Impact of prior anterior cruciate ligament, hamstring or groin injury on lower limb strength and jump kinetics in elite female footballers

Collings, Tyler J., Diamond, Laura E., Barrett, Rod S., Timmins, Ryan G., Hickey, Jack T., du Moulin, William S., Gonçalves, Basílio A. M., Cooper, Christopher and Bourne, Matthew N.

Collings, Tyler J., Diamond, Laura E., Barrett, Rod S., Timmins, Ryan G., Hickey, Jack T., du Moulin, William S., Gonçalves, Basílio A. M., Cooper, Christopher and Bourne, Matthew N.. (2021). Impact of prior anterior cruciate ligament, hamstring or groin injury on lower limb strength and jump kinetics in elite female footballers. *Physical Therapy in Sport*, 52, pp. 297-304. https://doi.org/10.1016/j.ptsp.2021.10.009

Impact of prior anterior cruciate ligament, hamstring or groin injury on lower limb strength and jump kinetics in elite female footballers.

Tyler J. Collings[a,b], Laura E. Diamond[a,b,c], Rod S. Barrett[a,b], Ryan G. Timmins [d,e], Jack T. Hickey [d,e], William S. du Moulin[a,b], Basílio A.M. Gonçalves[a,b], Christopher Cooper[a,b], Matthew N. Bourne[a,b,f].

[a] School of Health Sciences and Social Work, Griffith University, Gold Coast campus, Australia.

[b] Griffith Centre of Biomedical and Rehabilitation Engineering (GCORE), Menzies Health Institute Queensland, Griffith University, Gold Coast campus, Australia.

[c] Centre of Clinical Research Excellence in Spinal Pain, Injury & Health, School of Health & Rehabilitation Sciences, The University of Queensland, Brisbane, Australia.

[d] School of Behavioural and Health Sciences, Australian Catholic University, Melbourne, Australia.

[e] Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Fitzroy, Victoria, Australia.

[f] La Trobe Sport and Exercise Medicine Research Centre, La Trobe University, Melbourne, Australia.

ABSTRACT

Objective: To compare lower limb strength and countermovement jump (CMJ) kinetics between elite female footballers with and without a history of anterior cruciate ligament reconstruction (ACLR), hamstring strain, or hip/groin injury.

Design: Cross-sectional.

Setting: Field-based.

Participants: 369 elite female Australian football, soccer and rugby league players aged 15–35.

Main Outcome Measures: Isometric hip adductor and abductor strength, eccentric knee flexor strength, and CMJ vertical ground reaction forces, including between-leg asymmetry. Players reported their lifetime history of ACLR, and whether they had sustained a hamstring strain, or hip/groin injury in the previous 12-months.

Results: Players with a unilateral history of ACLR (n=24) had significant between-leg differences and asymmetry in eccentric knee flexor strength (mean=-6.3%, 95%CI=-8.7 to -3.9%, *P*<.001), isometric hip abductor strength (mean=-2.5%, 95%CI=-4.3 to -0.7%, *P*=.008), and between-leg asymmetry in CMJ peak landing force (mean=-5.5%, 95%CI=-10.9 to -0.1%, *P*=.046). Together, between-leg asymmetry in eccentric knee flexor strength, isometric hip abductor strength, and CMJ peak landing force distinguished between players with and without prior ACLR with 93% accuracy.

Conclusion: Elite female footballers with a history of ACLR, but not hamstring or hip/groin injury, exhibit persistent between-leg asymmetries in lower limb strength and jump kinetics following a return to sport.

Keywords: Rehabilitation; biomechanics; asymmetry; screening; anterior cruciate ligament reconstruction.

INTRODUCTION

Female participation in football has grown substantially in recent decades and has paralleled the development of professional football leagues around the world. Female footballers are at high risk of lower limb injuries, many of which are characterized by high rates of recurrence (DiStefano et al., 2018; Sandon, Engström, & Forssblad, 2020). Two of the most common injuries are hamstring strains (Dalton, Kerr, & Dompier, 2015) and hip/groin pain (Kerbel, Smith, Prodromo, Nzeogu, & Mulcahey, 2018). Anterior cruciate ligament (ACL) ruptures are less common (Montalvo et al., 2018), but can be catastrophic, and occur up to 3-times more frequently in female than male footballers (Montalvo et al., 2018). Typically, ACL injuries require expensive reconstructive surgery and lengthy periods of playing time-loss. Only half of players (male or female) return to football after ACL injury, and of those, approximately one-third suffer a recurrent or contralateral ACL injury (Sandon et al., 2020). Despite the economic, health, and performance implications of injuries in female footballers, the majority of research has focused on male players. Consequently, there is limited evidence to guide injury risk mitigation strategies for female players.

Recent systematic reviews have concluded that prior injury is one of the strongest independent risk factors for future lower limb injury (Collings et al., 2021). Although the mechanism(s) by which prior injury predisposes players to subsequent injury is not fully understood, injury may result in maladaptation to tissue structure and function that persists long after a return to sport (Fulton et al., 2014). For example, ACL reconstruction (ACLR) involving a hamstring tendon autograft typically results in chronic deficits in medial hamstring activation and remodeling of the muscle-tendon unit (Messer, Shield, Williams, Timmins, & Bourne, 2020). Impaired hamstring function may, at least theoretically, increase ACL loads during high-risk tasks via a reduced ability to resist anterior tibial shear (N. Maniar, Schache, Sritharan, & Opar, 2018); however, the long-term effects of ACLR on eccentric knee flexor strength in female athletes remains unclear (Bourne et al., 2019; Messer et al., 2020). Computational modelling suggests that the gluteus medius contributes to ACL 'unloading' by opposing knee abduction moments (N. Maniar et al., 2018). It is unknown if hip abductor strength is altered as a consequence of prior ACLR. Persistent deficits in lower limb strength and function may, at least in part, explain observations of altered knee joint kinematics and kinetics during walking, running, jumping, and landing (Moore et al., 2020), greater between-leg asymmetries in countermovement jump (CMJ) force profiles (Baumgart, Schubert, Hoppe, Gokeler, & Freiwald, 2017; Hart et al., 2019; Read, Michael Auliffe, Wilson, & Graham-Smith, 2020), and impaired patient reported outcomes (Antosh, Svoboda, Peck, Garcia, & Cameron, 2018) in male athletes and mixed gender cohorts following ACLR. An improved understanding of the impact of ACLR on lower limb strength, biomechanics, and subjective knee function in elite female footballers is needed to inform the design of targeted rehabilitation strategies in this cohort.

Limited research has examined the impact of prior hamstring or hip/groin injury on lower limb strength and biomechanics in female footballers. However, male athletes with a history of unilateral hamstring strain injury display lower eccentric knee flexor strength during the Nordic hamstring exercise in their previously injured leg compared to their uninjured contralateral leg (Nirav Maniar, Shield, Williams, Timmins, & Opar, 2016). Nordic eccentric knee flexor weakness (Timmins et al., 2016) and between-leg asymmetry (Bourne, Opar, Williams, & Shield, 2015) has also been associated with an increased risk of future hamstring strain injury in elite male footballers. Further, male footballers with current hip/groin pain display reduced isometric (Nevin & Delahunt, 2014) and eccentric adductor strength (Thorborg, Branci, Nielsen, et al., 2014), and lower Copenhagen Hip and Groin Outcome Scores (HAGOS) (Thorborg, Branci, Stensbirk, Jensen, & Hölmich, 2014), all of which have been associated with the development of future hip/groin injury (Bourne et al., 2020).

Whether female footballers exhibit similar strength deficits following a return to sport from hamstring strain or hip/groin injury is not known.

The purpose of this study was to (1) compare lower limb strength and jump/landing kinetics, including between-leg asymmetries, between elite female footballers with and without a history of ACLR, hamstring strain or hip/groin injury; and (2) when group differences arose, assess the ability of the test battery to discriminate between players with and without prior injury. We hypothesized that, compared to uninjured players, those with an injury history would exhibit lower muscle strength and greater between-leg asymmetries in strength and CMJ force production, and that these deficits would be most pronounced in those with ACLR.

MATERIAL AND METHODS

Participants

A total of 369 elite female footballers (mean ± standard deviation [SD], age = 21.7 ± 5.1 years, body mass = 65.8 ± 9.1 kg, stature = 1.77 ± 0.07 m) volunteered to participate in this study. Participants consisted of four player groups (Table 1): 157 senior national-level Australian rules football players competing in the Australian Football League Women's competition (AFLW), 77 senior national and international soccer players competing in the Australian professional women's soccer league (W-league), 22 senior national-level rugby league players (NRLW), and 113 under-17 female state representative soccer players. Players with current or recent injuries that may have impeded their ability to perform the testing protocol were excluded based on team physiotherapists' advice. This study was approved by the University's human research ethics committee (reference number: 2019/423), and all players provided written informed consent prior to data collection. The parents/guardians of players under 18 years of age also provided written informed consent.

Table 1. Participant characteristics for players with and without prior lower limb injury.

	ACLR	Prior hamstring strain injury	Prior hip/groin injury	Uninjured players
Total players (n)	24	26	25	198
Age (years) ‡	**23.1 (5.3)***	21.0 (6.2)	19.4 (7.2)	20.3 (8.6)
Body mass (kg) †	**69.7 (12.0)***	67.8 (9.0)	66.2 (10.4)	65.0 (8.7)
Stature (m) †	1.78 (0.07)	1.80 (0.10)	1.76 (0.07)	1.76 (0.07)

* Indicates significant difference (P < .05) compared to uninjured players. † Data are mean (standard deviation). ‡ Data are median (interquartile range). ACLR = anterior cruciate ligament reconstruction.

Study design

Data were collected from each player in a single testing session. Players were asked to complete an injury questionnaire (Supplementary 1), detailing their history of hamstring strain, hip/groin injury, and any other major lower limb injuries over the prior 12 months, and their lifetime history of ACLR. In addition, players completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) pain and KOOS sports and recreation function (shortened to sport/rec) sub-scales (Roos et al., 1998), as well as the HAGOS pain and HAGOS sport/rec sub-scales (Thorborg, Hölmich, Christensen, Petersen, & Roos, 2011). Scores for each sub-scale was calculated between 0 and 100, where 0 indicates extreme knee or hip/groin problems, and 100 indicates no reported knee or hip/groin problems (Roos et al., 1998; Thorborg et al., 2011). Age, years of sports participation, stature, mass, and dominant leg (preferred kicking foot) were also recorded for all players.

Lower limb strength and jump/landing kinetics were assessed using a field-based testing battery purposefully designed to take ≤10 minutes per player. Tests included isometric hip adductor and abductor strength, eccentric knee flexor strength, and CMJ on dual force plates.

Players typically performed a warm-up of one or two submaximal efforts for each test. Lower limb strength and jump/landing kinetics were compared between players with a history of hamstring strain or hip/groin injury in the previous 12 months, or any history of ACLR, and uninjured players who reported no major time-loss injury (ankle or knee ligament sprain, calf, hamstring, quadriceps muscle strain, Achilles or patellar tendinopathy, or hip/groin pain) in the previous 12 months. Players with a prior hamstring strain or hip/groin injury who also had a history of ACL injury were removed from subsequent analysis to avoid confounding results with the possible deficits associated with ACLR. All ACLR graft types were included in the analysis, as the majority of variables analyzed were not-specific to a certain graft type.

Isometric hip adductor and abductor strength

Isometric hip adductor and abductor strength were measured at 100 Hz using a portable frame-fixed strength testing device (ForceFrame, Vald Performance Pty Ltd, Brisbane, Australia). Players were positioned supine underneath the frame with straight legs and load cells were aligned with the lateral and medial malleoli. Players completed three maximal voluntary isometric contractions of bilateral hip adduction by ‘squeezing’ against the inside load cells, and three maximal voluntary isometric contractions of bilateral hip abduction by ‘pushing’ against the outside load cells. Players were first given a demonstration from investigators and performed 1-2 warm-up/practice repetitions. Each contraction was held for approximately 5-seconds, with players alternating between adduction and abduction after 5-10-seconds of rest. Excellent reliability (intraclass correlation coefficient [ICC] = 0.94) (Ryan, Kempton, Pacecca, & Coutts, 2019) and validity (O'Brien, Bourne, Heerey, Timmins, & Pizzari, 2019) have been previously reported for isometric hip adductor and abductor strength assessments using similar test positions with the ForceFrame device. Hip adductor and abductor strength were determined using the maximum peak force of the three trials (N). These values were subsequently converted to joint torques (N.m) using right leg length (anterior superior iliac spine to lateral malleolus) and reported relative to body mass ($N.m.kg^{-1}$).

Eccentric knee flexor strength

Eccentric knee flexor strength was measured at a 100 Hz during the Nordic hamstring exercise (NordBord, Vald Performance Pty Ltd, Brisbane, Australia). Players kneeled on the padded device, with the ankles secured immediately superior to the lateral malleoli by individual ankle hooks connected to uniaxial load cells. From the initial kneeling position, players were instructed to lower themselves as slowly as possible towards the ground, while maintaining straight alignment between the trunk, pelvis and thighs, until they could no longer support their own body weight. Players performed three maximal effort trials. Peak force measured bilaterally during the Nordic hamstring exercise has been shown to have moderate-to-high reliability (ICC = 0.83 for left and 0.90 for right leg) (Opar, Piatkowski, Williams, & Shield, 2013). Peak eccentric knee flexor strength was determined using the maximum force of the three trials (N) and was converted to a joint torque (N.m) using the right shank length (lateral tibial condyle to lateral malleolus). To account for the correlation between body mass and eccentric knee flexor torque observed in the current cohort (r = 0.58), torque was allometrically scaled (equation = $N.m.kg^{-k}$, where ^{k} was 0.89) (Buchheit, Cholley, Nagel, & Poulos, 2016).

Countermovement jump kinetics

Vertical ground reaction forces (GRF) were collected from the left and right legs separately during a bilateral CMJ using portable dual force plates sampling at 1000 Hz (ForceDecks, FDLite, Vald Performance Pty Ltd, Brisbane, Australia). Trials were performed with hands on hips, using a countermovement to a self-selected depth before jumping for maximal height, and landing on two feet. Players completed a total of three successful trials. Players rested for 5-10 seconds between trials. Peak forces and impulses measured during a CMJ on the ForceDecks have demonstrated excellent reliability (ICC > 0.90) (Heishman et al., 2020). Jump/landing variables (mean of three trials) were automatically calculated and extracted from the ForceDecks' software (Version 2.0), and included peak take-off force, peak landing force, and take-off impulse. Take-off included the eccentric countermovement and concentric propulsion phase, and landing was defined from initial ground contact until returning to a standing position. Take-off impulse was calculated as the area under the force-time curve above standing bodyweight force. To account for the effect of body mass on CMJ kinetics, ground reaction force and impulse were normalized to body weight force in Newtons (i.e. times body weight [BW]).

Between-leg asymmetry calculation

For all tests, between-leg asymmetry (%) was calculated as (dominant leg – non-dominant leg) / (dominant leg + non-dominant leg) x 100, where the dominant leg was defined as the preferred kicking leg. For players in the prior injury groups, the dominant leg was substituted for the leg with a prior injury, and the non-dominant leg was substituted for the uninjured contralateral leg. This method of calculating asymmetry in bilateral tasks was selected based on published recommendations (Bishop, Read, Lake, Chavda, & Turner, 2018). Players with bilateral injury histories were removed from the analysis (n = 0 ACLR, n = 2 prior hamstring strains, and n = 7 prior hip/groin injuries) to enable calculation of between-leg asymmetry using a healthy contralateral leg.

Statistical analysis

Statistical analyses were performed in R Studio (version 1.2.1, Boston, US). Variables were assessed for normality using Shapiro-Wilk tests and inspection of quantile-quantile plots. Homogeneity of variance was assessed using Levene's test. Strength and jump/landing kinetics were compared between players with and without an injury history (between-group factor) and between legs (within-group factor) using mixed-model analyses of variance

(ANOVA). Separate mixed-model ANOVAs were performed for each injury type: ACLR, hamstring strain injury, or hip/groin injury. Post-hoc pairwise comparisons were performed using Student's (independent) two-tail t-tests for parametric variables, and Wilcoxon rank-sum tests for non-parametric variables. Between-leg asymmetry for each group (prior ACLR, hamstring strain, hip/groin injury, or uninjured players) was assessed using a one-sample two-tailed t-test, with a null hypothesis of 0% asymmetry. This approach to assessing asymmetry was chosen over comparing injured and uninjured player groups due to the effect of leg dominance on leg asymmetry in the uninjured group.

Given the wide range of age groups included in this study, age was also investigated as a covariate for each outcome variable in supplementary 3 using Pearson's Correlation Coefficients and analysis of covariance (ANCOVA). The relationship between time since ACLR and strength and jump/landing kinetics was explored by visualizing data in supplementary 4 (no inferential statistics performed due to low subgrouping numbers). The effect of ACLR graft type was also investigated by removing players with non-hamstring grafts (n=2 patellar; n=1 quadricep tendon) and repeating the analysis. This analysis did not alter study conclusions, and therefore the full dataset and analysis is presented only.

When significant between-group differences were found, logistic regression was used to explore the physical profiles that best discriminated between players with and without an injury history. Univariable and multivariable logistic regression models were evaluated using receiver operating characteristic (ROC) curves and area under the curve (AUC). Variables included in the multivariable models were selected based on the combination of strength, jump kinetic (absolute and asymmetry measures), and patient reported outcome variables that produced the highest AUC. To determine whether a multiple test battery provided a better indication than a single test, the multivariable model was compared against the three univariable models with the highest accuracy. Model coefficients were converted to standardized odds ratios and reported per 1 standard deviation change.

RESULTS

Age had a weak relationship with all outcome variables (largest r = 0.26) and inclusion of age as a covariate within an ANCOVA did not influence study findings (Supplementary 3).

Prior ACLR

Twenty-four players reported a unilateral history of ACL injury (88% were to senior players and 54% affected the dominant leg). All ACL injured players received surgical reconstruction, with 20 (83%) receiving a hamstring tendon graft, 2 (8%) receiving a quadriceps tendon graft, 1 (4%) receiving a patellar tendon graft, and 1 (4%) was unknown. Of the players with a history of ACLR, 3 were 6-12 months post-surgery, 8 were 1-2 years post-surgery, and 13 were two or more years post-surgery at the time of testing. Players with a history of ACLR were older (P = .041) and had greater body mass (P = .030) than uninjured players (Table 1).

Strength and jump/landing kinetics were not significantly different between players with and without ACLR (Table 2). However, surgically reconstructed legs displayed less eccentric knee flexor torque (P < .001) and isometric hip abductor torque (P = .012) than uninjured contralateral legs (Table 2). Players with a history of ACLR displayed between-leg asymmetry in eccentric knee flexor strength (mean = -6.3%, 95% CI = -8.7 to -3.9%, P < .001), isometric hip abductor strength (mean = -2.5%, 95% CI = -4.3 to -0.7%, P = .008), and CMJ peak landing force (mean = -5.5%, 95% CI = -10.9 to -0.1%, P = .046) (Figure 1). Both KOOS pain (median = 97, interquartile range [IQR] = 9) and KOOS sport/rec function (median = 100, IQR = 10) sub-scale scores were lower in players with a prior ACLR compared to those with no history of injury (median = 100, IQR = 0, P < .001). Subgrouping by time since surgery is presented in Supplementary 4.

Table 2. Comparison of lower limb strength and jump/landing kinetics between legs (within group) and between players (between group) with and without a history of ACLR, hamstring strain, or hip/groin injury.

	Prior injury group				Uninjured players	
	Leg	ACLR	Hamstring strain	Hip/groin injury	Leg	
Isometric hip adductor torque (N.m.kg^{-1}) †	Injured	1.85 (0.38)	1.93 (0.37)	1.92 (0.41)	Dominant	2.01 (0.38)
	Contralateral	1.87 (0.36)	1.96 (0.41)	1.92 (0.39)	Non-dominant	2.00 (0.37)
Isometric hip abductor torque (N.m.kg^{-1}) †	Injured	**1.92 (0.29)***	2.01 (0.31)	1.85 (0.32)	Dominant	**1.95 (0.32)***
	Contralateral	**2.04 (0.33)**	2.05 (0.28)	1.90 (0.33)	Non-dominant	**1.99 (0.33)**
Eccentric knee flexor torque (N.m.kg^{-k}) †	Injured	**5.86 (1.25)***	5.77 (0.75)	5.42 (1.10)	Dominant	6.02 (0.99)
	Contralateral	**6.59 (1.08)**	5.87 (0.71)	5.47 (1.47)	Non-dominant	5.98 (0.96)
CMJ peak take-off force (BW) ‡	Injured	1.18 (0.16)	1.13 (0.11)	1.17 (0.11)	Dominant	**1.16 (0.14)***
	Contralateral	1.20 (0.16)	1.14 (0.1)	1.17 (0.11)	Non-dominant	**1.15 (0.13)**
CMJ peak landing force (BW) ‡	Injured	2.22 (0.69)	2.39 (0.68)	2.45 (0.60)	Dominant	2.41 (0.69)
	Contralateral	2.46 (0.64)	2.45 (0.58)	2.41 (0.64)	Non-dominant	2.40 (0.63)
CMJ take-off impulse (BW.s) †	Injured	0.37 (0.05)	0.39 (0.05)	0.37 (0.05)	Dominant	**0.39 (0.05)***
	Contralateral	0.39 (0.07)	0.39 (0.05)	0.38 (0.05)	Non-dominant	**0.39 (0.05)**

*Indicates significant differences ($P < .05$) within group (between-legs). No significant differences between-groups.

† Data are mean (standard deviation). ‡ Data are median (interquartile range). ACLR = anterior cruciate ligament reconstruction; BW = body weights; CMJ = countermovement jump.

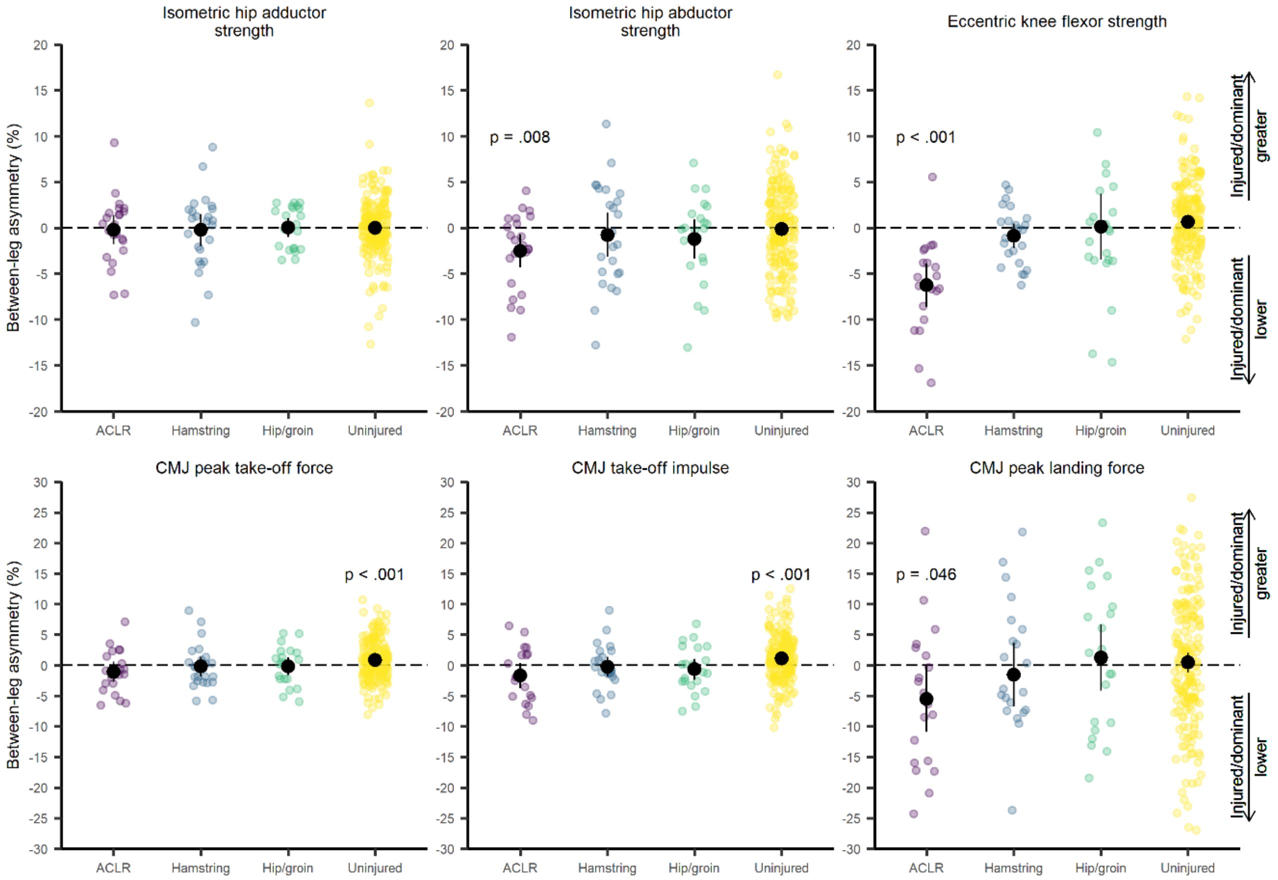

Figure 1. Mean and 95% confidence interval between-leg asymmetry for lower limb strength (top row) and countermovement jump (CMJ) kinetics (bottom row) for players with and without prior anterior cruciate ligament reconstruction (ACLR), hamstring strain, or hip/groin injury.

<u>Prior hamstring strain injury</u>

Twenty-six players reported a time-loss unilateral hamstring strain injury in the previous 12 months (77% were senior players and 58% affected the dominant leg). There were no significant differences in lower limb strength and jump/landing kinetics (Table 2), including between-leg asymmetries (Figure 1), between players with and without a prior hamstring strain injury.

<u>Prior hip/groin injury</u>

Twenty-five players reported a time-loss hip/groin injury in the previous 12 months (64% were senior players and 50% affected the dominant side). Both HAGOS pain (median = 90, IQR = 15) and HAGOS sport/rec function (median = 84, IQR = 28) sub-scale scores were lower in those with a prior hip/groin injury compared to uninjured players (median = 100, IQR = 0 and 2 respectively, $P < .001$) (Table 2). There were no significant differences in lower limb strength and jump/landing kinetics (Table 2), including between-leg asymmetries (Figure 1), between players with and without a prior hip/groin injury.

Logistic regression

Logistic regression models are presented for players with and without a history of ACLR only (Figure 2), as there were no group differences in strength and jump/landing kinetics between players with and without prior hamstring strain or hip/groin injuries. The physical profile that best discriminated between players with and without a history of ACLR (AUC = 0.93) included eccentric knee flexor strength between-leg asymmetry ($P < .001$), isometric hip abductor strength between-leg asymmetry ($P = .003$), and peak landing force between-leg asymmetry ($P = .004$) (Figure 2). Greater eccentric knee flexor strength between-leg asymmetry alone discriminated between players with and without ACLR history with 86% accuracy (AUC = 0.86), while KOOS pain and CMJ take-off impulse asymmetry achieved AUCs of 0.68 and 0.67, respectively (Figure 2).

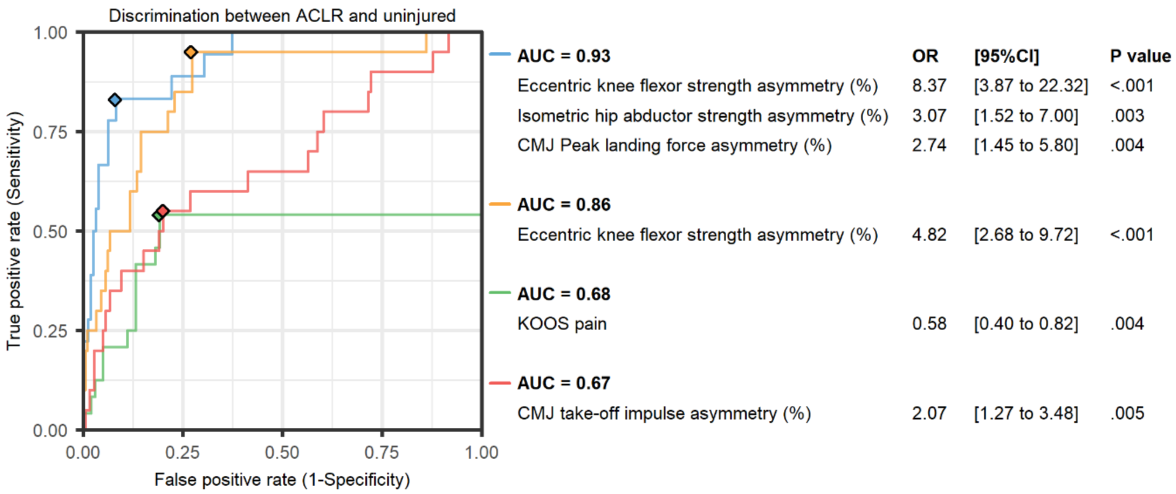

Figure 2. Receiver operating characteristic curves for univariable and multivariable logistic regression models summarizing their ability to discriminate between players with and without a history of anterior cruciate ligament reconstruction (ACLR). Each line indicates an individual variable/model. Diamonds indicate points of maximum area under the curve (AUC), which describes the ability of the model to discriminate between previously injured players and uninjured players; AUC can be interpreted as excellent (0.90-1.00), good (0.80-0.90), fair (0.70-0.80), poor (0.60-0.70), or fail (0.50-0.60) (Altman & Bland, 1994). Model coefficients are reported as standardized odds ratios and 95% confidence intervals (95%CI) and reported per 1 standard deviation (SD) change. OR = odds ratio.

DISCUSSION

This study demonstrated that field-based measures of lower limb strength and CMJ kinetics in elite female football players differ between those with and without prior ACLR, but not hamstring strain or hip/groin injuries. Players with a history of ACLR exhibited between-leg asymmetries in eccentric knee flexor strength, isometric hip abduction strength, and peak landing forces, that distinguished previously injured from uninjured players with 93% accuracy. Players with a recent hamstring strain or hip/groin injury did not display deficits in eccentric knee flexor strength, hip adductor or abductor strength, or jump/landing kinetics compared to uninjured players. These findings suggest the possibility that conventional ACLR rehabilitation strategies in elite female footballers may not adequately restore deficits in lower limb strength and CMJ kinetics, which may persist for months to years following a return to high-level sport. Future work should seek to determine whether redressing these deficits leads to a reduction in injury recurrence.

Prior ACLR

Players with a unilateral history of ACLR displayed 6% greater between-leg asymmetry in eccentric knee flexor strength compared to uninjured players due to lower values in the injured leg. These findings are consistent with a report of asymmetries in eccentric knee flexor force during the Nordic hamstring exercise in female Australian footballers 1-10 years following ACLR using a hamstring graft (Bourne et al., 2019). The majority of players in the current study (79%) received hamstring tendon grafts. Surgically harvesting the semitendinosus tendon for ACLR results in long-term deficits in voluntary activation (Messer et al., 2020), atrophy, and retraction of this muscle (Konrath et al., 2016), which likely explains the reduced knee flexor strength in the injured compared to uninjured contralateral leg following a return to sport. This reasoning was further substantiated when we removed the three players with non-hamstring grafts (n=2 patellar; n=1 quadricep tendon) from the ACLR group and observed an increase in effect size (d = 1.70, +0.28) for eccentric knee flexor strength between-leg asymmetry between ACLR and uninjured players. The semitendinosus plays a pivotal role in supporting the ACL by resisting anterior tibial shear and providing transverse plane knee joint stability (Toor et al., 2019). Players with a history of ACLR also demonstrated greater isometric hip abductor strength asymmetry due to lower strength in the previously injured leg. The hip abductors are an important contributor to reducing knee valgus moments (a surrogate of ACL load) during side-step cutting (N. Maniar et al., 2018). Consequently, reduced strength of the knee flexors and hip abductors may contribute to an elevated risk of reinjury. Future work is required to determine how rehabilitation strategies influence strength deficits associated with ACLR and investigate whether addressing strength asymmetries reduces the risk of secondary ACL injury in female footballers.

Players with a history of ACLR displayed 5.5% between-leg asymmetry in CMJ peak landing forces due to lower values generated by the injured leg. Previous studies examining male soccer players (Hart et al., 2019; Read et al., 2020), or mixed gender cohorts (Baumgart et al., 2017) after ACLR have also reported between-leg asymmetries in CMJ impulses and peak forces during the take-off and landing phases which were comparable to the current study. Landing during a bilateral task with greater peak force on the uninjured leg is a movement strategy that may be used to protect the previously injured leg, however, this may simultaneously expose the contralateral leg to more force, potentially contributing to greater contralateral ACL injury risk (King et al., 2020). Further work is required to determine whether reducing between-leg asymmetry in landing forces, reduces the risk of recurrent or contralateral ACL injury.

Logistic regression showed that players with a history of ACLR demonstrated a distinct physical profile to uninjured players, including greater asymmetry in eccentric knee flexor strength, isometric hip abductor strength, and CMJ peak landing force asymmetry. Evaluating each of these asymmetry measures in players following ACLR may provide greater insight into players' rehabilitation status and readiness to return to play. However, caution should be taken when using asymmetry measures as a rehabilitation criterion, as restoration of symmetry may reflect reductions in contralateral leg strength/kinetics and not recovery in the injured leg (Read et al., 2020). Whether asymmetries in strength or jump/landing kinetics increase subsequent injury risk remains to be seen. Based on small subsets of players by time since ACLR (Supplementary 4), the largest CMJ take-off force and impulse asymmetries was observed in those between 6- and 12-months post-surgery, after which, asymmetry was similar to the uninjured group. No other patterns were observed between time since ACLR sub groups, and further studies with larger sample sizes are required to investigate recovery from ACLR. Players with a history of ACLR also had significantly lower KOOS pain and sport/rec function scores than uninjured players, although these ranged substantially between individuals. Approximately half of players with ACLR reported no joint pain or dysfunction, and lower scores were not related to time since surgery.

Prior hamstring strain injury

Players who had sustained a recent (<12 months) unilateral hamstring strain injury did not differ in lower limb strength or jump/landing kinetics, including between-leg asymmetry, when compared to uninjured players. Absence of between-group differences is consistent with a recent small-scale study involving six hamstring strain injuries in 84 elite female Australian footballers, which reported no significant effect of prior hamstring injury on eccentric knee flexor strength (Bourne et al., 2019). However, studies of predominantly male athletes have observed persistent deficits in isokinetically-derived concentric and Nordic eccentric knee flexor strength following a return to sport from hamstring injury (Nirav Maniar et al., 2016). In male athletes, preferential reductions in eccentric knee flexor torque (~13%) and work (~10%) have been observed as long as 19 ± 12.5 months after moderate to severe hamstring injury (Lee, Reid, Elliott, & Lloyd, 2009). Although injury time-loss was not collected in this study, female footballers tend to sustain fewer severe hamstring strain injuries than male footballers (Larruskain, Lekue, Diaz, Odriozola, & Gil, 2018), which may explain the absence of strength deficits in the current cohort. Furthermore, previous studies have predominantly recruited recreational or sub-elite athletes, who may not have had access to the same level of rehabilitation as the elite athletes involved in the current study.

Prior hip/groin injury

Players with and without a history of hip/groin injury in the prior 12 months did not differ in lower limb strength or jump/landing kinetics. To the authors' knowledge, this is the first study to explore the impact of hip/groin injury on hip adductor and abductor strength in elite female footballers, which precludes direct comparison with previous work. A recent systematic review and meta-analysis (Mosler, Weir, Hölmich, & Crossley, 2015) of four studies revealed that athletes with hip/groin pain display lower isometric adductor strength than those without. However, only ~6% (12/218) of included athletes were female, all taken from a single study (Mens, Inklaar, Koes, & Stam, 2006), which limits the generalisability of these findings to our cohort. We also observed no effect of prior hip/groin injury on jump/landing kinetics, which has not been examined previously. However, recent data suggest that male athletes with longstanding groin pain display aberrant trunk and lower limb biomechanics during a maximum effort change of direction manoeuvre (Franklyn-Miller et al., 2017). Despite the absence of strength deficits, HAGOS pain and sport/rec function sub-scale scores were significantly lower in players with a prior hip/groin injury. These observations are consistent with earlier work demonstrating that patients with chronic groin pain report worse HAGOS scores despite performing similarly to matched controls in a range of physical performance tests (squats, single leg triple jumps, single leg rises, barbell rollouts, and plank exercises) (Wörner, Sigurðsson, Pålsson, Kostogiannis, & Ageberg, 2017). According to a recent systematic review (Mosler et al., 2015), there is strong evidence that patient reported outcome measures, including the HAGOS, can differentiate athletes with and without hip/groin pain. Poor HAGOS scores have also been associated with an increased risk of subsequent hip/groin injury in elite male footballers (Bourne et al., 2020), though no such work exists in female athletes. The results of the current study suggest that isometric hip adductor and abductor strength may not be associated with ongoing hip/groin pain or symptoms in elite female footballers, or alternatively, that the hip/groin problems sustained in our cohort were not severe enough to cause long-term impairment of lower limb strength or jump/landing kinetics.

Limitations

All prior injuries were self-reported by players and may have been subject to recall errors, though 12 month injury history can generally be performed with high accuracy (Gabbe, Finch, Bennell, & Wajswelner, 2003). It is possible that some players within the uninjured group had lower limb injuries that occurred greater than 12 months ago. However, due to a large sample size, the influence of these cases on the overall uninjured group will be minimal. Details on the location and severity of hamstring or hip/groin injuries were not available. Players recovering from recent injury may not have completed testing, as advised by team medical staff. Players did not complete a dedicated familiarization session due to time restrictions allowed for testing, but all tests involved movements performed routinely in training (e.g. Nordic hamstring exercise and CMJs). Given the study's cross-sectional design, it is impossible to determine if the observed deficits predated or were a result of prior injury. Lastly, it is unknown whether between-leg asymmetry findings would be the same if assessed using unilateral tasks. Future prospective studies of female footballers should explore whether measures of strength and jump/landing kinetics are associated with the risk of subsequent lower limb injury or its recurrence.

CONCLUSION

Elite female footballers with a history of unilateral ACLR, but not hamstring or hip/groin injury, exhibit between-leg asymmetries in lower limb strength and bilateral landing kinetics months to years after injury, despite the majority of players returning to their pre-injury levels of training and competition. These findings provide insight into the long-term consequences of some of the most common and traumatic lower limb injuries sustained by elite female footballers and may be used to inform the design of targeted rehabilitation programs and return to sport criteria for this cohort. Future large-scale prospective studies are needed to determine if the deficits observed after ACLR are associated with an increased risk subsequent ACL injury and whether redressing them leads to a reduction in injury recurrence.

REFERENCES

Altman, D. G., & Bland, J. M. (1994). Diagnostic tests 3: receiver operating characteristic plots. *BMJ: British Medical Journal, 309*(6948), 188.

Antosh, I. J., Svoboda, S. J., Peck, K. Y., Garcia, E. S. J., & Cameron, K. L. (2018). Change in KOOS and WOMAC scores in a young athletic population with and without anterior cruciate ligament injury. *Am J Sports Med, 46*(7), 1606-1616. doi:10.1177/0363546518768753

Baumgart, C., Schubert, M., Hoppe, M. W., Gokeler, A., & Freiwald, J. (2017). Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction? *Knee Surg Sports Traumatol Arthrosc, 25*(5), 1385-1394. doi:10.1007/s00167-015-3623-7

Bishop, C., Read, P., Lake, J., Chavda, S., & Turner, A. (2018). Interlimb Asymmetries: Understanding How to Calculate Differences From Bilateral and Unilateral Tests. *Strength Cond J, 40*(4), 1-6. doi:10.1519/ssc.0000000000000371

Bourne, M. N., Bruder, A. M., Mentiplay, B. F., Carey, D. L., Patterson, B. E., & Crossley, K. M. (2019). Eccentric knee flexor weakness in elite female footballers 1–10 years following anterior cruciate ligament reconstruction. *Physical Therapy in Sport, 37*, 144-149. doi:10.1016/j.ptsp.2019.03.010

Bourne, M. N., Opar, D. A., Williams, M. D., & Shield, A. J. (2015). Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby Union: A Prospective Study. *Am J Sports Med, 43*(11), 2663-2670. doi:10.1177/0363546515599633

Bourne, M. N., Williams, M. D., Jackson, J., Williams, K. L., Timmins, R. G., & Pizzari, T. (2020). Preseason Hip/Groin Strength and HAGOS Scores Are

Associated With Subsequent Injury in Professional Male Soccer Players. *J Orthop Sports Phys Ther, 50*(5), 234-241. doi:10.2519/jospt.2020.9022

Buchheit, M., Cholley, Y., Nagel, M., & Poulos, N. (2016). The effect of body mass on eccentric knee-flexor strength assessed with an instrumented nordic hamstring device (Nordbord) in football players. *Int J Sports Physiol Perform, 11*(6), 721-726. doi:10.1123/ijspp.2015-0513

Collings, T. J., Bourne, M. N., Barrett, R. S., du Moulin, W., Hickey, J. T., & Diamond, L. E. (2021). Risk Factors for Lower Limb Injury in Female Team Field and Court Sports: A Systematic Review, Meta-analysis, and Best Evidence Synthesis. *Sports Medicine*. doi:10.1007/s40279-020-01410-9

Dalton, S. L., Kerr, Z. Y., & Dompier, T. P. (2015). Epidemiology of hamstring strains in 25 NCAA sports in the 2009-2010 to 2013-2014 academic years. *Am J Sports Med, 43*(11), 2671-2679. doi:10.1177/0363546515599631

DiStefano, L. J., Dann, C. L., Chang, C. J., Putukian, M., Pierpoint, L. A., Currie, D. W., . . . Comstock, R. D. (2018). The first decade of web-based sports injury surveillance: descriptive epidemiology of injuries in US high school girls' soccer (2005–2006 through 2013–2014) and national collegiate athletic association women's soccer (2004–2005 through 2013–2014). *J Athl Train, 53*(9), 880-892.

Franklyn-Miller, A., Richter, C., King, E., Gore, S., Moran, K., Strike, S., & Falvey, E. C. (2017). Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns. *Br J Sport Med, 51*(5), 460-468. doi:10.1136/bjsports-2016-096050

Fulton, J., Wright, K., Kelly, M., Zebrosky, B., Zanis, M., Drvol, C., & Butler, R. (2014). Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther, 9*(5), 583.

Gabbe, B. J., Finch, C. F., Bennell, K. L., & Wajswelner, H. (2003). How valid is a self reported 12 month sports injury history? *Br J Sport Med, 37*(6), 545. doi:10.1136/bjsm.37.6.545

Hart, L. M., Cohen, D. D., Patterson, S. D., Springham, M., Reynolds, J., & Read, P. (2019). Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. *Transl Sports Med, 0*(0). doi:10.1002/tsm2.92

Heishman, A. D., Daub, B. D., Miller, R. M., Freitas, E. D. S., Frantz, B. A., & Bemben, M. G. (2020). Countermovement Jump Reliability Performed With and Without an Arm Swing in NCAA Division 1 Intercollegiate Basketball Players. *J Strength Cond Res, 34*(2), 546-558. doi:10.1519/jsc.0000000000002812

Kerbel, Y. E., Smith, C. M., Prodromo, J. P., Nzeogu, M. I., & Mulcahey, M. K. (2018). Epidemiology of Hip and Groin Injuries in Collegiate Athletes in the United States. *Orthop J Sports Med, 6*(5), 2325967118771676. doi:10.1177/2325967118771676

King, E., Richter, C., Jackson, M., Franklyn-Miller, A., Falvey, E., Myer, G. D., . . . Moran, R. (2020). Factors Influencing Return to Play and Second Anterior Cruciate Ligament Injury Rates in Level 1 Athletes After Primary Anterior Cruciate Ligament Reconstruction: 2-Year Follow-up on 1432 Reconstructions at a Single Center. *Am J Sports Med, 48*(4), 812-824. doi:10.1177/0363546519900170

Konrath, J. M., Vertullo, C. J., Kennedy, B. A., Bush, H. S., Barrett, R. S., & Lloyd, D. G. (2016). Morphologic characteristics and strength of the hamstring muscles remain altered at 2 years after use of a hamstring tendon graft in anterior cruciate ligament reconstruction. *Am J Sports Med, 44*(10), 2589-2598. doi:10.1177/0363546516651441

Larruskain, J., Lekue, J. A., Diaz, N., Odriozola, A., & Gil, S. M. (2018). A comparison of injuries in elite male and female football players: A five-season prospective study. *Scandinavian journal of medicine & science in sports, 28*(1), 237-245. doi:10.1111/sms.12860

Lee, M., Reid, S. L., Elliott, B. C., & Lloyd, D. G. (2009). Running biomechanics and lower limb strength associated with prior hamstring injury. *Medicine and science in sports and exercise, 41*(10), 1942-1951. doi:10.1249/MSS.0b013e3181a55200

Maniar, N., Schache, A. G., Sritharan, P., & Opar, D. A. (2018). Non-knee-spanning muscles contribute to tibiofemoral shear as well as valgus and rotational joint reaction moments during unanticipated sidestep cutting. *Sci Rep, 8*(1), 2501. doi:10.1038/s41598-017-19098-9

Maniar, N., Shield, A. J., Williams, M. D., Timmins, R. G., & Opar, D. A. (2016). Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. *Br J Sport Med, 50*(15), 909. doi:10.1136/bjsports-2015-095311

Mens, J., Inklaar, H., Koes, B. W., & Stam, H. J. (2006). A new view on adduction-related groin pain. *Clin J Sport Med, 16*(1), 15-19.

Messer, D. J., Shield, A. J., Williams, M. D., Timmins, R. G., & Bourne, M. N. (2020). Hamstring muscle activation and morphology are significantly altered 1–6 years after anterior cruciate ligament reconstruction with semitendinosus graft. *Knee Surg Sports Traumatol Arthrosc, 28*(3), 733-741. doi:10.1007/s00167-019-05374-w

Montalvo, A. M., Schneider, D. K., Silva, P. L., Yut, L., Webster, K. E., Riley, M. A., . . . Myer, G. D. (2018). 'What's my risk of sustaining an ACL injury while playing football (soccer)?' A systematic review with meta-analysis. *Br J Sport Med, 53*(21), 1333-1340. doi:10.1136/bjsports-2016-097261

Moore, J. M., Cessford, K., Willmott, A. P., Raj, D., Exell, T. A., Burbage, J., & Mullineaux, D. R. (2020). Lower limb biomechanics before and after anterior cruciate ligament reconstruction: A systematic review. *J Biomech, 106*, 109828. doi:10.1016/j.jbiomech.2020.109828

Mosler, A. B., Weir, A., Hölmich, P., & Crossley, K. M. (2015). Which factors differentiate athletes with hip/groin pain from those without? A systematic review with meta-analysis. *Br J Sports Med, 49*(12), 810-810.

Nevin, F., & Delahunt, E. (2014). Adductor squeeze test values and hip joint range of motion in Gaelic football athletes with longstanding groin pain. *J Sci Med Sport, 17*(2), 155-159. doi:10.1016/j.jsams.2013.04.008

O'Brien, M., Bourne, M., Heerey, J., Timmins, R., & Pizzari, T. (2019). A novel device to assess hip strength: Concurrent validity and normative values in male athletes. *Physical Therapy in Sport, 35*, 63. doi:10.1016/j.ptsp.2018.11.006

Opar, D. A., Piatkowski, T., Williams, M. D., & Shield, A. J. (2013). A Novel Device Using the Nordic Hamstring Exercise to Assess Eccentric Knee Flexor Strength: A Reliability and Retrospective Injury Study. *J Orthop Sports Phys Ther, 43*(9), 636-640. doi:10.2519/jospt.2013.4837

Read, P. J., Michael Auliffe, S., Wilson, M. G., & Graham-Smith, P. (2020). Lower Limb Kinetic Asymmetries in Professional Soccer Players With and Without Anterior Cruciate Ligament Reconstruction: Nine Months Is Not Enough Time to Restore "Functional" Symmetry or Return to Performance. *Am J Sports Med, 48*(6), 1365-1373. doi:10.1177/0363546520912218

Roos, E. M., Roos, H. P., Lohmander, L. S., Ekdahl, C., Beynnon, B. D. J. J. o. O., & Therapy, S. P. (1998). Knee Injury and Osteoarthritis Outcome Score (KOOS)—development of a self-administered outcome measure. *J Orthop Sports Phys Ther, 28*(2), 88-96.

Ryan, S., Kempton, T., Pacecca, E., & Coutts, A. J. (2019). Measurement Properties of an Adductor Strength-Assessment System in Professional Australian Footballers. *Int J Sports Physiol Perform, 14*(2), 256-259. doi:10.1123/ijspp.2018-0264

Sandon, A., Engström, B., & Forssblad, M. (2020). High Risk of Further Anterior Cruciate Ligament Injury in a 10-Year Follow-up Study of Anterior Cruciate Ligament-Reconstructed Soccer Players in the Swedish National Knee Ligament Registry. *Journal of Arthroscopic and Related Surgery, 36*(1), 189-195. doi:10.1016/j.arthro.2019.05.052

Thorborg, K., Branci, S., Nielsen, M. P., Tang, L., Nielsen, M. B., & Hölmich, P. (2014). Eccentric and isometric hip adduction strength in male soccer players with and without adductor-related groin pain: an assessor-blinded comparison. *Orthop J Sports Med, 2*(2), 2325967114521778. doi:10.1177/2325967114521778

Thorborg, K., Branci, S., Stensbirk, F., Jensen, J., & Hölmich, P. (2014). Copenhagen hip and groin outcome score (HAGOS) in male soccer: reference values for hip and groin injury-free players. *Br J Sport Med, 48*(7), 557-559. doi:10.1136/bjsports-2013-092607

Thorborg, K., Hölmich, P., Christensen, R., Petersen, J., & Roos, E. M. J. B. j. o. s. m. (2011). The Copenhagen Hip and Groin Outcome Score (HAGOS): development and validation according to the COSMIN checklist. *Br J Sport Med, 45*(6), 478-491. doi:10.1136/bjsm.2010.080937

Timmins, R. G., Bourne, M. N., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *Br J Sport Med, 50*(24), 1524-1535. doi:10.1136/bjsports-2015-095362

Toor, A. S., Limpisvasti, O., Ihn, H. E., McGarry, M. H., Banffy, M., & Lee, T. Q. (2019). The significant effect of the medial hamstrings on dynamic knee stability. *Knee Surg Sports Traumatol Arthrosc, 27*(8), 2608-2616. doi:10.1007/s00167-018-5283-x

Wörner, T., Sigurðsson, H. B., Pålsson, A., Kostogiannis, I., & Ageberg, E. (2017). Worse self-reported outcomes but no limitations in performance-based measures in patients with long-standing hip and groin pain compared with healthy controls. *Knee Surg Sports Traumatol Arthrosc*, *25*(1), 101-107. doi:10.1007/s00167-016-4101-6