effect size, and independent two-tail *t*-test *P* value.
[a] Nonparametric variable, presented as median (interquartile range), Wilcoxon effect size and Wilcoxon rank sum test *P* value.
[b] Categorical variables compared with Fisher's exact test. Prior knee, hamstring, and hip/groin injury in previous 12 months, and prior ACL is lifetime.

TABLE 3. ACL injury risk estimates expressed as standardized OR (increase in odds per 1-SD change in each variable) with and without the inclusion of potential covariates (prior ACL injury and age).

		Standardized OR (95% CI)		
	1-SD Change	Unadjusted	Adjusted for Prior ACL	Adjusted for Age
Strength				
Isometric hip adductor force	−27 N	1.51 (0.85–2.68)	1.61 (0.90–2.90)	1.46 (0.82–2.60)
Isometric hip abductor force	25 N	1.13 (0.67–1.88)	1.03 (0.61–1.75)	1.18 (0.69–2.02)
Isometric hip adductor/abductor force ratio	−0.14	**1.97 (1.08–3.58)**	**1.85 (1.00–3.44)**	**1.96 (1.08–3.59)**
Eccentric knee flexor force	54 N	1.33 (0.76–2.33)	1.15 (0.64–2.06)	1.44 (0.81–2.54)
Eccentric knee flexor force allometrically scaled	2.8 N·kg^{-k}	1.25 (0.69–2.25)	1.11 (0.62–2.01)	1.27 (0.71–2.3)
CMJ kinetics				
Peak take-off force	0.13 BW	**1.77 (1.11–2.82)**	**1.67 (1.02–2.72)**	**1.73 (1.08–2.78)**
Take-off positive impulse	−0.05 BW·s	1.48 (0.84–2.60)	1.39 (0.78–2.47)	1.42 (0.80–2.53)
Take-off eccentric RFD	1.9 BW·s^{-1}	1.43 (0.91–2.26)	1.36 (0.84–2.18)	1.39 (0.87–2.22)
Peak landing force	−0.57 BW	1.00 (0.59–1.70)	1.00 (0.58–1.72)	1.02 (0.60–1.72)
Landing RFD	−36.8 BW·s^{-1}	1.05 (0.58–1.90)	1.12 (0.56–2.21)	1.03 (0.58–1.84)
Hop kinematics (average angle)				
Knee flexion angle	−9.9°	1.35 (0.77–2.38)	1.38 (0.78–2.46)	1.30 (0.73–2.30)
Dynamic knee valgus	7.2°	**1.96 (1.06–3.64)**	**2.17 (1.12–4.23)**	**1.88 (1.01–3.50)**
Trunk flexion angle	5.8°	1.10 (0.65–1.86)	1.01 (0.57–1.78)	1.16 (0.69–1.98)
Ipsilateral trunk flexion	2.4°	**1.60 (1.01–2.55)**	1.39 (0.85–2.26)	**1.62 (1.02–2.59)**

Missing data imputed using multiple imputation. Bold font indicates statistically significant 95% CI. OR <1 have been inverted and are indicated by a negative SD change.

with predictive mean matching (Multivariate Imputation by Chained Equations, *mice* package) (26). Injury risk estimates were analyzed using logistic regression and presented as odds ratios (OR; Table 3). To aid the comparison between variables with different units, standardized OR values that represent the change in odds of sustaining an ACL injury per 1 SD change in each variable were used, and OR values <1 were inverted so that higher OR values were always associated with greater ACL injury risk. Wald 95% confidence intervals (95% CI) for OR were calculated, with intervals that did not contain one considered statistically significant. The influence of confounding factors on ACL injury risk was explored by including potential covariates in logistic regression models. Covariates included prior ACL injury and age. Variables with significant OR were further explored by plotting the predicted probability of sustaining a future ACL injury as a function of strength/biomechanics (Fig. 2). Predicted probabilities were determined using unadjusted logistic regression models (Table 3), as models adjusted for covariates showed very small differences in OR. Without considering strength or biomechanics, the risk of sustaining an ACL injury in this cohort was calculated as 5.4% (15 injuries out of 277 participants). Based on this, values of strength and biomechanics with a predicted injury probability of less than 5.4% were considered to reduce injury risk, and values greater than 5.4% were considered to increase the risk of injury.

To evaluate the overall ability of the test battery to assess ACL injury risk, a multivariable prediction model was developed in accordance with guidelines for prognostic studies (27). Missing data were handled using multiple imputation (m = 20). The number of predictor variables was determined using the *pmsampsize* package (28). Assuming a Cox–Snell R^2 of 0.09, with an ACL injury proportion of 5%, and target shrinkage of less than 10%, a maximum of three predictor variables were deemed appropriate (29). All variables analyzed in the univariable analysis were considered, and the model with the highest accuracy is presented in the Results section, with remaining high-performing models presented in Supplemental Digital Content 5, http://links.lww.com/MSS/C548. Models

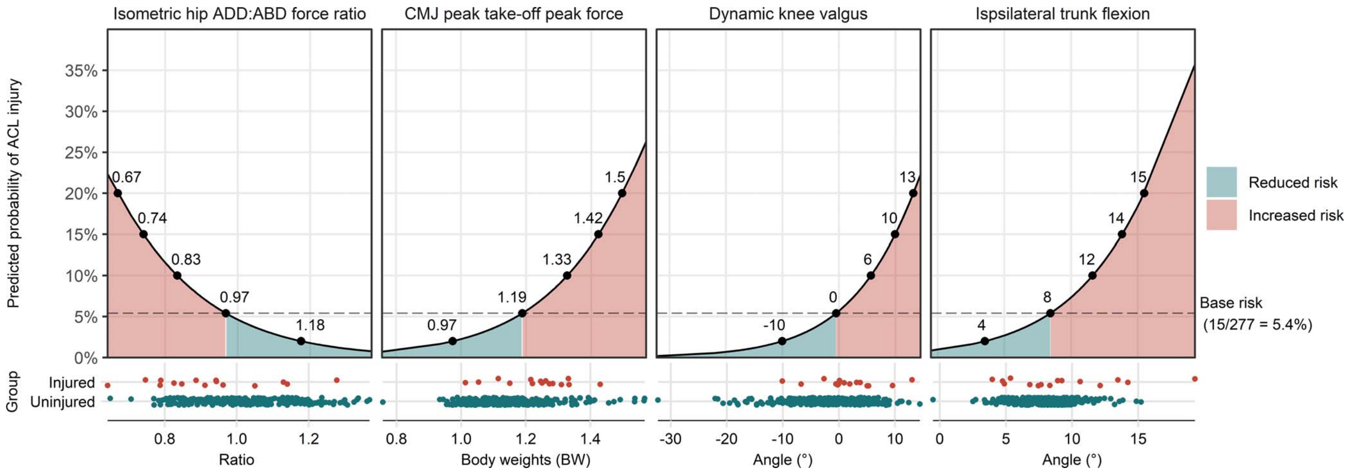


FIGURE 2—Predicted probability of sustaining an ACL injury over a range of strength and biomechanics values. Predicted probabilities derived from univariable (unadjusted) logistic regression models. *Horizontal dashed line* indicates base risk (5.4%), and the intersection with predicted probability indicates the value at which ACL injury risk increases/decreases relative to base risk. Values corresponding with 2%, 5.4%, 10%, 15%, and 20% predicted probabilities of ACL injury are highlighted on the curve with *black dots*. *Bottom panel* displays the distribution of individual ACL injured and uninjured data.

were created using multiple logistic regression with penalized coefficients (ridge regression) to reduce overfitting. Lambda (λ) was determined by selecting the smallest value that minimized model deviance using 10-fold cross-validation (*glmnet* package). The final model was formed by averaging coefficients across imputed data sets and evaluated on the original training data set to obtain apparent predictive performance (sensitivity, specificity, and area under the curve (AUC)) (30). Internal validation was performed by determining optimism-adjusted predictive performance using bootstrapping resampling with replacement (B = 200) (31), which incorporated multiple imputation within each bootstrap sample (30). Calibration plots were used to assess the agreement between predicted and observed probability of sustaining a subsequent ACL injury, with risk estimates determined using a rolling mean (window of 50 observations) because of a low number of injured to uninjured players.

RESULTS

Participant and injury characteristics. Of the 322 players who underwent data collection, 277 (86%) completed the 18-month injury follow-up (Table 1). The main reason for players not completing the injury follow-up was not replying to text messages/emails (n = 28; see Figure, Supplemental Digital Content 4, for participant flow diagram, http://links.lww.com/MSS/C547). Of the players who did not complete the 18-month injury follow-up (n = 45), 51% were junior soccer players, 40% were senior soccer players, and 9% were Australian Rules Football players. The players who did not complete the 18-month follow-up were significantly younger, had less body mass, and had lower eccentric knee flexor strength during the NHE ($P < 0.05$, d = 0.36–0.44) than those who did.

In total, 15 of the 277 prospectively followed players sustained an ACL injury within the 18-month follow-up period (Table 1). The median time from testing to injury was 100 d (range, 58–453 d; interquartile range, 184 d). Ten of the 15 injuries (67%) were index injuries. Of the 5 players who sustained a second ACL injury, 1 (7%) was a reinjury to the surgically reconstructed leg and 4 (27%) were sustained on the contralateral side. For 12 injuries (80%), the primary injury mechanism was change of direction and 10 (67%) occurred during match play (Table 1).

Group demographic, strength, and biomechanical differences. Players who went on to sustain an ACL injury were more likely to have a prior ACL injury (33% of injured group vs 5% of uninjured group; P = 0.001; OR, 9.68; 95% CI, 2.67–31.46), had lower KOOS pain scores before injury (47% of subsequently injured players had some degree of knee pain during preseason vs 32% of uninjured players, P = 0.046), had a lower isometric hip adductor to abductor strength ratio (d = 0.51, P = 0.022), greater CMJ peak take-off force (d = 0.75, P = 0.013), greater dynamic knee valgus (d = 0.71, P = 0.030), and greater ipsilateral trunk flexion (d = 0.31, P = 0.046) average angles during the triple vertical hop landing phase (Table 2).

Strength and biomechanical ACL injury risk factors. For the unadjusted logistic regression analysis (Table 3), a lower isometric hip adductor to abductor strength ratio (1.97 increase in odds per 0.14 decrease in ratio; 95% CI, 1.08–3.58), greater CMJ peak take-off force (1.77 increase in odds per 0.13 BW increase; 95% CI, 1.11–2.82), greater dynamic knee valgus (1.96 increase in odds per 7.2° increase; 95% CI, 1.06–3.64), and ipsilateral trunk flexion average angles during single-leg triple vertical hop landing (1.60 increase in odds per 2.4° increase; 95% CI, 1.01–2.55) were independently associated with an increased risk of subsequent ACL injury. Ipsilateral trunk flexion was not statistically significant when adjusting for prior ACL injury (95% CI, 0.85–2.26).

Without considering the effect of strength or biomechanics, an individual's probability of sustaining an ACL injury ("base risk") was determined to be 5.4% (15 ACL injuries in 277 players). Based on univariable logistic regression model predicted probabilities (Fig. 2), an isometric hip adductor to abductor strength ratio less than 0.97, CMJ peak take-off force greater than 1.19 BW, dynamic knee valgus greater than 0° (i.e., valgus not varus), or ipsilateral trunk flexion greater than 8° increased ACL injury risk beyond base risk (>5.4%). Conversely, increasing/decreasing values in the opposite direction of these cutoffs were indicative of a reduction in ACL injury risk relative to the expected base risk (<5.4%).

Between-leg asymmetry risk factors. Directional between-leg asymmetry (i.e., injured leg is lower or greater) in isometric hip adductor/abductor strength, eccentric knee flexor strength, or CMJ kinetics was not associated with ACL injury risk (OR ranging from 1.00 to 1.03 per 1% change in asymmetry; Fig. 3). However, nondirectional between-leg asymmetry (i.e., either leg lower or greater) resulted in a significant OR for eccentric knee flexor strength asymmetry (OR, 1.10 increase in odds per 1% increase; 95% CI, 1.03–1.17).

Multivariable ACL injury prediction model. The multivariable ACL injury prediction model with the highest prediction accuracy included CMJ peak take-off force, single-leg triple vertical hop dynamic knee valgus, and prior ACL injury (Fig. 4A). This model predicted future ACL injury in the training data set (apparent performance) with a sensitivity of 0.80, a specificity of 0.71, and an AUC of 0.80. When adjusting for optimism, it was estimated that this model would identify ACL injury in unseen data with a sensitivity of 0.74, a specificity of 0.71, and an AUC of 0.78. Model calibration (Fig. 4B) generally showed a small amount of underestimation of ACL injury probability. There were three other multivariable model combinations that performed similarly to the best model (optimism-adjusted AUC, 0.75), with the additional use of ipsilateral trunk flexion and the isometric hip adduction to abduction ratio (see Figure, Supplemental Digital Content 5, for alternative models, http://links.lww.com/MSS/C548).

DISCUSSION

This prospective study was the first to investigate if a preseason, field-based test battery consisting of lower limb

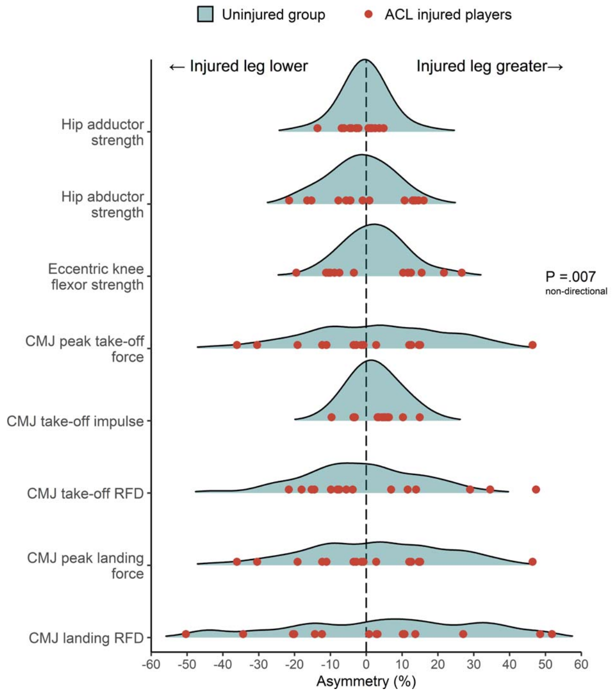
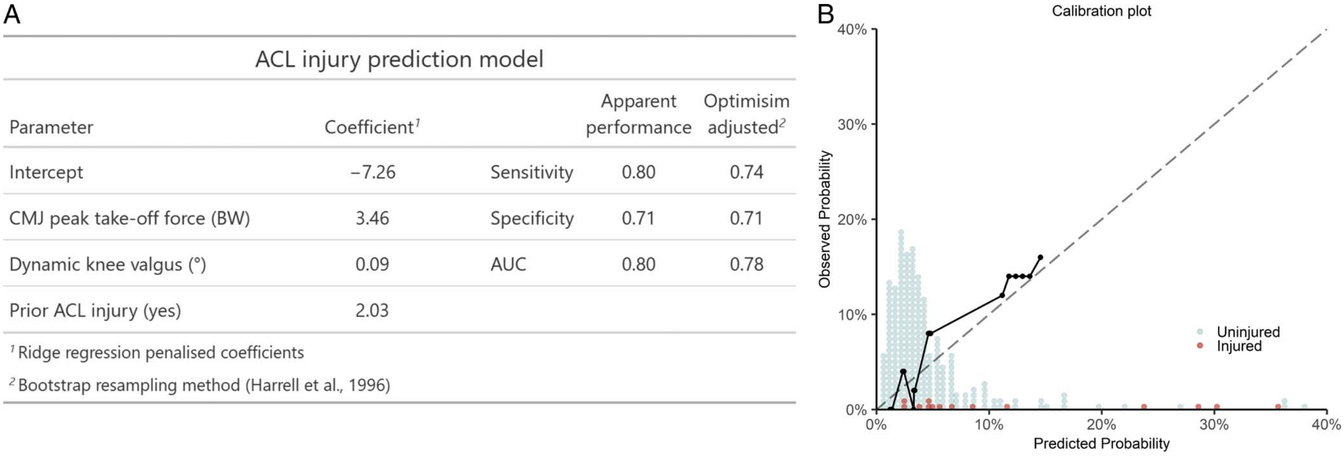


FIGURE 3—Between-leg asymmetry in hip strength, knee flexor strength, and CMJ kinetics for players who sustained an ACL injury (ACL injured players) and players who did not (uninjured group). Uninjured players (n < 262) are represented by density curve, with shaded areas indicating increasing amounts of asymmetry. Players who sustained an ACL injury are presented with *black dots*. Significant variables indicated with a *P* value.

muscle strength and jump-landing biomechanics was associated with future noncontact ACL injury in elite female footballers in Australia. We found that 1) prior ACL injury, 2) lower hip adductor to abductor strength ratios, 3) greater dynamic knee valgus and ipsilateral trunk flexion during a single-leg triple vertical hop, and 4) greater CMJ peak take-off force all independently increased the risk of subsequent noncontact ACL injury. Using these variables together, a multivariable model was able to predict ACL injury with 78% accuracy. These results may be used to improve injury screening and inform the design of targeted injury prevention training in elite female footballers.

Hip muscle strength. Lower isometric hip adductor to abductor strength ratios were associated with greater risk of ACL injury. Individually, absolute isometric hip adductor or abductor strength were not significantly associated with ACL injury risk. However, by observing the underlying data, ratios of lower hip adductor to abductor strength were predominantly driven by lower hip adductor strength. Strength of the adductors relative to the abductors may influence lower limb coordination arising from the hip during high-risk maneuvers (e.g., single-leg landings and decelerations) (32). The hip adductor muscles also provide small contributions to knee varus moments early in single-leg landing that may support the ACL against knee valgus moments (33). Furthermore, adductor magnus is a strong hip extensor, particularly when the hip is flexed (34), and weakness of this muscle may limit the ability to absorb energy at the hip, thereby increasing loads applied to the knee (35). Nevertheless, the mechanism linking hip adductor function and ACL injury risk is not well understood and warrants exploration in future studies.

Single-leg triple vertical hop. Players who sustained a future ACL injury performed single-leg triple vertical hops with greater dynamic knee valgus and ipsilateral trunk flexion (i.e., toward stance leg) during landing than uninjured players. Dynamic knee valgus (hip internal rotation and adduction, knee abduction, and ankle eversion) is observed more frequently in females than males in a range of landing tasks (36), but evidence for an association with ACL injury risk is unclear (8,12). Conflicting evidence may relate to biomechanical differences in bilateral versus single-leg landing tasks. Studies using single-leg drop vertical jumps in other female populations have found dynamic knee valgus to be associated with future ACL injury risk (10,37); however, this seems to not be the case in studies using double-leg drop vertical jumps (9,12). Previous work has also reported that the combination



ACL injury prediction model

Parameter	Coefficient[1]		Apparent performance	Optimisim adjusted[2]
Intercept	−7.26	Sensitivity	0.80	0.74
CMJ peak take-off force (BW)	3.46	Specificity	0.71	0.71
Dynamic knee valgus (°)	0.09	AUC	0.80	0.78
Prior ACL injury (yes)	2.03			

[1] Ridge regression penalised coefficients

[2] Bootstrap resampling method (Harrell et al., 1996)

FIGURE 4—Best-performing ACL injury prediction model. A, Multiple logistic regression model with ridge regression penalized coefficients, and model-predictive performance using training data set (apparent) and bootstrapped samples (optimism adjusted). B, Calibration plot indicating agreement between predicted and observed ACL injury risk across a range of probabilities (*black line*). The *gray dashed line* indicates perfect agreement between model-predicted injury risk and actual injury risk observed with data.

of knee valgus and trunk lateral flexion during single-leg drop vertical jumps was associated with noncontact knee injuries in female athletes (10). The ability to control lateral trunk displacement during a perturbation task has also been highlighted as a risk factor for ACL injury (38). Lateral trunk flexion toward the stance leg shifts the moment arm of the trunk lateral to the knee joint center and therefore increases the knee abduction moment, which may contribute to ACL injury (39). Training female footballers to perform high-risk single-leg movements with less dynamic knee valgus and ipsilateral trunk flexion (40) may represent an effective strategy to mitigate the risk of future ACL injury.

CMJ kinetics. Those who produced greater CMJ peak take-off force were at greater risk of sustaining a future ACL injury. The ability to generate high force during a CMJ may be a general indicator of (i.e., correlated with) a player's ability to generate knee loads in other dynamic tasks. For example, ACL loading during a land-and-cut task is predominantly generated by quadriceps and gastrocnemius muscle forces (41), which are prime contributors to jumping vertical ground reaction forces (42). Reducing peak CMJ force to mitigate ACL injury risk is likely counterproductive for players who aim to maximize power during jumping. Instead, players with a high-risk CMJ kinetic profile may benefit from interventions targeted at altering other modifiable factors, such as decreasing joint loads or increasing the contribution of muscles to unload the ACL. Furthermore, between-leg asymmetries in CMJ kinetics were not associated with ACL injury risk. The amount of asymmetry varied widely between variables (7%–28% per SD), indicating that no single asymmetry threshold provides a clear indication of injury risk (43).

Prior ACL injury. In the present study, players with a history of ACL reconstruction were 9.7 times more likely to sustain a future ACL injury than those without. Prior ACL injury has consistently been identified as a risk factor for future ACL injury in female athletes from a wide range of field and court sports (7). Although the specific mechanism(s) by which prior injury predisposes players to reinjury is not fully understood, risk factors for ACL reinjury include greater dynamic knee valgus during a drop vertical jump, postural instability (44), and quadriceps weakness and sagittal plane single-leg landing biomechanics (45). Females with a history of ACL injury also demonstrate persistent deficits in lower limb strength and biomechanics that may contribute to the subsequent injury (46). Interestingly, KOOS was not associated with ACL injury risk in the current study, with both ACL injured and uninjured players reporting much higher (and often perfect) pain and sport/rec scores compared with previous studies (47). Higher KOOS scores are likely reflective of our elite-level cohort and those returning from ACL injury having better knee-related symptoms and function than the general population.

Between-leg asymmetry. Directional between-leg asymmetry in strength and CMJ kinetics was not associated with an increase in ACL injury risk. Within the players who sustained a future ACL injury, no consistent asymmetry was observed (e.g., lower values in the injured compared with uninjured leg; Fig. 3), and asymmetries were within similar ranges of uninjured players (~10%–20% for strength and ~10%–50% for CMJ kinetic variables). However, nondirectional asymmetry for eccentric knee flexor strength was significantly associated with increased ACL injury risk. This finding can be explained by a previous study in the same cohort of players (48), which found that those with a history of ACL injury demonstrate long-lasting eccentric knee flexor strength asymmetries. In the current study, the same players were found to be at high risk of sustaining a second ACL injury. Therefore, eccentric knee flexor strength asymmetry is associated with prior ACL injury and may not be an independent risk factor, particularly given that the stronger leg was injured as frequently as the weaker leg. These findings question the utility of between-leg symmetry for evaluating ACL injury risk and as a return to play criterion. However, the results should be interpreted with caution given the mix of first time (two-thirds) and second time (one-third) ACL injuries included in the analysis.

Multivariable prediction model. Together, CMJ peak take-off force, single-leg triple vertical hop dynamic knee valgus, and ACL injury history predicted subsequent ACL injury risk with acceptable accuracy (AUC, 0.78), successfully classifying 74% of all ACL injuries and 71% of all uninjured players. The calibration plot (Fig. 4) indicated good agreement between predicted and actual ACL injury risk across the spectrum of probabilities. The combination of tests provided in Figure 4 or any of the alternative models in Supplemental Digital Content 5, http://links.lww.com/MSS/C548, could be used to identify players at risk of ACL injury, with the AUC suggesting an accuracy of 75% to 78%. However, this accuracy is an estimation based on current data and requires validation in an independent cohort (49). The predictive ability of the current model performed better than a previous model built using medial knee displacement during a bilateral drop vertical jump (AUC, 0.60) (13), and similarly to one built using dynamic knee valgus and lateral trunk flexion during single-leg drop vertical jumps (AUC, 0.80) (10). Prediction performance is likely to vary widely between studies depending on cohort characteristics, sample size, study design, and model development. Importantly, the current study is one of the first in the ACL injury literature to apply model regularization techniques to reduce overfitting and hence increase model generalizability to future data. Such predication models may be useful for deciding which players require additional targeted injury risk reduction training.

Study strengths and practical implications. One of the main strengths of this study is the large sample size that captures approximately 50% of players in the Australian Football League Women's and senior soccer (National Australian Women's Soccer League) competitions, which increases the generalizability of the findings. In addition, the field-based testing battery was designed in collaboration with team medical staff to ensure clinical feasibility and applicability to end-users. Findings can also be directly translated into practice, with the field-based testing devices commercially available, and currently in use by several elite female football teams in Australia and abroad. Compared to previous prospective studies that use laboratory equipment (i.e., three-dimensional motion capture and isokinetic dynamometry), the current testing battery is quick and easy to perform, which is important when practitioners typically have very limited time to perform injury screening. Based on this study and the broader literature (50), it is clear that all female footballers are at relatively high risk of sustaining an ACL injury, and therefore, it is likely beneficial that all players undergo some form of regular risk reduction training. At present, there is low-level evidence that multicomponent exercise programs reduce the risk of ACL injuries in female footballers by 45% (51). The results of the present study may therefore be used to identify players with elevated ACL injury risk who may benefit from additional training that specifically targets factors that are mechanistically linked to injury. However, future work is needed to determine whether individualized programs, targeted at addressing the strength and biomechanical risk factors observed in the current study, lead to a greater reduction in injury rates.

Limitations. Associations with injury risk were drawn from measures of strength and biomechanics taken at a single time point (i.e., preseason), whereas ACL injuries occurred months after the time of testing. More frequent in-season assessments of strength and biomechanics may provide greater insight into ACL injury risk. Although our injury rate (5.4%) and total number of injuries were consistent with previous ACL injury risk factor studies (7), this may have limited the accuracy of risk estimates and prediction models. Injury follow-ups were predominantly performed using team medical staff; however, where this was not possible, players were contacted directly via mobile or email and asked to self-report knee injuries. Although self-report may result in inaccurate recall for some injuries, it is likely that most elite players were accurately diagnosed via medical imaging and aware they had an ACL rupture. Kinematics were measured using a novel markerless motion capture system that does not provide the same level of accuracy as a gold-standard laboratory-based marker tracking system. Given the exploratory nature of this study, no corrections for multiple comparisons were made, and further sufficiently powered studies with strict type 1 error rate control are required to confirm the findings.

CONCLUSIONS

Preseason measures of hip strength, single-leg triple vertical hop frontal plane knee and trunk kinematics, and CMJ kinetics were independently associated with future noncontact ACL injury, supporting the use of a field-based test battery at the outset of preseason. A prediction model built using a combination of these measures provided acceptable levels of accuracy at identifying players who went on to sustain ACL injury. These results may be used to guide ACL injury screening practices and inform the design of targeted injury prevention training in elite female footballers.

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