Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players

Luke M. Hart[1,2] **Daniel D Cohen**[3] **Stephen D. Patterson**[1] **Matt Springham**[1]
James Reynolds[4] **Paul Read**[5,6,7]

[1]Faculty of Sport, Health and Applied Sciences, St Mary's University, London, UK

[2]Sports Medicine Department, Sports Surgery Clinic, Dublin, Ireland

[3]Faculty of Health Sciences, University of Santander, Bucaramanga, Colombia

[4]Department of Science and Technology, Faculty of Health and Science, University of Suffolk, Ipswich, UK

[5]Athlete Health and Performance Research Centre, Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

[6]School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff, UK

[7]School of Sport and Exercise, University of Gloucestershire, Gloucester, UK

Correspondence
Luke M. Hart, ASCC, St. Marys University, London, Waldegrave Rd, Twickenham TW1 4SX, UK.
Email: lukehart@sportssurgeryclinic.com

Abstract

Previous injury is associated with increased risk of future injury. Residual inter-limb deficits are a potential contributing factor leading to compensatory movement patterns on return to sport. The purpose of this study was to examine the effects of previous severe injury on bilateral ground reaction force asymmetries measured during a countermovement jump using a dual force platform. A total of 34 male professional soccer players (age 19 ± 2 years) were subdivided into two groups; previous severe injury (N = 17) or no severe injury (N = 17). Previously injured players showed significantly greater asymmetry in concentric phase variables ($P < 0.05$) with strong effect sizes (range = 0.99-1.35). These players also showed significantly elevated asymmetry in eccentric phase variables ($P < 0.05$) and medium to large effect sizes (range = 0.73-1.05), with the exception of eccentric deceleration impulse ($P > 0.05$; $d = 0.33$). There were no significant between-group differences in bilateral jump performance parameters ($P > 0.05$). These data indicate that despite being cleared to return to sport, participating in elite-level training, full competition and exhibiting no decrements in jump performance, significant inter-limb asymmetries persist in the concentric and eccentric phases of the CMJ.

KEYWORDS
countermovement jump, ground reaction force, inter-limb asymmetry

1 INTRODUCTION

Soccer is characterized by high physiological and mechanical demands, with an inherent risk of lower extremity injury due to the frequency of repeated high speed, multidirectional movements such as sprinting, jumping, landing, and changing direction in chaotic environments. Evidence indicates that previous injury is the strongest risk factor for future injury, with players sustaining a lower limb injury 2-3 times more likely to experience an identical injury in subsequent seasons.[1,2] Residual inter-limb deficits are a possible contributory risk factor leading to compensatory movement patterns at the time of return to sport.[3] Re-injury also results in increased duration of rehabilitation in comparison to the time-loss for the original injury.[4] Thus, there is a need for practical and easy to implement tools to quantify deficits in players who have sustained a previous injury, providing a comprehensive neuromuscular profile prior to their return to sport.

In soccer, a degree of asymmetry is expected to develop as a result of limb dominance, specific task, and positional requirements.[5-9] For example, studies show that 39%-60% of players have >15% between-limb strength differences.[10-13] Limb dominance also appears to be established early in childhood with no obvious differences across jumping tasks in youth soccer players who are either pre-, circa, or post-pubertal.[14] Increased asymmetry may also be a consequence of injury and incomplete rehabilitation following a prior lower limb injury.[13,15,16] Few studies are available to describe the characteristics of previously injured soccer players during athletic performance tasks and how their movement and asymmetry profiles compare to those who have not previously sustained a severe injury.

In addition to isokinetic or isometric strength testing of specific muscle groups, there are a range of other assessment modes to assess inter-limb asymmetry.[17] These approaches are commonly designed for the purposes of clinical utility and transfer to sport-specific activities such as jumping and hopping tasks.[18-20] The sensitivity of these tests for the identification of compensatory movement patterns is questionable if distance and jump height are the sole outcome measures. These metrics alone do not account for the variability in movement execution which may persist consequent to previous injury.[14,21] Furthermore, force measures have been shown to display a greater level of asymmetry than those of hop distance.[21] To provide a more accurate indication of the deficits underlying physical performance following a severe injury, more comprehensive assessments are warranted, particularly as alterations appear to persist for months to years after return to sport.[22-24]

Previous research has indicated that inter-limb vertical ground reaction force (VGRF) asymmetries remain up to 2 years following anterior cruciate ligament (ACL) injury measured during a drop vertical jump.[24] More recently, VGRF asymmetries in different phases of the countermovement jump (CMJ) have been shown following ACL reconstruction (ACL-R).[22,23,25] The CMJ is used to measure physical performance and is routinely included in elite sport settings. Studies which have examined VGRF profiles during this test in elite soccer players who have sustained a previous severe injury are sparse. Cohen, Clarke, Harland, Lewin[26] found that preseason peak landing but not takeoff force asymmetries were significantly higher in professional players who had sustained a lower extremity injury, resulting in more than 7 days' time-loss in the previous season compared to uninjured players. Time efficient assessments, capable of identifying inter-limb asymmetries in different phases of the CMJ may provide practitioners with useful information to optimize performance and determine a player's level of injury risk and readiness to return to sport. However, for practitioners to confidently classify an asymmetry as "abnormal," we must also establish a "normal" asymmetry profile of players competing in the professional soccer.

The purpose of this study was to compare bilateral CMJ performance and VGRF asymmetries in a group of previously injured and non-injured professional soccer players. It was hypothesized that those who had sustained a previous severe injury would display greater inter-limb asymmetries in both concentric and eccentric phases than players who had been injury free for a period of up to 12 months prior to testing, but bilateral performance variables would not differ between groups.

2 METHODS

2.1 Experimental approach to the problem

This study utilized a between subject's cross-sectional design to examine and compare bilateral performance and asymmetries in previously injured compared to uninjured professional soccer players. Following familiarization, participants were required to attend 1 formalized testing session which included a standardized, dynamic warm-up, and three practice trials prior to the completion of 3 maximal CMJ's. Players were asked to refrain from strenuous physical activity for 48 hours prior and to maintain their normal diet.

2.2 Participants

A total of 34 male professional soccer players (age 19 ± 2.3 years; height 179.91 ± 6.44 cm; body mass 76.59 ± 8.93 kg) from an English Championship Football League club volunteered to take part in this study and were subdivided into two groups; previously injured and non-injured athletes (Table 1). The inclusion criteria for a previously injured player were to have returned to training and competitions following a serve lower extremity injury (>28 days' time-loss) which occurred within the prior 12- month period.[27] Participant consent and ethical approval was attained prior to testing. This study was conducted in accordance with the principles for medical research as outlined in the Declaration of Helsinki by the World Medical Association.[28]

TABLE 1 Subject characteristics (Mean ± SD)

Status	n	Age (years)	Height (cm)	Mass (kg)
Previously injured	17	19 ± 2	179.91 ± 7.04	76.88 ± 9.60
Uninjured	17	18 ± 2	179.97 ± 5.98	75.79 ± 8.51

2.3 Procedures

2.3.1 Injury reporting

Injuries experienced prior to the study period and used for player classification were diagnosed and prospectively recorded by the medical personnel of the club. Injuries were documented if they occurred during soccer-related activities and if the player was subsequently unable to participate in training or competition for a minimum of 48 hours following the incident, not including the day of injury (Price et al, 2004). Players were classified as injured until the medical staff (chartered physiotherapists) deemed they were fit to resume full training.

2.3.2 Anthropometry

Body mass (kg) was measured on a calibrated physician scale (Seca 786 Culta). Standing height (cm) was recorded on a measurement platform (Seca 274).

2.3.3 Countermovement jumps

Participants were instructed to stand on two synchronized single axis (vertical ground reaction force) force platforms (Pasco) erect with hands on hips and remain motionless for a minimum period of 2 seconds. Players were then directed to descend to their self-selected depth to jump as high as possible, involving triple extending at the ankle, knee, and hip with the aim of achieving their maximal vertical acceleration and displacement of the center of mass. Participants kept their hands on their hips during the jump to limit involvement of arm swing, and no bending of the knees was permitted while airborne. Three trials were recorded with a 2-minute rest period between each jump. The mean values of the 3 jumps were used for subsequent analysis.

2.4 Force platform analysis

VGRF were recorded with a sampling rate of 1000 Hz using proprietary software (NMP ForceDecks v1.2.6109). CMJ phases were defined, and calculations were analyzed in accordance with previous recommendations.[22,23,29] Specifically, the initiation of the jump was defined by a 20N change from bodyweight, the eccentric phase as the time from initiation of the jump to zero velocity, the eccentric deceleration phase from the maximum negative velocity to zero center of mass velocity, and the concentric phase from zero velocity to the takeoff. Forces for both the concentric and eccentric phases were calculated. Eccentric:concentric ratio was defined as the contribution and output of force from each phase toward the sum total recorded during the CMJ. It is suggested that when reporting asymmetries during bilateral tasks, inter-limb differences should be calculated relative to the sum total for that variable.[30] However, to permit comparisons with previous research[15,22,23] and make the interpretation more meaningful, absolute percentage asymmetry was calculated using the formula: (Left limb−right limb)/(maximum left and right) × 100.[23,31]

2.5 Statistical analysis

Descriptive statistics (mean ± SD) were calculated for each group. An independent-samples *t* test was utilized to compare injured versus non-injured players in concentric and eccentric and phases of the CMJ, with the level of significance was set at alpha level $P \leq 0.05$. Cohen's *d* effect sizes (ES) were calculated to interpret the magnitude of between-group differences using the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for small, medium, and large effect sizes, respectively. Statistical power was determined (G Power 3.1.9.2) for the primary variables. To attain a statistical power of 80%, a minimum sample size of 10 participants per group was required.

3 RESULTS

Previous injuries sustained are displayed in Table 2. The knee and ankle injuries were the anatomical sites with the highest occurrence; most frequently ligament sprains and cartilage lesions. Thigh strains were the most common muscular injuries.

TABLE 2 Injury location and type for previous injured players

	n = 17	%
Injury location		
Ankle	5	29.41
Lower leg/Achilles	2	11.76
Knee	7	41.17
Thigh	2	11.76
Hip/Groin	1	5.88
Injury type		
Ligament/Cartilage	10	58.82
Muscular	4	23.52
Tendon	3	17.64

Previously injured players showed significantly greater asymmetry in all of the concentric phase variables assessed ($P < 0.05$) with strong effect sizes (range = 0.99-1.35) (Table 3). These players also showed significant greater asymmetry in all eccentric phase variables ($P < 0.05$) with medium to large effect sizes (range = 0.73-1.05), with the exception of eccentric exception of deceleration impulse ($P > 0.05$; $d = 0.33$). We also subdivided the previously injured group and compared asymmetry % in players with dominant (N = 11) versus non-dominant (N = 6) limb injury (Table 4). Asymmetries were higher in those with non-dominant limb injuries for most variables, but these differences were not significant. However, con peak force and con impulse 100 ms showed large effect sizes and a trend toward significance ($P = 0.59$, and $P = 0.54$, respectively).

TABLE 3 Mean ± SD of Countermovement jump asymmetry variables in the concentric and eccentric phases

Variable	Status	Asymmetry %	CI	Effect size
Concentric imp 100 ms	Previously injured	10.85 ± 5.85[a]	7.84-13.85	0.99
	Uninjured	5.73 ± 4.33	3.51-7.96	
Concentric imp	Previously injured	7.34 ± 3.62[a]	5.48-9.20	1.01
	Uninjured	4.06 ± 2.82	2.61-5.51	
Concentric peak force	Previously injured	8.23 ± 4.80[a]	5.76-10.70	1.35
	Uninjured	3.17 ± 2.28	2.00-4.34	
Eccentric: Concentric force ratio	Previously injured	10.91 ± 6.86[a]	7.38-14.44	0.87
	Uninjured	5.45 ± 5.62	2.56-8.34	
Eccentric deceleration RFD	Previously injured	20.52 ± 10.64[a]	15.06-25.99	1.05
	Uninjured	10.52 ± 8.24	6.28-12.87	
Eccentric deceleration impulse	Previously injured	12.60 ± 8.59	8.18-17.01	0.33
	Uninjured	9.66 ± 6.24	6.45-12.87	
Eccentric peak force	Previously injured	11.98 ± 7.51[a]	8.11-15.84	0.73
	Uninjured	7.38 ± 4.81	4.91-9.85	
Force at zero velocity	Previously injured	11.93 ± 7.45[a]	8.10-15.76	0.73
	Uninjured	7.34 ± 4.89	4.82-9.86	

*Significant difference (p < 0.05)

TABLE 4 Countermovement jump asymmetry % (mean ± SD) in previously injured in players with dominant (N = 11) versus non- dominant (N = 6) limb injuries

Variable	Status	Asymmetry %	Effect size
Concentric impulse 100 ms	Non-dominant	14.30 ± 5.79	1.05
	Dominant	8.98 ± 4.62	
Concentric impulse	Non-dominant	6.65 ± 2.51	0.30
	Dominant	7.71 ± 3.81	
Concentric peak force	Non-dominant	11.2 ± 5.29	1.13
	Dominant	6.61 ± 3.28	
Eccentric: Concentric force ratio	Non-dominant	12.54 ± 9.52	0.39
	Dominant	10.02 ± 4.08	
Eccentric deceleration RFD	Non-dominant	22.05 ± 12.10	0.23
	Dominant	19.69 ± 9.09	
Eccentric deceleration impulse	Non-dominant	14.03 ± 9.26	0.27
	Dominant	11.81 ± 7.66	
Eccentric peak force	Non-dominant	15.64 ± 6.19	0.84
	Dominant	9.98 ± 6.91	
Force at zero velocity	Non-dominant	15.48 ± 6.50	0.73
	Dominant	10.00 ± 6.86	

There were no significant differences between groups in bilateral jump performance variables ($P > 0.05$). This was particularly evident for traditional performance measures including jump height and peak power corresponding to small effect sizes (Table 5). While not statistically significant, flight time: contraction time and eccentric: concentric force ratio showed small-medium effect size differences between injured and non-injured players (Table 4).

4 DISCUSSION

The present study compared performance variables and inter-limb VGRF asymmetries during a bilateral CMJ in elite male soccer players with a history of severe previous lower extremity injury in the previous 12 months versus those who were injury free during the same period. The principle finding was that despite no meaningful differences in bilateral performance variables between groups, significant inter-limb differences in both concentric and eccentric phase variables were present. These data indicate that players who are cleared for return to sport and are actively participating in elite-level training and soccer competitions display significant neuromuscular compensations during CMJ.

These findings support existing research[15,22-26] and show evidence of compensatory strategies or strength deficits in previously injured athletes when attempting to maximize vertical displacement in the CMJ. It is suggested that these strategies are expressed during bilateral tests whereby inter-limb asymmetries may represent avoidance of excessive loading of previously injured tissues.[23] While comparisons between studies are difficult due to differences in asymmetry calculations or reporting of descriptive statistics, an asymmetry index of 5.1% and 6.8% has been reported for concentric peak force[24] and concentric impulse,[23] respectively, following

Performance variable	Injury status	Mean ± SD	Effect size
Jump height (cm)	Previously injured	33.9 ± 4.7	−0.24
	Uninjured	34.9 ± 3.6	
Peak power/ BW	Previously injured	50.5 ± 6.1	−0.22
	Uninjured	51.7 ± 5.2	
Flight:Contraction time (s)	Previously injured	0.63 ± 0.08	−0.47
	Uninjured	0.67 ± 0.09	
Eccentric: Concentric force ratio	Previously injured	52.1 ± 3.7	0.51
	Uninjured	50.2 ± 3.3	
Concentric RPD/BW	Previously injured	235.1 ± 61.4	−0.40
	Uninjured	258.6 ± 54.5	

TABLE 5 Mean ± SD of Countermovement jump performance variables

ACL-R, aligning with our findings. Other research in both ACL-R[25] and non-injured athletes[31] have shown CMJ inter-limb asymmetries of up to 20%, consistent with eccentric deceleration RFD values in the present study. This variable displayed the highest asymmetry in both injured and uninjured players (20.52% and 10.52%, respectively) and large and significant intergroup difference ($d = 1.05$). Interestingly, however, there were no significant differences in eccentric deceleration impulse asymmetry, which is determined by both the magnitude of the force and the time over which it is produced, thus representing a global evaluation across the whole phase. In line with this, significantly higher concentric impulse but not eccentric impulse asymmetry was shown in ski athletes with prior ACL-R, while eccentric deceleration RFD was not reported in this study.

While prior injury may not be associated with elevated asymmetry in overall eccentric phase force production, eccentric deceleration RFD which takes into account the rate of force rise as the athlete decelerates their mass at the end of the descent, does appear to show a persistent residual deficit following lower extremity injury. Therefore, athletes with prior injury may exhibit alterations in the shape of the eccentric force-time curve rather than in magnitude of overall force production. These athletes adopt a compensatory strategy of extending the time period of force application on the previously involved side as observed in post-ACL-R individuals with low, but not high function.[29] While we did not compare phase durations in injured vs non-injured players, significantly higher asymmetry in eccentric to concentric force ratio in the injured players (Table 3) and the tendencies observed in the bilateral variables eccentric: concentric ratio and flight time: contraction time (Table 5), seems to support the concept that prior injury can lead to relative increases in the overall eccentric force and time contribution to the jump.

In healthy athletes, functional deficits can exist between dominant limb (D) and non-dominant limb (ND),[6] with injury to the latter potentially exacerbating these deficits. It was therefore of interest to evaluate if in previously injured players in the present study the magnitude of the asymmetry observed was influenced by whether the injury was to the dominant or the non-dominant limb. In line with epidemiological evidence showing higher incidence on the dominant side for most injuries in elite male footballers, only 6 of the 17 players in the present study sustained a non-dominant limb injury.[32,33] As such, the sample size may have been inadequate for a robust statistical comparison and we found no significant differences in the magnitude of asymmetry between players with D and ND limb injuries. Large effect size differences in concentric peak force and concentric impulse 100ms asymmetry suggest greater asymmetry in players with prior ND injury. Further, medium effect sizes for other variables appear to indicate that at least with respect to bilateral CMJ performance, non-dominant limb injuries may be associated with larger asymmetries. Few studies have examined this interaction, but Strandberg, Lindström, Wretling, Aspelin, Shalabi[34] reported a larger inter-limb quadricep cross-sectional asymmetry area after a right side (typically the dominant limb) than a left side ACL injury in footballers awaiting surgery for reconstruction. Given these apparently contradictory findings which may need consideration in the rehabilitation process, the interaction between side of injury and magnitude of asymmetry/deficit warrants further investigation.

There were no significant between-group differences in bilateral performance variables in “conventional” performance metrics such as jump height and peak power. However, flight time: contraction time, eccentric: concentric force ratio and rate of power development showed heightened differences with values approaching a moderate effect size, although these differences were not significant. Nonetheless, the results of the current study indicate that previously injured soccer players demonstrate compensatory patterns in their jump strategy to achieve the desired performance outcome and these variables may be more sensitive to the effects of previous injury than conventionally reported parameters. Previous injury has been associated with future injury in professional soccer players[35] and while the mechanistic link between prior and future risk of injury is not well defined,[27] it is plausible that post-injury residual deficits or accentuated inter-limb asymmetries may be an important contributing factor.[36] Further research is warranted to more fully elucidate the effects of these compensatory strategies on the incidence of future injury.

Previous research has suggested that an asymmetry >10%-15% should be considered “abnormal” and potentially indicative of dysfunction.[24] Our analysis suggests that a global threshold is not appropriate as we found substantial differences in the magnitude of asymmetry in the concentric and eccentric phases in the previously injured and non-injured players. For example in non-injured players, setting an asymmetry threshold of 10%, in concentric impulse would equate to more than two standard deviations above the mean values; whereas this value represents the mean eccentric deceleration RFD. Additionally, non-injured elite alpine ski controls have also shown asymmetry values of close to 0% during the CMJ,[23] whereas, the non-injured soccer players in the current study recorded asymmetry values ranging from ~3%-11% dependent upon the variable selected. These data indicate that if pre-determined thresholds are to be used to identify “abnormal” levels of asymmetry, they should be sport, test, variable, and phase-specific.

Our findings have implications for athlete monitoring and decision making as part of the return to play process. While a comprehensive rehabilitation program may have been adhered to, relative to non-injured players, pronounced inter-limb asymmetries appear to persist in both concentric and eccentric vGRF derived kinetic variables. However, when interpreting our findings, some limitations should be considered. Firstly, we have inferred that the between-group differences in inter-limb asymmetries we observed were a consequence of the prior injury and rehabilitation. Yet, the cross-sectional nature of the study means that we cannot rule out the possibility that these players displayed greater asymmetries prior to their injury. There is evidence that inter-limb strength asymmetries are a risk factor for muscle injuries,[36] although CMJ asymmetries and prospective injury have not been investigated. Secondly, due to the sample size subanalysis of the asymmetry profile associated with specific injuries was not possible and we pooled all lower extremity incidence to perform the analysis. Thirdly, our analysis does not allow us to determine whether the inter-limb asymmetries we observed are driven by neural, tendinous, and or muscle cross-sectional area deficits. Finally, considering the differences between the asymmetry profile we observed and those reported in elite athletes in different sports, these findings may also be specific to professional soccer.

Future research should therefore both consider characterizing the asymmetry profile of other athletic populations and determine if deficits in specific variables are related to the anatomical location and type of injury or are global deficits associated with lower extremity injury per se. Nonetheless, the current findings do suggest that assessing inter-limb asymmetries during the bilateral CMJ may provide practitioners with a diagnostic tool that more fully informs decisions for return to play and recommendations for future training.

4.1 Perspectives

The CMJ is routinely used to profile soccer players to monitor athlete readiness following rehabilitation, training, and competition. By comparing the profile of asymmetry in players with and without prior injury in specific variables, we have demonstrated both the magnitude of “normal” asymmetry in professional soccer and specific variables within the CMJ phases that show larger inter-limb differences in those with prior injury. The present study indicates that despite elite soccer players being successfully returned to play with no obvious bilateral jump performance deficits, a range of asymmetries remain. While the mechanisms and consequence of these differences were not measured, it is plausible that the identified imbalances are a compensation strategy to avoid excessive loading of previously injured tissues. Assessment of VGRF asymmetry during the CMJ could therefore be considered a practical and efficient tool to identify residual neuromuscular deficits following previous severe injury. Inter-limb differences also appear to be magnified in variables measured during the eccentric phase, and, those characterized by rapid force production. Rehabilitation programs following severe lower extremity injury may be more effective if training strategies are informed by objective assessment of these deficits and then targeted as part of an individualized approach for return to sport.

ORCID

Luke M. Hart https://orcid.org/0000-0003-4305-7093

Daniel D Cohen https://orcid.org/0000-0002-0899-4623

Stephen D. Patterson https://orcid.org/0000-0003-4667-9939

Paul Read https://orcid.org/0000-0002-1508-8602

REFERENCES

1. Hurley M. The effects of joint damage on muscle function, proprioception and rehabilitation. *Man Ther*. 1997;2(1):11-17.
2. Ekstrand J, Tropp H. The incidence of ankle sprains in soccer. *Foot Ankle*. 1990;11(1):41-44.
3. Dvorak J, Junge A. Football Injuries and physical symptoms. *Am J Sports Med*. 2000;28(5_suppl):S3-S9.
4. Hägglund M, Waldén M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *Br J Sports Med*. 2006;40(9):767-772.
5. Croisier J-L, Ganteaume S, Binet J, Genty M, Ferret J-M. Strength imbalances and prevention of hamstring injury in professional soccer players a prospective study. *Am J Sports Med*. 2008;36(8):1469-1475.
6. Newton RU, Gerber A, Nimphius S, et al. Determination of functional strength imbalance of the lower extremities. *J Strength Cond Res*. 2006;20(4):971-977.
7. Knapik JJ, Bauman CL, Jones BH, Harris JM, Vaughan L. Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *Am J Sports Med*. 1991;19(1):76-81.
8. Read P, Oliver JL, Croix M, Myer GD, Lloyd RS. Injury risk factors in male youth soccer players. *Strength Cond J*. 2015;37(5):1-7.
9. Hopkins JT, Ingersoll CD. Arthrogenic muscle inhibition: a limiting factor in joint rehabilitation. *J Sport Rehabil*. 2000;9(2):135-159.
10. Mognoni P, Narici M, Sirtori M, Lorenzelli F. Isokinetic torques and kicking maximal ball velocity in young soccer players. *J Sports Med Phys Fitness*. 1994;34(4):357-361.
11. Fousekis K, Tsepis E, Vagenas G. Multivariate isokinetic strength asymmetries of the knee and ankle in professional soccer players. *J Sports Med Phys Fitness*. 2010;50(4):465-474.
12. Croisier JL, Reveillon V, Ferret JM, et al. Isokinetic assessment of knee flexors and extensors in professional soccer players. *Isokinet Exerc Sci*. 2003;11(1):61-62.
13. Rahnama N, Lees A, Bambaecichi E. A comparison of muscle strength and flexibility between the preferred and non-preferred leg in English soccer players. *Ergonomics*. 2005;48(11–14):1568-1575.
14. Read PJ, Oliver JL, De Ste CM, Myer GD, Lloyd RS. A prospective investigation to evaluate risk factors for lower extremity in- jury risk in male youth soccer players. *Scand J Med Sci Sports*. 2018;28(3):1244-1251.
15. Impellizzeri FM, Rampinini E, Maffiuletti N, Marcora SM. A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Med Sci Sports Exerc*. 2007;39(11):2044.
16. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower-extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther*. 2000;80(3):251.
17. Bishop C, Turner A, Jarvis P, Chavda S, Read P. Considerations for selecting field-based strength and power fitness tests to measure asymmetries. *J Strength Cond Res*. 2017;31(9):2635-2644.
18. Hamilton AT, Shultz SJ, Schmitz RJ, Perrin DH. Triple-hop distance as a valid predictor of lower limb strength and power. *J Athl Train*. 2008;43(2):141.
19. Fitzgerald GK, Lephart SM, Hwang JH, Wainner M. Hop tests as predictors of dynamic knee stability. *J Orthop Sports Phys Ther*. 2001;31(10):588-597.
20. Petschnig R, Baron R, Albrecht M. The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 1998;28(1):23-31.
21. Read PJ, Oliver JL, Myer GD, De Ste Croix MB, Lloyd RS. The effects of maturation on measures of asymmetry during neuromuscular control tests in elite male youth soccer players. *Pediatr Exerc Sci*. 2018;30(1):168-175.

22. Baumgart C, Schubert M, Hoppe MW, Gokeler A, Freiwald J. Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction? *Knee Surg Sports Traumatol Arthrosc*. 2017;25(5):1385-1394.
23. Jordan M, Aagaard P, Herzog W. Lower limb asymmetry in mechanical muscle function: a comparison between ski racers with and without ACL reconstruction. *Scand J Med Sci Sports*. 2015;25(3):301-309.
24. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med*. 2007;17(4):258-262.
25. Dai B, Butler R, Garrett W, Queen R. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. *Scand J Med Sci Sports*. 2014;24(6):974-981.
26. Cohen D, Clarke N, Harland S, Lewin C. Are force asymmetries measured in jump tests associated with previous injury in professional footballers? *Br J Sports Med*. 2014;48(7):579-580.
27. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med*. 2011;45: 553–558.
28. Association WM. World. Medical association declaration of Helsinki. Ethical principles for medical research involving human subjects. *Nurs Ethics*. 2002;9(1):105.
29. Baumgart C, Hoppe MW, Freiwald J. Phase-specific ground reaction force analyses of bilateral and unilateral jumps in patients with ACL reconstruction. *Orthop J Sports Med*. 2017;5(6):2325967117710912.
30. Bishop C, Read P, Lake J, Chavda S, Turner A. Inter-limb asymmetries: understanding how to calculate differences from bilateral and unilateral tests. *Strength Cond J*. 2018; 40(4): 1–6.
31. Menzel H-J, Chagas MH, Szmuchrowski LA, Araujo SR, de Andrade AG, de Jesus-Moraleida FR. Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. *J Strength Cond Res*. 2013;27(5):1370-1377.
32. Hägglund M, Waldén M, Ekstrand J. Risk factors for lower extremity muscle injury in professional soccer: the UEFA injury study. *Am J Sports Med*. 2013;41(2):327-335.
33. Waldén M, Hägglund M, Ekstrand J. Time-trends and circumstances surrounding ankle injuries in men's professional football: an 11-year follow-up of the UEFA champions league injury study. *Br J Sports Med*. 2013;47(12):748-753.
34. Strandberg S, Lindström M, Wretling M-L, Aspelin P, Shalabi A. Muscle morphometric effect of anterior cruciate ligament injury measured by computed tomography: aspects on using non-injured leg as control. *BMC Musculoskelet Disord*. 2013;14(1):150.
35. Fulton J, Wright K, Kelly M, et al. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther*. 2014;9(5):583.
36. Fousekis K, Tsepis E, Vagenas G. Lower limb strength in professional soccer players: profile, asymmetry, and training age. *J Sports Sci Med*. 2010;9(3):364-373.