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Original Research

Eccentric knee flexor weakness in elite female footballers 1–10 years following anterior cruciate ligament reconstruction

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ABSTRACT

Objectives: To determine eccentric knee flexor strength in elite female Australian Rules Football (ARF) players with and without a history of unilateral anterior cruciate ligament reconstruction (ACLR) using an ipsilateral semitendinosus graft.
Design: Case-control.
Setting: Elite ARF Women's competition.
Participants: Eighty-four elite female ARF players (mean age, 25 ± 4.9 years; height, 1.71 ± 0.73 m; weight, 67 kg ± 7.4 kg) with (n = 12) and without (n = 72) a history of unilateral ACLR in the previous 10 years.
Main outcome measures: Peak eccentric knee flexor force during the Nordic hamstring exercise (NHE).
Results: Players with a history of unilateral ACLR displayed lower levels of eccentric knee flexor strength in their surgically reconstructed limb than their uninjured contralateral limb (mean difference −53.77 N, 95% CI = −85.06 to −24.27, $d = -0.51$) and compared to the limbs of players with no history of injury (mean difference = −46.32 N, 95% CI = −86.65 to −11.13, $d = -0.73$).
Conclusion: Elite female ARF players with a history of unilateral ACLR display deficits in eccentric knee flexor strength in their surgically reconstructed limb for up to 10 years following surgery.

1. Introduction

Anterior cruciate ligament (ACL) ruptures are prevalent in female Australian Rules Football (ARF) players (Fortington, Donaldson, & Finch, 2016). This statistic is particularly concerning in light of evidence that two in three female athletes will not return to sport within 12 months following ACL injury (Ardern, Webster, Taylor, & Feller, 2011), one in four may experience a second ACL injury in that same period (Paterno, Rauh, Schmitt, Ford, & Hewett, 2012), and 50–90% will develop knee osteoarthritis in the subsequent 10–15 years (Beynnon, Johnson, Abate, Fleming, & Nichols, 2005). ACL reconstruction (ACLR) surgery is typically recommended to restore knee joint stability, and in ARF players, this most often involves an autogenous graft harvested from the ipsilateral semitendinosus (with or without the gracilis) (Ardern, Webster, Taylor, & Feller, 2010; Paterno et al., 2010).

A number of extrinsic and intrinsic factors may be associated with the high rates of ACL injuries in sub-elite and elite female football players. ARF involves frequent exposure to high risk activities such as cutting, pivoting, and landing and all of these manoeuvres are commonly cited mechanisms for ACL injury (Liptak & Angel, 2017; Saw et al., 2018). Further, it is well recognised that women playing the same sport are 4–6 times more likely to be injured than their male counterparts (Boden, Dean, Feagin, & Garrett, 2000), and this may be the result of modifiable or non-modifiable factors including anatomical, biomechanical, neuromuscular or hormonal differences between genders (Hewett, Ford, Hoogenboom, & Myer, 2010). Knee flexor strength is potentially an important modifiable risk factor for ACL injury (Hewett et al., 2010) given that the hamstrings resist anterior tibial shear, and therefore, represent the primary form of muscular support for this ligament. However, prospective data in support of this hypothesis are limited.

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One study demonstrated that 1–24 months before an ACL rupture, female soccer and basketball players displayed lower levels of hamstring but not quadriceps strength compared to uninjured male athletes (Myer et al., 2009). However, no known studies have measured eccentric knee flexor strength in elite female football players, nor its association with ACL injury.

Graft failure and subsequent revision surgery is a significant concern following ACLR and female athletes are four times more likely to suffer a re-injury than their male counterparts (Paterno et al., 2012). The mechanism(s) responsible for the high rates of re-injury are not fully understood. However, ACLR surgery using an ipsilateral semitendinosus graft may result in chronic reductions in knee flexor (Konrath et al., 2016; Nomura, Kuramochi, & Fukubayashi, 2015; Snow, Wilcox, Burks, & Greis, 2012) and internal rotator strength (Konrath et al., 2016) and these deficits may be at least partly explained by observations of reduced activation (Arnason, Birnir, Guethmundsson, Guethnason, & Briem, 2014) and/or atrophy of the medial hamstrings (Konrath et al., 2016; Messer, Shield, Timmins, Williams, Bourne). Given that graft failure likely occurs when the hamstrings actively lengthen to resist dynamic anterior tibial translation, it seems sensible to prioritise the assessment of eccentric knee flexor strength following ACLR. Timmins and colleagues (Timmins et al., 2016b) recently reported that elite male ARF and soccer players with a history of ACLR displayed significantly lower levels of eccentric knee flexor strength in their surgically reconstructed limb than the uninjured contralateral limb during the performance of the eccentric Nordic hamstring exercise (NHE). However, this study (Timmins et al., 2016b) is one of the few to have assessed eccentric knee flexor strength after ACLR (Andersson, Samuelsson, & Karlsson, 2009; Hiemstra, Webber, MacDonald, & Kriellaars, 2000), and none of these investigations have included female athletes, so it remains unclear if female ARF players would experience a similar deterioration in this parameter after surgery.

An improved understanding of the impact of prior ACLR on knee flexor strength in elite female ARF players represents an important first step towards optimising injury risk reduction training programs and rehabilitation strategies for these athletes. The NHE is a commonly performed strengthening exercise in elite ARF (Pizzari, 2010) and an important component of evidence-based ACL injury prevention programs (Finch et al., 2016). Furthermore, the assessment of eccentric knee flexor strength during this exercise is reliable (Opar, Piatkowski, Williams, & Shield, 2013), can indicate a level of risk for future hamstring strain injury (Bourne, Opar, Williams, & Shield, 2015; Opar et al., 2015; Timmins et al., 2016a), and is a common screening protocol in several elite football codes. The primary aim of this study was to assess eccentric knee flexor strength during the NHE in elite female ARF players with and without a history of unilateral ACLR (using an ipsilateral semitendinosus graft). A secondary aim was to report normative strength values for players with no history of injury. We hypothesised that elite female ARF players with a history of ACLR would display lower levels of strength and greater strength imbalances between limbs, than those without such history.

2. Materials & methods

2.1. Study design & participants

This case-control study was undertaken during the pre-season of the 2018 elite Australian Football League Women's (AFLW) competition. Ninety footballers from three AFLW clubs were invited to participate as part of their usual pre-season musculoskeletal screening. Sociodemographic data including age, height, weight, and foot dominance (defined as preferred kicking limb) were recorded. Players were asked to self-report if they had sustained an ACL injury at any time throughout their life and/or any time loss hamstring strain injury (missing at least one game of competitive sport) in the previous 12 months. Football players had their eccentric knee flexor strength assessed during the NHE at a single time point during the 2018 AFLW pre-season. All players provided written, informed consent for their involvement in this study, which was approved by the La Trobe University Human Research Ethics Committee.

2.2. Eccentric knee flexor strength assessment

The assessment of eccentric knee flexor force using the NHE was consistent with previous studies (Bourne et al., 2015; Opar et al., 2013, 2015; Timmins et al., 2016a). Players knelt on a padded board, with their ankles secured immediately superior to the lateral malleolus by individual ankle hooks which were attached to uniaxial load cells (Vald Performance, Queensland, Australia). The ankle hooks and load cells were secured to a pivot which allowed the force generated by the knee flexors to be measured through the long axis of the load cells. Immediately prior to testing, players were provided with a demonstration of the NHE from investigators (Fig. 1). Once in the kneeling position, athletes were instructed to gradually lean forward and lower their trunk to the ground as slowly as possible (Bourne, Opar, Williams, Al Najjar, & Shield, 2016). Players performed only the lowering (eccentric) portion of the exercise and were instructed to use their arms and flex at the hips and knees to push back into the starting position after each repetition. All players completed a standard lower limb warm up, which consisted of burpees, squats and running on the spot. Subsequently, players completed a single set of three maximal repetitions of the bilateral NHE on the testing device. All trials were closely monitored by investigators to ensure strict adherence to proper technique and players received verbal encouragement throughout each repetition to encourage maximal effort. A repetition was deemed acceptable when the force output reached a distinct peak (indicative of maximal eccentric strength), followed by a rapid decline in force which occurred when the athlete was no longer able to resist the effects of gravity acting on the segment above the knee joint. All eccentric strength testing was performed in a non-fatigued state, as part of a larger musculoskeletal screening session.

2.3. Data analysis

Force data for the dominant and non-dominant limbs were sampled at 50 Hz and transferred via USB cable to a cloud-based software program (Scorebord, Vald Performance) on a personal computer. Data were subsequently exported as comma separated value files for analysis. Eccentric knee flexor strength was determined for all limbs as the peak force generated during the three repetitions of the NHE. This value was reported in absolute terms (N) and relative to bodyweight ($N.kg^{-1}$).

2.4. Statistical analysis

Mean and standard deviations (SD) of age, height, weight and eccentric knee flexor strength for the dominant and non-dominant limbs of healthy control participants, or previously injured and uninjured contralateral limbs for those with a history of injury, were determined and reported descriptively. Correlation coefficients were calculated to determine the relationship between eccentric knee flexor force and body mass, and time elapsed since injury. Mean absolute differences with bootstrapped 95% confidence intervals (CIs) and Cohen's *d* effect sizes were calculated to

Fig. 1. The Nordic hamstring exercise, progressing from left to right.

compare peak eccentric knee flexor strength for 1) the surgically reconstructed and uninjured contralateral limbs of players with a history of ACLR; 2) surgically reconstructed limbs and the limbs of control players with no history of ACLR or hamstring injury; and 3) the dominant versus non-dominant limbs of players with no history of injury. Given that 25% of surgically reconstructed limbs had also experienced a hamstring strain injury in the prior 12 months, an additional analysis was conducted to compare the eccentric knee flexor strength of these limbs to uninjured contralateral limbs.

The combined effects of previous ACLR, time-loss hamstring strain injury and limb dominance on eccentric knee flexor strength were estimated using a linear mixed effect model (lme4) (Bates, Machler, Bolker, & Walker, 2015). Random intercepts were included for each player to account for intra-person correlation between limbs. All statistical analysis was performed using the R statistical computing language [Rcore]. Null hypothesis significance testing and interpretation of results using p-values was avoided; instead, all analyses are presented as estimated effects with 95% CIs (Stovitz, Verhagen, & Shrier, 2017).

3. Results

3.1. Participants

Eighty-four football players (mean age, 25 ± 4.9 years; height, 1.71 ± 0.73 m; weight, 67 kg ± 7.4 kg) from three AFLW clubs consented to be assessed during pre-season of the 2018 AFLW competition. Seventy-two (n = 72) footballers (age, 24 ± 5 years, height, 1.71 ± 0.08 m; weight, 66 ± 7 kg) had no history of ACLR. Two of these footballers without a previous ACLR (2/72) reported a unilateral time-loss hamstring strain injury in the previous 12 months. Twelve (n = 12) athletes had a history of unilateral ACLR (age, 28 ± 5 years; height, 1.69 ± 0.05 m; weight, 69 ± 8 kg) in the past 10 years (median, 4.5 years; range, 1–10 years). Four out of the 12 footballers with a previous ACLR (4/12) reported a unilateral time-loss hamstring strain injury in the previous 12 months (3 of these on the ipsilateral ACLR side, and 1 on the contralateral ACLR side). All players with a history of ACLR had undergone reconstructive surgery involving an autogenous graft harvested from the ipsilateral semitendinosus but had since undertaken rehabilitation and returned to their pre-injury (or higher) level of training and competition. Footballers with a history of ACLR were older (mean difference = 3.45 years, 95% CI = 0.33 to 6.38, $d = 0.72$), but similar in height (mean difference = −1.53 cm, 95% CI = −4.60 to 1.72, $d = -0.21$) and weight (mean difference = 2.70 kg, 95% CI = −2.63 to 7.47, $d = 0.36$) than those with no such history.

3.2. Peak eccentric knee flexor strength

Players with a history of unilateral ACLR were weaker in their surgically reconstructed limb than their uninjured contralateral limb (mean difference = −53.77 N, 95% CI = −85.06 to −24.27, $d = -0.51$) and compared to the two-limb average of control participants with no history of ACLR or hamstring injury (mean difference = −46.32 N, 95% CI = −86.65 to −11.13, $d = -0.73$) (Fig. 2). The magnitude of the difference between surgically reconstructed and uninjured contralateral limbs was augmented when players with a history of hamstring strain injury were excluded (mean difference = −84.00 N, 95% CI = −106.25 to −61.00, $d = -1.25$). No difference was observed between the uninjured contralateral limbs of players with a history of ACLR and control limbs with no history of injury (mean difference = 7.44 N, 95% CI = −33.82 to 51.62, $d = -0.10$). Peak eccentric knee flexor strength for players with no history of injury was greater in the dominant than non-dominant limb (mean difference = 16.15 N, 95% CI = 8.53–23.81, $d = 0.21$). For all comparisons, similar differences were observed when peak eccentric knee flexor force was normalised to body mass; these results are presented in Supplementary Fig. 1.

3.3. Effects of prior ACLR, hamstring injury and limb dominance on eccentric knee flexor strength

The estimated effects of limb dominance, previous ACLR and hamstring strain injury history on peak eccentric knee flexor strength are presented in Fig. 3 (and Supplementary Table 1). The effect of previous ACLR on eccentric strength was estimated to be −49.96 N (95% CI = −70.11 to −29.81). The estimated effect of limb dominance was a decrement of 17.73 N (95% CI = −25.44 to −10.02) on the non-dominant side. The effect of hamstring injury in the previous 12 months was estimated as an increase of 16.50 N (95% CI = −11.80 to 44.80), however, the small number of hamstring injuries and large confidence interval suggest this is an imprecise estimate that requires further investigation. Linear mixed model results for eccentric knee flexor strength normalised to bodyweight were similar (see Supplementary Fig. 2 and Supplementary Table 2).

3.4. Time elapsed since ACLR and eccentric knee flexor strength

No correlation was observed between time since ACLR and peak eccentric knee flexor strength (r = −0.14, 95% CI = −0.66 to 0.48) or between-limb imbalance (r = −0.03, 95% CI = −0.60 to 0.55).

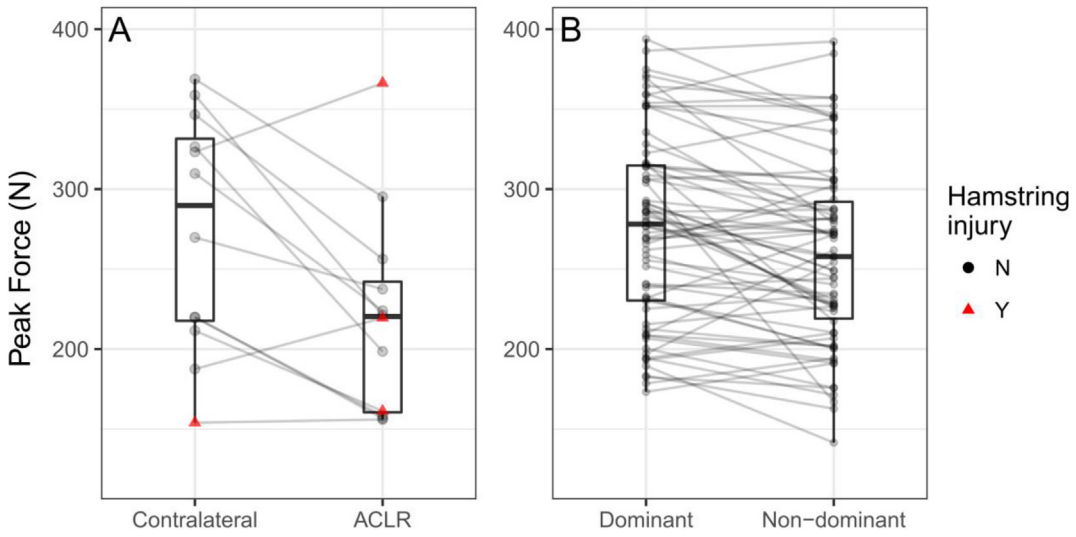

Fig. 2. Comparison of peak eccentric knee flexor strength (N) between **(a)** limbs with a history of anterior cruciate ligament reconstruction (ACLR) and uninjured contralateral limbs; and **(b)** dominant and non-dominant limbs of healthy controls. Red triangles indicate time-loss hamstring injury in the previous 12 months. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

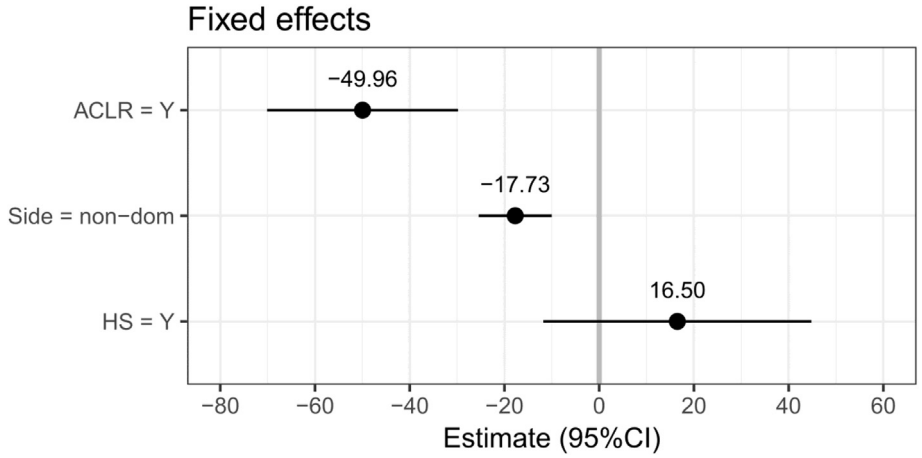

Fig. 3. Estimated fixed effects for linear mixed effect model of peak eccentric knee flexor strength (N).

3.5. Bodyweight and eccentric knee flexor strength

A moderate correlation was observed between peak eccentric knee flexor force and body mass for footballers in this study (r = 0.40, 95% CI = 0.27 to 0.52).

4. Discussion

Elite female ARF players with a history of ACLR using a semitendinosus graft display lower levels of eccentric knee flexor strength in their surgically reconstructed limb than their uninjured contralateral limb, and compared to the limbs of players with no history of injury.

Eccentric knee flexor strength deficits observed in elite female ARF players with a history of ACLR are consistent with earlier investigations in male football players. Timmins and colleagues (Timmins et al., 2016b) recently reported that 1–9 years after ACLR, male soccer and ARF players were 43 N weaker (between-limb imbalance = 14%, $d = 0.51$) in their surgically reconstructed limb compared to their uninjured contralateral limb during the performance of the NHE. Earlier work employing isokinetic dynamometry reported similar between-limb differences (16.9%) in eccentric knee flexor strength for up to ~23 years following a unilateral ACLR (Tengman, Brax Olofsson, Stensdotter, Nilsson, & Hager, 2014). In the current study, elite female ARF players with a history ACLR were, on average, 54 N weaker (between-limb imbalance = 20% $d = -0.51$) in their surgically reconstructed limb than their uninjured contralateral limb, and 46 N weaker ($d = -0.73$) than the limbs of players with no history of injury. Interestingly, these strength deficits persisted despite players being a median of 4.5 years (range = 1–10 years) post-reconstructive surgery and having undergone post-operative rehabilitation sufficient to return to their pre-injury (or higher) level of training and competition. Eccentric knee flexor weakness after ACLR may be mediated by observations of reduced activation (Arnason et al., 2014) and atrophy of the medial hamstrings (Konrath et al., 2016; Messer, Shield, Timmins, Williams, Bourne). For example, Messer and colleagues (Messer, Shield, Timmins, Williams, Bourne) recently observed with functional magnetic resonance imaging that the surgically grafted semitendinosus of men and women with a history of ACLR is ~45% smaller and ~34% less active than the homonymous muscle in the uninjured contralateral limb during performance of the NHE. Given

that the semitendinosus is preferentially activated during the NHE (Bourne, Opar, Al Najjar, & Shield, 2017) and other knee flexion oriented movements (Bourne et al., 2018), strategies targeted at improving strength and hypertrophy of this muscle may have implications for improving eccentric knee flexor strength following ACLR. However, it should be acknowledged that other muscles besides the hamstrings (i.e., gastrocnemius, sartorius and gracilis) also contribute to eccentric knee flexor strength and it remains unclear if these muscles are altered in limbs following an ACLR.

Graft failure and subsequent revision surgery are a major concern after ACLR, particularly for female athletes – who are 4 times more likely (Paterno et al., 2012) to suffer a re-injury than their male counterparts. While the mechanism(s) responsible for the increased risk of re-injury in women remains unclear, it has been proposed that lower hamstring relative to quadriceps strength during dynamic knee loading may be partly responsible (Hewett et al., 2010). For example, female athletes typically have higher quadriceps activation relative to hamstring activation than male athletes while running and cutting (Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001) and during drop jump landings from incrementally greater heights (Ford, Myer, Schmitt, van den Bogert, & Hewett, 2008). Preferential activation of the knee extensors has also been observed in elite female athletes in response to experimentally induced anterior tibial translation (Huston & Wojtys, 1996). In comparison, male athletes display higher relative strength (Hewett, Stroupe, Nance, & Noyes, 1996; Holm & Vollestad, 2008) and activation (Hewett et al., 1996; Malinzak et al., 2001) of the hamstrings compared with the quadriceps during dynamic knee loading, and up to 3-fold greater knee flexion moments than size-matched female athletes when landing from a jump (Hewett et al., 1996). Low levels of hamstring activity during dynamic knee loading may lead to a number of deleterious biomechanical alterations that would serve to increase strain on the ACL. For example, relatively higher quadriceps than hamstring activation when landing is associated with lower knee flexion moments (Hewett et al., 2005), increased ground reaction forces (Hewett et al., 1996) and greater knee valgus moments (Hewett et al., 1996), all of which may increase the risk of ACL injury. Given that the hamstrings are antagonists to knee extensor torques and therefore represent the primary form of muscular support for the ACL, the restoration of eccentric knee flexor strength may have implications for mitigating the risk of re-injuries, and this should be a focus of future work.

A further consequence of prior ACLR could be a greater risk of hamstring strain injury (Toohey, Drew, Cook, Finch, & Gaida, 2017). Indeed, in the current study, 25% (4/12) of female football players with a history of ACLR had suffered a hamstring strain in the prior 12 months, compared with 2.8% (2/72) of players with no such history. Although the mechanism by which prior ACLR predisposes to future hamstring injury is not fully understood, eccentric knee flexor weakness (Opar et al., 2015; Timmins et al., 2016a), and strength imbalances between limbs (Bourne et al., 2015), are independent risk factors for hamstring strain injury. For example, elite ARF (Opar et al., 2015) and professional soccer players (Timmins et al., 2016a) with low levels of strength (<279 N[29] and <337 N[38], respectively) were ~4 fold more likely to sustain a future hamstring strain injury than their stronger counterparts. Further, rugby union players (Bourne et al., 2015) with between-limb imbalances in eccentric knee flexor strength of ≥15% and ≥20%, were 2.4-fold and 3.4-fold, respectively, more likely to suffer a hamstring injury than those with smaller imbalances. In the current study, surgically reconstructed limbs were ~20% weaker than uninjured contralateral limbs, although it should be noted that football players with a history of ACLR and hamstring injury were slightly more symmetrical than those with only an ACLR history ($d = 0.30$).

To date, no known study has explored the relationship between eccentric knee flexor strength or imbalance and hamstring strain injury in female athletes, so it remains unclear if the aforementioned findings can be extended to the current population. However, it is plausible that higher levels of eccentric hamstring strength may improve the ability of these muscles to decelerate the shank during the ostensibly injurious terminal-swing phase of high speed running (Schache, Wrigley, Baker, & Pandy, 2009), which may confer a protective benefit against running-induced strain injury (Bourne et al., 2018).

Uninjured female ARF players displayed average (±SD) eccentric knee flexor forces of 267 N ± 58 N, which are considerably lower than forces reported in healthy uninjured limbs of elite male ARF (Opar et al., 2015), soccer (Timmins et al., 2016a; van Dyk et al., 2017), and Rugby union players (Bourne et al., 2015) (ranging from 299 N–368 N). Lower levels of strength in our cohort than those reported for elite male football players is unsurprising given that female footballers are considerably lighter and shorter than their male counterparts. We observed that heavier female ARF players were able to produce greater peak forces than lighter players ($r = \sim 0.4$). These observations are consistent with Buchheit and colleagues (Buchheit, Cholley, Nagel, & Poulos, 2016) who observed a similar relationship ($r = 0.55$) between eccentric knee flexor strength during the NHE and body mass in amateur and professional male soccer and ARF players. However, it should be acknowledged that several earlier studies (Bourne et al., 2015; Opar et al., 2015; Timmins et al., 2016a) failed to observe any such relationship. We also observed a small effect for limb dominance whereby the dominant (kicking) limb was ~17 N stronger than the non-dominant limb ($d = 0.21$). Again, these observations are in contrast to earlier work in male footballers (Bourne et al., 2015; Buchheit et al., 2016; Opar et al., 2015; Timmins et al., 2016a), and given that the error of the Nordic strength testing device is ~30 N (Opar et al., 2013), this difference should be interpreted with caution.

One limitation of this retrospective study is that it is impossible to determine if eccentric knee flexor weakness was present before or manifested as a consequence of ACLR. Future large-scale prospective cohort investigations are needed to determine if eccentric knee flexor weakness is a risk factor for ACL injury and its recurrence. Further, the assessment of eccentric knee flexor strength during the NHE does not allow for an assessment of the angle at which the knee flexors produce maximum torque and does not permit force to be expressed relative to quadriceps or hip flexor strength, which may provide more information on an athlete's recovery from ACLR. It should also be acknowledged that specific details on the rehabilitation programs used by footballers in this study were not available, and different practices may have influenced the recovery of knee flexor strength. However, all players underwent post-operative rehabilitation under the guidance of a qualified practitioner sufficient to return to the highest level of training and competition (i.e., elite sport), so it seems unlikely that this was a confounding factor. It is also important to consider that ARF players with a history of ACLR were heterogenous in terms of time since injury (median, 4.5 years; range, 1–10 years) at the time of testing. Nevertheless, no relationship between time since ACLR and peak eccentric knee flexor strength ($r = -0.14$) or between-limb imbalance ($r = -0.03$) was observed, which is consistent with previous work. (Messer, Shield, Timmins, Williams, Bourne).

In conclusion, elite female ARF players with a history of ACLR using a semitendinosus graft, display deficits in eccentric knee flexor strength 1–10 years after surgery and apparently successful rehabilitation. Future large-scale prospective studies are needed to determine if eccentric knee flexor weakness is a risk factor for ACL injury or its recurrence.

Ethics approval

This study was approved by the La Trobe University Human Research Ethics Committee.

Conflicts of interest

None declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.03.010.

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