Quadriceps Strength and Functional Performance After Anterior Cruciate Ligament Reconstruction in Professional Soccer players at Time of Return to Sport

Lee Herrington,[1] Hussain Ghulam,[2] and Paul Comfort[1]

[1]Center for Health, Sport and Rehabilitation Sciences, University of Salford, Salford, United Kingdom; and [2]Medical Rehabilitation Center, Madinah Region, Kingdom of Saudi Arabia

Abstract

Herrington, L, Ghulam, H, and Comfort, P. Quadriceps strength and functional performance after anterior cruciate ligament reconstruction in professional soccer players, at time of return to sport. *J Strength Cond Res* 35(3): 769–775, 2021—Poor quadriceps strength has been associated with poor outcome after anterior cruciate ligament (ACL) reconstruction (ACLR). This study aims to assess quadriceps strength, muscle inhibition, and hop test performance in professional soccer players after ACLR. Fifteen professional soccer players (age 22.3 ± 3.1 years, body mass 81.0 ± 11.5 kg, and height 1.75 ± 0.1 m) who had undergone ACLR participated. Isometric, eccentric, and concentric quadriceps strength was assessed, along with quadriceps inhibition and single and cross-over hop performance, at the time of return to full-time unrestricted play. In comparison with the uninjured leg, the ACLR leg demonstrated large significant ($d \geq 0.84$, $p < 0.01$) deficits in isometric, eccentric, and concentric quadriceps strength, quadriceps inhibition, and hop distance. Over 80% of the players failed to exceed the limb symmetry criteria of ≥90% for strength tests, although 75% of the cohort passed the ≥90% criteria for hop tests. The outcome from ACLR in professional soccer players who received full-time intensive rehabilitation has not previously been reported in detail. There were significant deficits in quadriceps strength at the time of return to sport, whereas hop testing, a commonly used outcome measure, failed to show the same levels of deficit. These deficits in quadriceps function may have implications for the development of ongoing knee symptoms and risk of future ACL injury. If this proves to be the case, then it would seem that greater attention should be paid to re-establishing full quadriceps strength before returning to unrestricted sporting activity.

Key Words inhibition, asymmetry, concentric, eccentric, isometric

Introduction

A recent systematic review of outcome from anterior cruciate ligament (ACL) reconstruction (ACLR) in elite sports people reported that pooled return to sport (RTS) rate was 83% (95% confidence interval 77–88%) (14). Six of 9 studies included in the review that had a noninjured control group found no deterioration in athletic performance after ACLR in elite sports performers. When assessing return to elite soccer, Walden et al. (21) reported that greater than 90% of professional soccer players returned to play, with 2/3 still playing at the same level 3 years after surgery. Zaffagnini et al. (25) reported a similar level of return (95%) with 71% still playing at the same level, whereas Erickson et al. (8) reported a slightly lower level of return (77%). Unsurprisingly, these levels of RTS are higher than those reported for nonelite/professional populations, with Ardern et al. (3) reporting the figure to be around 55%. The reasons for the disparity seem to be obvious, full time professionally supervised rehabilitation and higher baseline (preoperative) levels of fitness and strength, alongside the financial imperative to return to play. These reports on return to play come from retrospective audits of injury data, what is current lacking in the literature, is data on the physical status of these athletes when they return to play, and if they have superior physical qualities compared with those previously reported for nonelite patients which have supported these achievements.

Individuals who undergo ACLR frequently have been found to have deficits in quadriceps activation (level of inhibition) and rate of force development (RFD), which can persist for greater than 1–2 years after surgery (2,9). These

Address correspondence to Dr. Lee Herrington, l.c.herrington@salford.ac.uk.

35(3)/769–775

Journal of Strength and Conditioning Research

deficits in muscle function (activation, strength, and RFD) have been linked to decreased performance both in the sporting environment and also in activities of daily living and quality of life (7,9). Furthermore, poor muscle function has been linked to poor movement quality during landing tasks, walking, running, and cutting performance, which exposes the athlete to increased risk of further ACL injury (12) and osteoarthritis (OA) (1,7). What is currently unclear in the literature is whether the higher levels of RTS in professional soccer players could be attributed to overcoming these deficits. The first stage in possibly improving the outcome for nonelite patients with ACLR might be to understand the performance characteristics and physical qualities of elite athletes at RTS. Then, from this information, goals were informed and defined for rehabilitation of all patients with ACLR.

Logerstedt et al. (16) commented that both short-term and long-term outcomes after ACLR require attention and action because of the relatively poor outcomes, with less than 55% of nonelite athletes making a full recovery (3) and greater than 50% developing significant OA within a decade of surgery (6). Despite the relative advances in surgical techniques in the past 10 years, the outcomes for the patients have remained unchanged (20). The rehabilitation undertaken by the patients after reconstructive surgery is regarded as equally important as the surgery itself in defining the patient's outcome (18), but this has altered relatively little in this period, and no consensus still exists on the optimal strategies to rehabilitate these patients after ACLR (11).

Culvenor et al. (7) clearly identified, in their review, the relationship between poor quadriceps strength and the increased risk of symptomatic and functional deterioration of the knee during activities of daily living and sport-recreational activities. Furthermore, persistent quadriceps dysfunction, both in terms of strength and activation pattern, after ACLR has been identified as a risk factor for reinjury, contralateral knee joint injury, and premature progression to degenerative knee joint changes (1,6,7). The absolute levels of quadriceps strength (strength normalized to body mass) as opposed to limb symmetry index (LSI) are rarely reported in the literature on outcome from ACLR. The most frequently reported variable is the LSI, thus making it difficult to understand the absolute levels of quadriceps performance. One of the few articles reporting strength found it to be a more significant predictor of outcome than LSI (19). The use of the contralateral leg as a performance comparison using metrics such as LSI has been questioned, because it may underestimate the true level of deficit, because the contralateral leg of an ACLR patient is often significantly weaker when compared with a control limb in noninjured individuals (5).

The aim of this study, therefore, was to assess the concentric, eccentric, and isometric quadriceps strength, and level of inhibition (central activation ratio [CAR]) of elite professional soccer players at the time of RTS, and to identify their level of performance in relation to their quadriceps muscles. Alongside direct measures of quadriceps performance, standard hop tests were assessed as a proxy for functional performance (12,13,18) As these athletes have returned to sport, it may then provide an insight into the physical qualities (measureable performance metrics) required to RTS. It was hypothesized that these athletes would show LSI >90% and not have significant performance deficits between limbs, due to lower levels of strength in the ACLR limb.

Method

Experimental Approach to the Problem

An observational cross-sectional design was used to determine the level of quadriceps strength and CAR of professional soccer players at the time of RTS, and to compare affected and unaffected limbs to determine whether any asymmetry was evident.

Subjects

Fifteen full-time professional soccer players (mean ± *SD*, age 22.3 ± 3.1 years [19.2-27.5 years], body mass 81.0 ± 11.5 kg, height 1.75 ± 0.1 m, and a global Knee injury and Osteoarthritis Outcome Score [KOOS] questionnaire score of 89.9 ± 5.1 at time of assessment), playing for clubs in the English premiership or championship divisions, who had undergone an ACLR participated in the study. Subjects were recruited through orthopedic surgeons or directly from their soccer teams, after an invitation letter to participate in the study. An initial screening of the volunteers was undertaken to exclude any individuals who had received more than primary ACL reconstructive surgery. Assessment was performed on all volunteers who met the inclusion criteria, between the period January 2015 and February 2017 (24 months). All subjects had undergone ACL reconstruction (time since surgery 7.8 ± 1.3 months). All subjects had been medically cleared to RTS and undertaken and passed functional return to play testing at their clubs, and all their rehabilitation had been undertaken on a full-time basis within their professional club environment supervised by a sports physiotherapist, sports physician, and orthopedic surgeon. Ten of the 15 had received a hamstring autograft and 5 had received a patella tendon autograft. All-surgery had been undertaken by experienced orthopedic surgeons using standard procedures, with none of the cases having any secondary procedures, beyond the primary ACLR. At the time of surgery, none of these athletes had any significant meniscus lesions or chondral damage reported (as assessed either from magnetic resonance imaging or by the orthopedic surgeon at the time of surgery). This study was approved by University Research Ethics and Governance Committee (ref: HSCR14/68). All subjects provided written informed consent.

Procedures

Tests were undertaken in the following order: isokinetic test, isometric test, quadriceps activation test, and hop tests with

Table 1. Reliability of dependent variable.*

Test	ICC (95% CI)	*SEM*†	%CV
Knee extensors eccentric peak torque ($N \cdot m \cdot kg^{-1}$)	0.76 (0.52–0.91)	0.48	14.3
Knee extensors concentric peak torque ($N \cdot m \cdot kg^{-1}$)	0.87 (0.66–0.95)	0.45	13.0
Knee extensors isometric peak force ($N \cdot m \cdot kg^{-1}$)	0.97 (0.91–0.99)	0.23	6.9
Central activation ratio (%)	0.89 (0.7–0.96)	2.3	9.8
Single hop for distance (% leg length)	0.85 (0.61–0.95)	7.9	7.8
Cross-over hop for distance (% leg length)	0.8 (0–0.93)	19.7	8.5

*ICC = intraclass correlation coefficient; CI = confidence interval; CV = coefficient of variation.
†*SEM* is presented for absolute units.

a 10-minute rest between each group of tests, to minimize any effect of fatigue.

Isokinetic Quadriceps Strength Test. Isokinetic eccentric and concentric strength of the quadriceps was assessed using a Biodex isokinetic dynamometer (Biodex Medical Systems, Shirley, NY). The test was conducted at an angular velocity of $60° \cdot s^{-1}$ through a range of 0–90° knee flexion. The subject performed 5 practice repetitions, followed 3 minutes later by 5 maximal repetitions of consecutive maximal-effort eccentric quadriceps actions, and followed by concentric quadriceps actions. The best trial (highest peak torque) was recorded from the 5 repetitions for the eccentric and concentric efforts, respectively. All data were gravity-corrected and normalized against body mass (absolute torque/body mass: $N \cdot m \cdot kg^{-1}$).

Isometric Quadriceps Strength Test. The isometric test of quadriceps strength was performed with the subjects seated in an isokinetic dynamometer and positioned in 90° hip flexion and 90° knee flexion (13,25). The subject performed 5 practice repetitions followed by 5 maximal (3–5 seconds) repetitions. The highest peak torque was recorded from the 5 repetitions and normalized against body mass.

Quadriceps Central Activation Ratio. The muscular inhibition of the quadriceps (CAR) was assessed, during a maximal isometric contraction (MVIC) of the quadriceps with the interpolated twitch technique (21). The subjects were seated in an isokinetic dynamometer and positioned in 90° hip flexion and 90° knee flexion. Two electrodes (proximal: 50 × 130 mm, distal: 7.5 × 100 mm) (Axelgaard, Fallbrook, CA) were placed on the quadriceps muscle at one-third and two-thirds from the distance between the anterior superior iliac spine and the upper border of the patella. Arthrogenic muscle inhibition measurements were taken using a Digitimer high-voltage stimulator (DS7AH Digitimer Ltd., Hertfordshire, United Kingdom). The subject undertook a maximal-voluntary isometric contraction for 5 seconds. During the MVIC contraction, 2 single pulses of 200-μs duration, 200 V, and 120 mA were triggered 3 times (beginning, mid, and end of the contraction; approximately at 1, 3, and 5 seconds, respectively) manually by the investigator when the MVIC

Table 2. Comparison between ACLR and noninjured legs across tests.*

Test	Limb	Mean ± *SD*	Range	*p*	*d*
Knee extensors eccentric peak torque ($N \cdot m \cdot kg^{-1}$)	ACLR	3.28 ± 0.79	1.89–4.72	0.0001	0.84
	Noninjured	3.97 ± 0.83	2.48–5.5		
Knee extensors concentric peak torque ($N \cdot m \cdot kg^{-1}$)	ACLR	2.76 ± 0.55	1.76–4.31	0.0001	0.99
	Noninjured	3.37 ± 0.68	2.15–5.0		
Knee extensors isometric peak force ($N \cdot m \cdot kg^{-1}$)	ACLR	2.9 ± 0.2	2.6–3.7	0.0001	2.53
	Noninjured	3.7 ± 0.4	3.0–4.8		
Central activation ratio (%)	ACLR	18.8 ± 7.9	11.1–32	0.0038	2.14
	Noninjured	4.6 ± 5.1	0–13		
Single hop for distance (% leg length)	ACLR	183.9 ± 26.1	141–226	0.0001	0.53
	Noninjured	197.7 ± 26.1	145–247		
Cross-over hop for distance (% leg length)	ACLR	692.0 ± 128.7	550–974	0.0002	0.38
	Noninjured	741.1 ± 129.6	560–1,012		

*ACLR = anterior cruciate ligament reconstruction.

Table 3. Limb symmetry index (LSI) across tests.

Test	Mean ± *SD* %	Range %	Percentage of players with LSI >90% (*n*)
Knee extensors eccentric peak torque	82.8 ± 10	59.7–98.3	20 (3)
Knee extensors concentric peak torque	83 ± 13.7	52.1–101.1	20 (3)
Knee extensors isometric peak force	80.7 ± 7.8	63.7–96.8	13 (2)
Single hop for distance	93.2 ± 7.4	71.4–105.3	67 (10)
Cross-over hop for distance	93.6 ± 7.6	66.9–113.8	73 (11)
Central activation ratio	85.1 ± 5.6	75.5–92.1	13 (2)

force had plateaued on the monitor. Thus, electrical twitches were evoked at rest and added during an MVIC. Before CAR analysis, torque data was low-pass filtered at 150 Hz using a second-order Butterworth filter. Central activation ratio was quantified by calculating the difference between the stimulus-evoked torque during MVIC to the stimulus-evoked torque at rest and expressed in %: activation deficit at 100% MVIC. The smaller the deficit, the less the inhibition, whereby an inhibition of 0% means that the subject was able to fully recruit the muscle without showing any signs of inhibition.

Hop Tests. The assessment of single hop for distance (SHD) and cross-over hop for distance (CHD) was undertaken (11,17). For the single hop, subjects were required to hop forward as far as possible along the line of the standard tape measure and land on the same limb. In the cross-over hop, subjects maximally hopped forward 4 times, alternately crossing 2 parallel lines 15 cm apart, therefore participating in 2 medial and 2 lateral direction landings. In both cases, distance was measured from the start line to the rear of the foot on final landing. The distance hopped was then normalized to a percentage of leg length, by dividing the distance hopped by the subject's leg length (distance from anterior superior iliac spine to medial malleolus) and multiplying by 100. The subjects performed 3 practice trials and then a test trial as per the method of Munro and Herrington (18).

Statistical Analyses

Reliability of Measures. Eight uninjured semiprofessional soccer players (age 20.1 ± 5.3 years, body mass 85.0 ± 10.1 kg, height 1.73 ± 0.2 m, and a global KOOS questionnaire score of 94.8 ± 4.3 at time of testing) undertook all the tests on 2 separate occasions to assess the reliability of the tests. The reliability of the tests was assessed using intraclass correlation coefficient (ICC model 2, 1), *SEM*, and percent coefficient of variance. Intraclass correlation coefficients were interpreted using established criteria (2) as follows: poor <0.40; fair 0.40–0.70; good 0.70–0.90; and excellent >0.90, and percent coefficient of variance <10% were regarded as acceptable (2).

Main Analysis. Data were assessed for normality using Shapiro-Wilks test. For each test, ACLR and contralateral limb performance was then compared using individual paired *t*-tests with Cohen's *d* effect sizes calculated and interpreted, with 0.5 and below being a small effect size; greater than 0.5 being a medium effect size; 0.8 and above being a large effect size (3). Limb symmetry index was calculated by dividing the ACLR limb performance by the contralateral limb performance and multiplying by 100 to give a percentage.

A previous power analysis (*G* Power, Version 3.1.7) with mean differences between 2 dependent mean values was used to calculate the required sample size, with an effect size of 2.53 (peak isometric force, ACLR, and noninjured knee) and an alpha level of $p \leq 0.05$, 10 subjects were required to obtain power of 1.0.

Results

The global KOOS score for the ACLR group was 89.9 ± 5.1, whereas the score from the uninjured group used for the reliability study was 94.8 ± 4.

All tests show good reliability; however, eccentric and concentric knee extensor strength exceeded the acceptable levels of variability (Table 1).

Medium-to-large significant differences in quadriceps strength (eccentric, concentric, and isometric) were found between and the difference was greater than the *SEM*, with the uninjured limb performing consistently better than the ACLR limb. There was a large and significant difference in the CAR between limbs, which was greater than the *SEM*. Single hop distance showed a medium and significant difference between limbs, but only had a 64% chance of being superior based on the medium effect size, with a the difference being greater than the *SEM*. There was a small, yet significantly greater CHD in the contralateral limb, with a difference greater than the *SEM* (Table 2).

The LSI percentages for all tasks along with the percentage of players, who achieved an LSI greater than the typical 90% cutoff, are presented in Table 3, highlighting that with the exception of the 2 hops tests, low percentages of the

players achieved the recommended level of LSI i.e., greater than 90%.

Discussion

This study has presented quadriceps strength and hop performance data from a group of professional soccer players after ACLR who had all been cleared to return to play. This is the first time that data of this type have been present for such high-level professional soccer players. Because of the unique nature of this group, data from uninjured players are limited or not available. This study's data have been presented with effect sizes for the differences and the *SEM* for all tests, to give the findings some context. Despite being cleared to play, the majority of these individuals showed moderate to large significant deficits in both their quadriceps strength and hop performance when compared with the uninjured leg. These differences are also reflected in the high percentage of individuals who failed to achieve a 90% LSI score for the tests. Gokeler et al. (10), using similar test battery on a more general population of patients with ACLR, found that for hop tests 78.5% patients passed LSI > 90% for SHD, but only 39.3% passed LSI >90% for quadriceps concentric contraction, whereas only 35.7% patients had >3.0 $N \cdot m \cdot kg^{-1}$ isometric quadriceps strength for the involved ACLR limb. Wellsandt et al. (23) reported that 23% of patients with ACLR assessed at 6 months after operation failed to have isometric quadriceps strength LSI greater than 90%, with 26% on SHD and 17% on CHD also failing to achieve an LSI greater than 90%. Both of these studies reflect the results found in this study despite differing populations. Overall, it would seem that despite being deemed fit to return to play, significant deficits exist in strength and, to a lesser extent, hop performance in a variety of populations at the time of RTS.

The use of the contralateral (noninjured) leg as a performance comparison has been questioned, because it may underestimate the true level of deficit. The contralateral leg of the patients with ACLR has frequently been found to be significantly weaker when compared with a control limb in uninjured individuals (4). This is highlighted in the Wellsandt et al. (23) study, when the ACLR limb was compared with the contralateral leg performance scores measured preoperatively, 37% failed to have an LSI greater than 90% for quadriceps strength, and when SHD and CHD were assessed, 26% failed to achieve an LSI greater than 90%. The levels of strength and hop performance of the contralateral limb in this study would seem not to fit this pattern, with performance in line or superior to previously reported values for noninjured limbs (23). Furthermore, in a group of similar strength levels, Zult et al. (26) found the uninjured contralateral leg to have had similar levels of strength to those of controls. Currently, few data are available to determine what might be an acceptable absolute level of strength. Both Gokeler et al. (10) and Pietrosimone et al. (19) proposed >3.0 $N \cdot m \cdot kg^{-1}$ isometric quadriceps strength. Comparable data for eccentric and concentric strength would seem not to be available, with few normative data present in the literature (in elite sportsman) to guide the decision-making process (24).

This study does call into question only using functional tests such as hop tests and questionnaires such as KOOS in isolation without also measuring strength. The majority of subjects (greater than 2/3) had LSI for hop tests of greater than 90% and global KOOS score over 90, which have been regarded a sufficient level of functional performance for RTS. The findings of this study then support those of Gokeler et al. (9) that a battery of tests is required including quadriceps strength to define a patient's readiness to RTS. The results of this study also call into question the continued reporting of LSI without also presenting absolute strength scores. Both would seem to be required to give a full picture of performance (9).

The absolute level of quadriceps strength and limb asymmetry have both been associated with the level of long-term functional performance (8,19,23). Furthermore, deficits in quadriceps strength have been related to the development of OA in an ACLR population (6). Because ongoing knee symptoms and OA occur frequently in this population (5), it might be that the ongoing deficits in quadriceps performance might be related to this occurrence (1). A second ACL injury (either contralateral or graft rupture) is another relatively high-frequency occurrence in this population, especially in those younger than 20 years (21). Pietrosimone et al. (19) reported that isometric quadriceps strength >3.1 $N \cdot m \cdot kg^{-1}$ increased the chances of achieving acceptable levels of self-reported outcome by 8.15 times (specificity 0.84, sensitivity 0.61), whereas having an LSI ≥96.5% for isometric quadriceps strength increased the likelihood of reporting an acceptable outcome by 2.78 times (specificity 0.70, sensitivity 0.55). Wellsandt et al. (23) reported that failure to achieve an LSI of greater than 90% for quadriceps strength gave a specificity of 0.31 and sensitivity of 0.82 for predicting a second ACL injury. Poor quadriceps performance at return to play could therefore be related to increased risk of further ACL injury, ongoing knee symptoms, and degenerative joint disease. What is unclear from the retrospective studies into ACLR outcome in soccer is whether players had ongoing issues because none of these studies (7,20,25) reported levels of symptoms through tools such as functional questionnaires. They do report that around a 1/3 of players are not playing at the same level, which coincides with the figure reported by Mai et al. (17) for American professional sports, but all these studies fail to indicate the reasons for this.

The levels of quadriceps inhibition in the ACLR leg reported in this article are similar to those previously reported by Kuenze et al. (13). The level of quadriceps inhibition has been shown to be significantly related to the level of quadriceps strength (15); so, it may in part provide an

explanation for the differences between the ACLR and the non-ACLR limbs.

A strength of this article is that it that it presents data on a unique population. This is obviously also a limitation because the findings might not be applicable to other sports or nonelite athletes. But, because of the full-time professional nature of these athletes, it could be expected that other athletes with less support through rehabilitation may not do as well as these individuals and have poorer results. Another limitation is that no detail was presented on the specific elements of the rehabilitation these athletes undertook. Future studies should identify whether the inclusion (or exclusion) of specific exercises and activities has a significant impact on results. The study also only included individuals who had had isolated ACL injury. This obviously limits applicability. Because more extensive damage to the knee is likely to create greater levels of inhibition, it is unlikely that these findings will be reversed in other populations and may even be accentuated. Finally, this study presents no follow-up on these athletes; so, the impact of these findings on future sporting performance and development of comorbidities is unknown. Future studies should attempt to track these individuals to understand the impact of findings. Furthermore, it is also not known whether these deficits will change over time. Some parameters such as RFD seem to normalize after 12 months (3), whereas others such as strength do not (15). Although in reality, in the world of professional sport, once findings such as these are identified, it is unlikely that there will be an attempt to address them, thereby confounding any follow-up.

Practical Applications

The retrospective studies into the professional sports would appear to indicate that a high proportion of players return to play at the same level after ACLR, but a significant number are not performing at that level within 3 years of surgical repair of their ACL. The findings of this article demonstrate significant deficits in quadriceps strength and activation and, to a lesser extent, performance during hop tests, despite the players being deemed fit to return to play. It might be hypothesized that there could be a link between the findings of this article and the players who fail to maintain their level of performance or develop secondary issues. If this proves to be the case, then significant attention should be paid to re-establishing full quadriceps activation and strength before returning to unrestricted sporting activity.

Acknowledgments

All procedures performed in studies involving human subjects were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

References

1. Amin, S, Baker, K, and Niu, J. Quadriceps strength and the risk of cartilage loss and symptom progression in knee osteoarthritis. *Arthritis Rheum* 60: 189–198, 2009.
2. Angelozzi, M, Madama, M, Corsica, C, Calvisi, V, Properzi, G, McCaw, S, et al. Rate of force development as an adjunctive outcome measure for return-to-sport decisions after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 42: 772–780, 2012.
3. Ardern, C, Taylor, N, Feller, J, and Webster, K. Fifty five percent return to sport following anterior cruciate ligament reconstruction surgery: An updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *Br J Sports Med* 48: 1543–1552, 2014.
4. Batterham, A and George, K. Reliability in evidence-based clinical practice: A primer for allied health professionals. *Phys Ther Sport* 4: 122–128, 2003.
5. Chung, K, Ha, J, Teom, C, Ra, H, Lim, J, Kwon, J, et al. Are muscle strength and function of the lower limb weakened after anterior cruciate ligament injury? A two year follow up after reconstruction. *Am J Sports Med* 43: 3013–3021, 2015.
6. Culvenor, A, Cook, J, Collins, N, and Crossley, K. Is patellofemoral joint osteoarthritis an under-recognised outcome of anterior cruciate ligament reconstruction? A narrative literature review. *Br J Sports Med* 47: 66–70, 2013.
7. Culvenor, A, Ruhdorfer, A, Carsten, J, Eckstein, F, and Oiestad, B. Knee extensor strength and risk of structural, symptomatic and functional decline in knee osteoarthritis: A systematic review and meta-analysis. *Arthritis Care Res* 69: 649–658, 2017.
8. Erickson, B, Harris, J, and Cvetanovich, G. Performance and return to sport after anterior cruciate ligament reconstruction in male Major League Soccer players. *Orthop J Sports Med* 1: 23–25, 2013.
9. Flosadottir, V, Roos, E, and Ageberg, E. Muscle function is associated with future patient reported outcomes in young adults with ACL injury. *BMJ Open Sport Exerc Med* 2: e000154, 2016.
10. Gokeler, A, Welling, W, Zaffagnini, S, Seil, R, and Padua, D. Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 25: 192–195, 2016.
11. Herrington, L and Comfort, P. Training for prevention ACL injury: Incorporation landing skill challenges into a program. *Strength Cond J* 35: 59–65, 2013.
12. Herrington, L, Myer, G, and Horsley, I. Task based rehabilitation protocol for elite athletes following anterior cruciate ligament reconstruction: A clinical commentary. *Phys Ther Sport* 14: 188–198, 2013.
13. Kuenze, C, Hertel, J, Weltman, A, Diduch, D, Saliba, S, and Hart, J. Persistent neuromuscular and corticomotor quadriceps asymmetry after anterior cruciate ligament reconstruction. *J Athl Train* 50: 303–312, 2015.
14. Lai, C, Ardern, C, Feller, J, and Webster, K. Eighty three percent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: A systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *Br J Sports Med* 52: 128–138, 2018.
15. Lepley, A, Ericksen, H, Sohn, D, and Pietrosimone, B. Contributions of neural excitability and voluntary activation to quadriceps muscle strength following anterior cruciate ligament reconstruction. *Knee* 21: 736–742, 2014.
16. Logerstedt, D, Di Stasi, D, Grundem, H, Lynch, A, Eitzen, I, Engebretsen, L, et al. Self reported knee function can identify athletes who fail return to activity criteria up to 1 year after anterior cruciate ligament reconstruction. A Delaware-Oslo ACL cohort study. *J Orthop Sports Phys Ther* 44: 914–923, 2014.

17. Mai, H, Chun, D, Schneider, A, Erickson, B, Freshman, R, Kester, B, et al. Performance based outcomes after anterior cruciate ligament reconstruction in professional athletes differ between sports. *Am J Sports Med* 45: 2226–2231, 2017.

18. Munro, A and Herrington, L. Between session reliability of four hop tests and the agility T-test. *J Strength Cond Res* 25: 1470–1477, 2011.

19. Pietrosimone, B, Lepley, A, Harkey, M, Luc, B, Blackburn, T, Gribble, P, et al. Quadriceps strength predicts self-reported function post ACL reconstruction. *Med Sci Sport Exs* 48: 1671–1677, 2017.

20. Risberg, A, Grinde, H, and Oiestad, B. We need to implement current evidence in the early rehabilitation programs to improve long term outcome after ACLR. *J Orthop Sports Phys Ther* 9: 710–713, 2016.

21. Walden, M, Hagglund, M, Magnusson, H, and Ekstrand, J. ACL injuries in men's professional football: A 15 year prospective study on time trends and return to play rates reveals only 65% of players still play at top level 3 years after ACL rupture. *Br J Sports Med* 50: 744–750, 2016.

22. Webster, K, Feller, J, and Leigh, W. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *Am J Sports Med* 42: 641–647, 2014.

23. Wellsandt, E, Failla, M, and Synder-Mackler, L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *J Orthop Sports Phys Ther* 47: 334–338, 2017.

24. Willigenburg, N, McNally, M, and Hewett, T. Quadriceps and hamstring strength in athletes. In: C Kaeding and J Borchers, eds. *Hamstring and Quadriceps Injuries in Athletes. A Clinical Guide* Chapter 2. New York, NY: Springer, 2014. ISBN: 978-1-4899-7509-6.

25. Zaffagnini, S, Grassi, A, and Marcheggiani Muccioli, G. Return to sport after anterior cruciate ligament reconstruction in professional soccer players. *Knee* 21: 731–735, 2014.

26. Zult, T, Gokeler, A, van Raay, J, Brouwer, R, Zijdewind, I, and Hortobagyi, T. An anterior cruciate ligament injury does not affect the neuromuscular function of the non-injured leg except for dynamic balance and voluntary quadriceps activation. *Knee Surg Sports Traumatol Arthrosc* 25: 172–183, 2016.