Read, Paul J ORCID logoORCID: https://orcid.org/0000-0002-1508-8602, Pedley, Jason S., Eirug, Ifan, Sideris, Vasileios and Oliver, Jon L. (2022) Impaired Stretch-Shortening Cycle Function Persists Despite Improvements in Reactive Strength After Anterior Cruciate Ligament Reconstruction. Journal of Strength and Conditioning Research, 36 (5). pp. 1238-1244. doi:10.1519/JSC.0000000000004208

Impaired Stretch-Shortening Cycle Function Persists Despite Improvements in Reactive Strength After Anterior Cruciate Ligament Reconstruction

Paul J. Read, Jason S. Pedley, Ifan Eirug, Vasileios Sideris, and Jon L. Oliver

Abstract: Impaired stretch-shortening cycle function persists despite improvements in reactive strength following after anterior cruciate ligament reconstruction. J Strength Cond Res 36(5): 1238–1244, 2022—Reactive strength index (RSI) during a single-leg drop jump (SLDJ) has been indicated to determine return-to-sport readiness after anterior cruciate ligament (ACL) reconstruction, but only cross-sectional studies are available. Ground reaction force data and characterization of stretch-shortening cycle (SSC) function also remain sparse. Single-leg drop jump performance, ground reaction force, and SSC function were examined in soccer players with ACL reconstruction (n 5 26) and matched controls (n 5 25). Injured players were tested at 2 time points (32 and 42 weeks post-surgery). Stretch-shortening cycle function was classified as good (no impact peak and spring like), moderate (impact peak but still spring like or no impact peak and not spring like), or poor (impact peak and not spring like). The involved limb displayed lower-jump height, poorer RSI, less spring-like behaviour, earlier peak landing force, and a greater ratio of landing peak to take-off peak force compared with the uninvolved limb and controls at the initial assessment (p, 0.001). Proportionally, more involved limbs were categorized as poor or moderate at the initial assessment (69.2%) and follow-up (50%) in comparison with the control limbs (14%). The reactive strength index was the only variable to change significantly between the initial assessment and follow-up on the involved limb (p, 0.05). No changes in the proportion of ACL reconstructed individuals categorized as poor or moderate SSC function at the follow-up assessment were observed. Residual deficits are present in SLDJ performance, SSC function, and ground reaction force characteristics after ACL reconstruction. The reactive strength index should not be the sole metric, as observed increases did not correspond with changes in SSC function.

Key Words: Anterior Cruciate Ligament; Drop Jump; Rebound

Introduction

Residual deficits in reactive strength and force production have been identified after anterior cruciate ligament (ACL) reconstruction (22,23,30,37,38). The drop jump is a reliable assessment of lower-limb function during a high-force movement (29) and has been studied in a range of cohorts after ACL reconstruction (34,41). It has been suggested that single-leg tasks are more indicative of limb capacity, with bilateral movements providing more options to unload the injured site through a strategy of interlimb compensation (1,8). Furthermore, in comparison with horizontal hops, the single-leg drop jump has been shown to identify greater limb deficits (22,23). This is likely because of the greater requirement for external work at the knee (26), supporting its use as a valid assessment tool to monitor dynamic knee function during rehabilitation.

In the drop jump task, athletes must decelerate their downward motion in an eccentric action until reaching the point of maximum centre of mass displacement and momentary zero velocity. This is followed by an immediate, propulsive reversal of this motion, providing an effective means of determining stretch-shortening cycle

(SSC) function (25). The SSC can not only increase force output in explosive activities but also reduces metabolic cost in submaximal and maximal efforts (4), making it an important neuromuscular quality for efficient locomotion. Previous research has indicated that during rebound tasks, the "spring-like" properties of the lower limb can be modelled, whereby the vertical ground reaction force and centre of mass displacement should display a "U"-shaped parabolic mirror image of each other (3). Observable differences such as a large force peak early in the landing phase of a drop jump and a force-time curve that appears less "spring like" are indicative of reduced SSC function (35). To the best of our knowledge, assessment of spring-like behaviour has not been examined in athletic populations after ACL reconstruction.

Assessment of function and performance monitoring is essential for target-driven programming and reconditioning after injury. During rebound tasks, the reactive strength index (RSI), calculated as the ratio of jump height to ground contact time, has been indicated as a useful performance metric in athletes after ACL reconstruction to determine plyometric ability (22,27,37). However, it is important to consider that athletes can adopt a range of strategies to achieve a given RSI score (18). For example, if performing a rebound test on a previously injured limb, individuals can increase their ground contact time to produce the requisite force and impulse needed for propulsion and compensate for reduced SSC function. Analysing RSI, alongside the recorded jump height and ground contact times, can assist in interpretation of the jump strategy. However, the RSI alone does not provide sufficient evidence to determine mechanical alterations in rebound tasks (42), and the effectiveness of SSC function which is underpinned by a short amortization with rapid transition from eccentric to concentric phases (25). Therefore, in addition to performance metrics, analysis of ground reaction force characteristics may be warranted to effectively assess jump mechanics and SSC function (35). This information can help to determine rehabilitation status and identify residual deficits that can be targeted through training interventions.

Within the literature, functional tests have often been used as part of a "discharge" protocol before return to sport (39). It is advised that clinicians monitor longitudinally during rehabilitation and not just use a single outcome variable from an assessment to determine changes in function over time in the injured vs. uninjured limb, to more accurately characterize the "patient's journey" (11). A number of cross-sectional studies have identified between-limb differences in RSI (22,27,37) and landing mechanics (41) after ACL reconstruction. However, there is a paucity of longitudinal evidence examining the sensitivity to change of drop jump performance outcomes (jump height and RSI) and mechanics indicative of SSC function during rehabilitation.

Therefore, the primary aim of this study was to examine single leg drop jump performance and ground reaction force characteristics to identify whether between-limb deficits (injured vs. non-injured) and between-group differences (ACL reconstruction vs. healthy matched controls) are present in the later stages of rehabilitation. Our secondary aim was to investigate the sensitivity of these metrics to change over time as an indication of restored knee function. Our hypothesis was that differences would be apparent between limbs and groups in both performance and jump mechanics, but longitudinal changes in performance outcomes would not correspond to observable differences in ground reaction force and SSC function.

Methods

Experimental Approach to the Problem

This study used a repeated measures design. After ACL reconstruction, subjects attended at 2 time points during their rehabilitation (32 6 7 and 42 6 11 weeks post-surgery, respectively). Matched controls attended once while taking part in an annual periodic health evaluation. For both groups, the single-leg drop jump formed part of a test battery, including clinical assessment (range of motion, laxity etc.), movement screening (single-leg squat, countermovement jumps, and single-leg drop jump), and isokinetics. The movement screening component was performed after clinical assessment and completion of a standardized warm up consisting of 5 minutes of pulse raising activity on a cycle ergometer and dynamic body weight movements (bilateral and unilateral squats and bilateral and unilateral countermovement jumps). All athletes obtained medical clearance from their treating physiotherapist before commencement. Test order and all procedures, including time of day, were standardized across the 2 time points.

Subjects

Fifty-one male soccer players volunteered to take part in this study and provided written informed consent. All players provided informed consent before participation. Subjects were subdivided as follows: group 1 (players post-ACL reconstruction, n 5 26, age 22.5 6 4.0 years, body mass 71.0 6 11.8 kg, and height 172.8 6 6.6 cm; 6SD) and group 2 (non-injured matched controls, n 5 25, age 25.2 6 4.4 years, body mass 74.7 6 8.5 kg, and height 175.9 6 6.7 cm). The inclusion criteria for group 1 required athletes to be men, having undergone primary surgical reconstruction, and competing as a registered soccer player within one of the recognized competitive leagues of the Qatar Football Association before their injury. Bone-patellar tendon-bone was the most commonly selected autograft type (72 vs. 28% hamstring). Players were excluded if they reported a history of previous ACL injury/surgery that was not associated with the primary surgical reconstruction or other knee ligament or cartilage injury/ surgery of either the operated or non-operated leg. Matched controls were of the same competitive standard, had no history of ACL or other serious knee injury and were free from severe injury (defined as 28 days' time loss) in the previous 12 months. Testing of these players took place during the preseason period. Ethical approval was provided by the Anti-Doping Lab, Qatar (IRB: F2017000227).

Procedures

The single-leg drop jump was performed on a force plate (Force Decks v1.2.6109, Vald Performance, Albion, Australia) recorded at a sampling rate of 1,000 Hz. Athletes began in a unilateral stance on their designated test leg and stepped directly off a 15-cm box, landing on the same leg. This box height was selected after pilot testing, ensuring safety of execution on the involved limb, to ensure contact times remained characteristic of those required for rebound jumps. Instructions were to minimize ground contact time and jump as high as possible, specifically, "jump fast and high." The hands were fixed on the hips throughout the test, and bending of the leg while airborne was not permitted. After 3 practice trials on each limb, 3 further jumps were performed. The trial that recorded the highest reactive strength index was reported and used to conduct the force-time analysis. The limb order was randomized. For the control subjects, both limbs were analysed (n 5 50).

Ground reaction force data were smoothed using a fourth-order recursive low-pass Butter worth filter with a cut off of 30Hz built into a customized Microsoft Excel (v16.0) spreadsheet. A fourth-order recursive low-pass Butter worth filter with a cut off of 30 Hz was used to ensure that the net phase shift in the signal was zero. The low-pass filter ensured the lower-frequency signal passed through unattenuated, although attenuating the higher-frequency noise in the signal to avoid overestimating force values, particularly the force peaks of interest (44). The force-time record was numerically integrated to calculate vertical impulse. Impulse momentum theory was then used to determine take-off velocity, which was subsequently used to derive jump height (displacement = final velocity^2 - initialvelocity^2/2 * acceleration). Ground contact time was defined as the time interval between when the vertical ground reaction force first exceeded 5 times the SD of the empty force plate (noise) until the instant of take off when vertical force dropped below 5 standard deviations of the unloaded force plate (32). The reactive strength index (RSI) was quantified using the equation jump height (m)/ground contact time (s) consistent with other studies that examined single-leg drop jump performance after ACL reconstruction (22–24), allowing valid comparisons as RSI, and the reactive strength ratio should not be used interchangeably (18). The velocity-time record was obtained by dividing the resultant force-time record by the individuals' body mass to provide acceleration and then numerically integrating about time using the trapezoid rule. The velocity-time record was numerically integrated to compute the displacement time record. The ground contact period was subdivided into landing and take-off phases separated by the timing of the peak centre of mass displacement. Peak landing force and take-off force peak were defined as the highest transient, visible force peak during the landing and take-off phases, respectively, with the ratio of these also recorded.

Stretch-Shortening Cycle Categorization. Two objective criteria were used to determine SSC classification: (a) the presence of an impact peak in their force-time profile (defined as the highest transient, visible force peak occur during the first 20% of ground contact) (35) and (b) whether they displayed spring-like behaviour (defined as a Pearson product-moment correlation between vertical ground reaction force and vertical centre of mass displacement during the entire contact phase with a threshold of ,20.80) (33). Subjects were classified as good (no impact peak and spring like), moderate (impact peak but still spring like or no impact peak and not spring like), or poor (impact peak and not spring like) in accordance with previous research (35).

Statistical Analyses

To examine the primary purpose of this study, 1-way analysis of variance (ANOVA) was conducted to determine differences in single leg drop jump ground reaction force variables between uninvolved and involved limbs of patients with ACL reconstruction and uninjured controls at the initial assessment. The level of significance was set at an alpha level of p # 0.05. Homogeneity of variance was assessed using Levene's test, and violated Welch's adjustment was used to calculate the F-ratio. Bonferroni's post hoc test was used to determine pairwise differences when equal variance was assumed. In the event of a significant Levene's outcome, Games-Howell post hoc tests were used to identify pairwise differences. Cohen's d effect sizes were calculated using a pooled SD to determine the magnitude of between-group differences (8). Paired samples t tests were computed to determine within limb changes between the initial assessment and follow-up in athletes with a history of ACL reconstruction. Effect sizes were categorized as trivial ,0.2, 0.20–0.59 small, 0.60–0.1.19 moderate, 1.20–1.99 large, 2.00–3.99 very large, and .4.0 extremely large (21). Chi-squared (x^2) analyses were used to investigate the interactions between limb, SSC function category, SSC category agreement between limbs, and timing of assessment post-surgery. In the chi-squared test, analysis of the adjusted standardized residuals was completed to identify frequencies that were .1.96 z-scores (p # 0.05) different from the whole group distribution. Adjusted residuals were converted into chi-squared values and subsequently into p values. The Bonferroni correction was used to produce an adjusted alpha level of p , 0.006 to reduce the potential for a type I error as a result of multiple comparisons. All t tests, ANOVA, and post hoc analyses were processed using SPSS (v24.0.0.2., Chicago, IL), whereas chi-squared and effect sizes were computed using Microsoft Excel.

Results

The involved limb displayed lower-jump height (F (2, 99) 5 24.663, p , 0.001), poorer reactive strength index (F (2, 99) 5 63.034, p , 0.001), less spring-like behaviour (F (2, 99) 5 28.373, p , 0.001), earlier peak landing force (F (2, 99) 5 13.875, p , 0.001), and a greater ratio of landing peak to take-off peak force (F (2, 99) 5 25.170, p , 0.001) in comparison with the uninvolved limb and control limbs at the initial assessment (Table 1). The magnitude of these effects ranged from moderate to large. The involved limbs displayed a significant moderate reduction in the centre of mass displacement (F (2, 99) 5 7.794, p 5 0.001) in comparison with the uninvolved limb, but there was no difference with the control limbs. There was a large effect for the involved limbs having significantly longer ground contact times than control limbs, but this was not significantly different to uninvolved limbs (F (2, 99) 5 33.525, p 5 0.001). The uninvolved limb displayed significantly longer ground contact times, poorer reactive strength index, reduced peak landing force (F (2, 99) 5 20.138, p, 0.001), and greater centre of mass displacement (F (2, 99) 5 7.794, p 5 0.001) in comparison with control limbs at the initial assessment, and these effects were all moderate in magnitude.

The reactive strength index was the only variable showing a significant change between the initial assessment (0.34 6 0.08) and follow-up (0.37 6 0.08) for the involved limb (t (25) 52 2.062, p, 0.05), and this effect was moderate in magnitude. There were no significant improvements in kinetic variables at the follow-up assessment (Table 2).

Example force-time curves to display each category of SSC function (poor, moderate, and good) are displayed in Figure1.When analysing the control limbs, 86.0% (n 5 43) of limbs were categorized as having good SSC function, 14.0% (n 5 7) as moderate, whereas 0% were categorized as poor (Figure 2). Owing to the expected count of poor SSC function being zero, chi-squared analysis could not be performed on 3 categories of SSC function. Therefore, for statistical analysis, frequency count of poor and moderate was

combined to produce 2 categories of function. Chi-squared analysis revealed a significant relationship between SSC function and leg assessment for the involved limb (x^2 (1) 5 93.860, p, 0.001). Proportionally, fewer involved limbs at the initial assessment (30.8%) and follow-up (50%) displayed good SSC function in comparison with the control limbs (p, 0.001). Proportionally, more involved limbs were categorized as poor or moderate at the initial assessment (69.2%) and follow-up (50%) in comparison with the control limbs (14%). No significant differences in the proportion of poor or moderate and good SSC function were observed between the uninvolved limb of injured subjects and control limbs at either assessment (p. 0.006).

The proportion of injured subjects (initial assessment and follow up) and controls displaying agreement between the limbs is shown in Figure 3. A significant relationship between group and agreement in SSC function between the limbs was observed (x^2(1)5156.000, p, 0.001). A significantly lower proportion of injured subjects displayed SSC function agreement between the limbs at both the initial assessment (46.2%) and follow-up (46.2%) in comparison with control subjects (92.3%) (p, 0.006). Furthermore, a significantly greater proportion of the injured subjects displayed differing SSC function between the limbs (53.8%) in comparison with control subjects (7.7%) (p, 0.006).

Discussion

The aims of this study were to (a) examine single-leg drop jump performance and ground reaction force characteristics in soccer players during the later stages of rehabilitation after ACL reconstruction and (b) investigate the sensitivity of these metrics to change over time as an indication of restored knee function. The results showed that all performance metrics were reduced, and most ground reaction force characteristics differed between the limbs, resulting in altered SSC function. Specifically, the involved limb was less spring like, displayed peak landing force in the earlier stages of ground contact, and exhibited a greater ratio of landing to peak take-off force compared with the non-injured limb. The magnitude of these differences increased when compared with healthy matched controls. Similarly, a greater proportion of ACL reconstructed athletes were characterized as having poor or moderate SSC function when performing the drop jump on their involved limb compared with the uninvolved limb and control subjects. The reactive strength index was the only variable to change significantly between the initial assessment and follow-up for the involved limb. The results of this study indicate that residual deficits are present in single-leg drop jump performance and ground reaction force characteristics after ACL reconstruction. In addition, clinicians should exercise caution in the sole use of RSI to determine readiness to return to sport, as observed increases did not correspond with SSC function.

Table 1

Single-leg drop jump variables for ACL reconstruction lower limbs and uninvolved limbs of injured subjects and controls at the initial assessment.*

	Mean ± *SD*			Effect size (±95% CI)		
	Involved	Uninvolved	Control	Involved-uninvolved	Uninvolved-control	Involved-control
Jump height (m)	0.13 ± 0.03	0.16 ± 0.02	0.17 ± 0.02	−0.94** (−1.51 to −0.37)	−0.46 (−1.12 to 0.20)	−1.40** (−1.92 to −0.88)
Ground contact time (s)	0.40 ± 0.06	0.37 ± 0.07	0.31 ± 0.03	0.49 (−0.06 to 1.04)	0.97** (0.29 to 1.65)	1.46** (0.93 to 1.99)
Reactive strength index	0.34 ± 0.08	0.44 ± 0.08	0.57 ± 0.10	−0.80** (−1.36 to −0.24)	−0.98** (−1.66 to −0.30)	−1.78** (−2.33 to −1.23)
Spring-like correlation	−0.86 ± 0.08	−0.93 ± 0.05	−0.96 ± 0.04	1.07** (0.49 to 1.65)	0.40 (−0.26 to 1.06)	1.46** (0.93 to 1.99)
Peak landing force (BW)	2.79 ± 0.31	2.84 ± 0.46	3.38 ± 0.50	−0.08 (−0.62 to 0.46)	−1.03** (−1.72 to −0.34)	−1.11** (−1.62 to −0.60)
Peak landing force time (%)	18.89 ± 8.17	29.65 ± 11.12	31.93 ± 11.01	−0.92** (−1.49 to −0.35)	−0.20 (−0.86 to 0.46)	−1.12** (−1.63 to −0.61)
Center of Mass displacement (m)	−0.17 ± 0.03	−0.20 ± 0.04	−0.17 ± 0.02	0.80* (0.24 to 1.36)	−0.86* (−1.54 to −0.18)	−0.06 (−0.53 to 0.41)
Landing: take-off peak ratio	1.20 ± 0.14	1.05 ± 0.09	1.02 ± 0.09	1.17** (0.58 to 1.76)	0.21 (−0.45 to 0.87)	1.38** (0.86–1.90)

*CI = Confidence Interval.

Our cross-sectional findings are in accordance with previous research indicating differences in drop jump performance and ground reaction force characteristics between the limbs after ACL reconstruction (22,23,41). A reduction in plyometric performance measured during a drop jump is associated with an increased risk of injury after ACL reconstruction (24). Our research, combined with that of others (22–24,27,37,38,41), provides further support of the importance of integrating biomechanics and, specifically, the single-leg drop jump into return to-sport assessment (22,23). There is also a need for a greater focus on periodization of physical capacity development and neuromuscular training, ensuring a foundation of strength and eccentric control has been developed before feed-forward and feed-back control mechanisms induced through plyometrics to optimize the later stages of rehabilitation (5).

The magnitude of the observed differences was increased when comparing both performance and ground reaction force characteristics on the involved limb to healthy matched controls, corresponding to large effect sizes. Our data suggest that although reductions on the involved vs. uninvolved limb were still observed, performance and function on the non-reconstructed limb was also affected. It could be speculated that subjects were working submaximally as a means of protecting the contralateral limb. The catastrophic nature of the injury and the subsequent extended absence from high-performance training and competition could also have resulted in changes in quadriceps activation on the uninvolved limb (46), but this requires further investigation. Our findings also support the notion that only using the uninvolved limb as a reference is not a valid indicator of function and return-to-sport readiness because it can overestimate performance when compared with controls and preoperative values (43,45) for up to 24 months post-surgery (7). Thus, practitioners are encouraged to collect routine “non-injured” baseline and/or preoperative data where possible. Normative values from similar populations can also be used, and further research is encouraged to help guide this process.

Previous research has revealed alterations in force production and attenuation in jumping tasks for up to 2 years after ACL reconstruction (12,34). Residual deficits in drop jump performance and ground reaction force characteristics on the involved limb may be due to reductions in quadriceps strength, which acts as a key decelerator and shock absorber during landing. Previous research in athletic populations after ACL reconstruction has shown significant relationships between knee extensor strength and vertical jump performance (31). Similarly, the knee extension rate of torque development has explained over half of the variance in rebound hop performance (2). In the drop jump, individuals’ post-ACL reconstruction with weaker quadriceps strength display altered ground reaction forces (41). Conversely, subjects who exhibited more symmetrical quadriceps strength post-ACL reconstruction, recorded

Table 2

Changes in single-leg drop jump variables from the initial assessment to follow-up in involved and uninvolved limbs of patients with ACL reconstruction.*

	Involved			Uninvolved		
	Initial assessment	Follow-up	Effect size (±95% CI)	Initial assessment	Follow-up	Effect size (±95% CI)
Jump height (m)	0.13 ± 0.03	0.14 ± 0.02	0.28 (−0.27 to 0.83)	0.16 ± 0.02	0.16 ± 0.03	0.23 (−0.32 to 0.78)
Ground contact time (s)	0.40 ± 0.06	0.38 ± 0.06	−0.38 (−0.93 to 0.17)	0.37 ± 0.07	0.36 ± 0.07	−0.06 (−0.60 to 0.48)
Reactive strength index	0.34 ± 0.08	0.37 ± 0.08	0.49* (−0.06 to 1.04)	0.44 ± 0.08	0.46 ± 0.10	0.28 (-0.27 to 0.83)
Spring-like correlation	−0.86 ± 0.08	−0.89 ± 0.06	0.45 (−0.10 to 1.00)	−0.93 ± 0.05	−0.92 ± 0.07	−0.01 (−0.55 to 0.53)
Peak landing force (BW)	2.79 ± 0.31	2.89 ± 0.40	0.27 (−0.28 to 0.82)	2.84 ± 0.46	2.91 ± 0.44	0.17 (−0.37 to 0.71)
Peak landing force time (%)	18.89 ± 8.17	19.70 ± 5.08	0.12 (−0.42 to 0.66)	29.65 ± 11.12	29.00 ± 13.00	−0.05 (−0.59 to 0.49)
Center of Mass displacement (m)	−0.17 ± 0.03	−0.17 ± 0.03	−0.08 (−0.62 to 0.46)	−0.20 ± 0.04	−0.20 ± 0.04	−0.05 (−0.59 to 0.49)
Landing: take-off peak ratio	1.20 ± 0.14	1.15 ± 0.10	−0.38 (−0.93 to 0.17)	1.05 ± 0.09	1.06 ± 0.10	−0.01 (−0.55 to 0.53)

*CI = Confidence Interval.

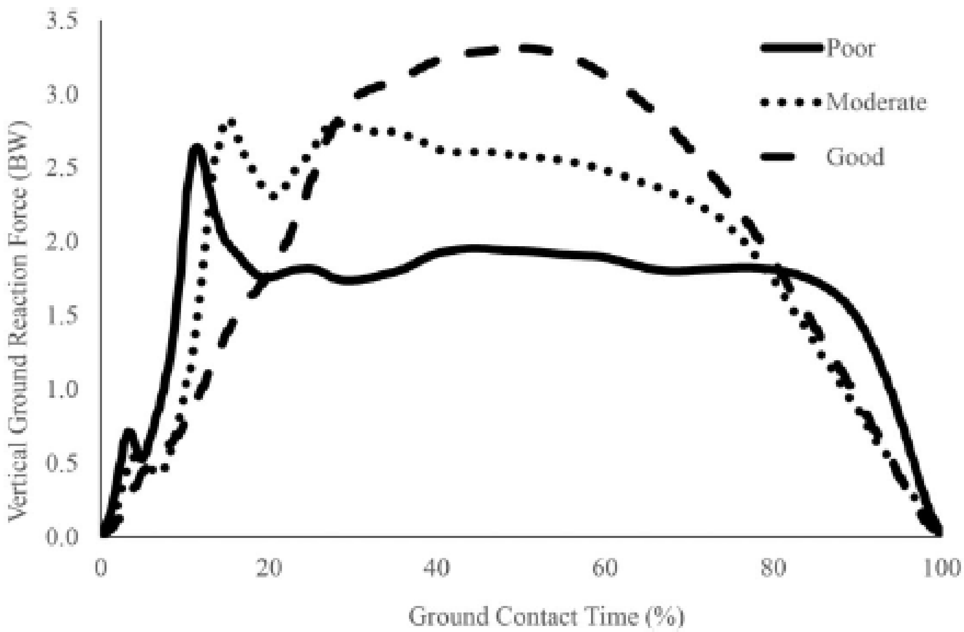

Figure 1. Force-time curves displaying categorization of poor, moderate, and good stretch-shortening cycle function.

ground reaction force characteristics during landing that were similar to uninjured controls (41). Quadriceps strength symmetry has also been shown to reduce the risk of secondary injury after ACL reconstruction (16). Thus, practitioners are encouraged to monitor and include targeted exercise prescription to reduce these deficits as a primary focus during rehabilitation.

Alterations in muscle activity may also have contributed to between-limb and group differences. Feed-forward mechanisms of neuromuscular control including pre-activation assist in optimizing SSC function by reducing the occurrence of an impact peak and increasing the storage of elastic energy during the amortization phase (15). In our study, the drop jump task may have been too demanding on the involved limb, which can alter muscular activation patterns (36). Neuromuscular inhibition serves as a protective strategy to prevent injury (40). Quadriceps concentric muscle activity has also been shown to reduce in more demanding rebound tasks (16). However, further research is required to examine muscular activation strategies in ACL reconstructed athletes during commonly used screening tests such as the single-leg drop jump to more clearly elucidate the observed differences in performance and ground reaction force characteristics this current study.

Recent research in athletes after ACL reconstruction has suggested the importance of analysing the entire force-time curve to examine different phases of ground contact (22). Previous association has been shown between elevated ground reaction forces and increased risk of ACL injury, particularly in the early phase of jump landings (20,28). Larger ground reaction forces are also associated with increased drop jump performance (35), and this was further evident in our study with greater peak landing forces displayed by the control group who also jumped higher and recorded superior RSI scores. However, the timings of the observed force peaks warrant consideration (35). Our results showed a higher landing take-off peak force ratio and lower % of stance time where peak landing force occurred on the involved vs. uninvolved limb and compared healthy controls indicating an impact peak. A greater proportion of the uninvolved limbs and non-injured athletes also recorded good SSC function, which is represented by the vertical ground reaction force and centre of mass displacement displaying a “U”-shaped parabolic mirror image of each other and peak force occurring around midstance (Figure 1). Therefore, we recommend that peak ground reaction force should not be used as the sole metric to measure landing mechanics during drop jumps. Practitioners should consider when the force peak occurs and analyse the overall force-time profile to provide a clearer indication of “optimal” ground reaction force characteristics and SSC function.

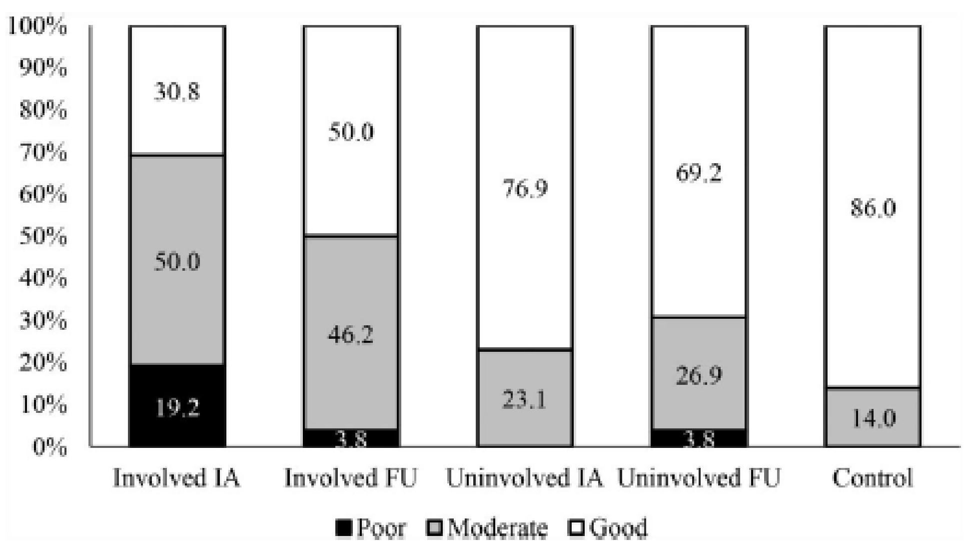

Figure 2. SSC category for involved, uninvolved (at the initial assessment and follow-up), and control limbs. Involved limb initial assessment: 19.2 POOR; 50 MODERATE; 30.8 GOOD; Controls: 14 MODERATE; 86 GOOD. IA = initial assessment; FU = follow-up assessment; SSC = stretch-shortening cycle.

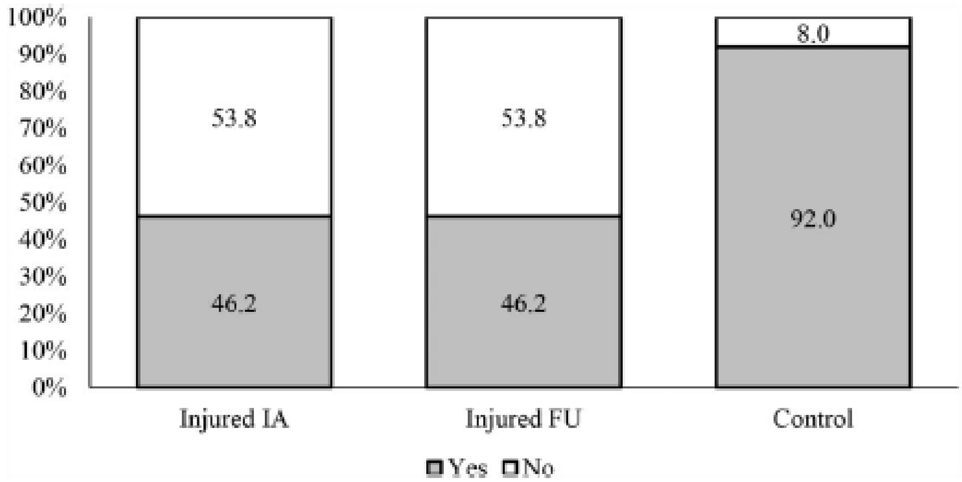

Figure 3. Proportion of injured subjects (at the initial assessment and follow-up) and controls displaying agreement in SSC classification between limbs. Controls: 92 Yes; 8 No. IA = initial assessment; FU = follow-up assessment; SSC = stretch-shortening cycle.

This study conducted the follow-up assessments to determine longitudinal changes in drop jump performance and SSC function during rehabilitation after ACL reconstruction (42 6 11 weeks post-surgery). The results showed that although a trend was evident of improved single-leg drop jump performance and ground reaction force characteristics, RSI was the only variable to change significantly on the involved limb across the 2 time points. The reactive strength index has previously been used as a method of determining plyometric capabilities in athletic cohorts after ACL reconstruction, with significant between-limb and group (compared with healthy controls) differences (22,37). However, alterations in outcome variables, including RSI, may not be reflective of changes in drop jump ground reaction force characteristics (42) and are unaffected by whether individuals possess spring-like characteristics (35). Our results are in agreement with these findings, and this was further evidenced by no significant changes in the proportion of ACL reconstructed individuals categorized as having poor or moderate SSC function at the follow-up assessment. This may be due to lower-strength capacity (41) and reductions in muscle pre-activation (15). A range of strategies can be adopted to achieve a given RSI score (18), indicating the need to examine the constituent parts of any ratio metric and the benefits of including kinetic analysis in addition to performance outcomes (jump height, RSI etc.,) to identify residual deficits in force attenuation and reutilization capacities after ACL reconstruction. Assessment of ground reaction force variables may also be considered as an important component of return-to-play criteria, but this requires further investigation.

Practical Applications

The results of our study indicate that performance metrics, including jump height and RSI, are reduced on the injured limb during a single-leg drop jump task. Ground reaction force characteristics also showed a profile in which the reconstructed limb was less spring-like, displayed peak landing force in the earlier stages of ground contact, and exhibited a greater ratio of landing to peak take-off force. The magnitude of these differences was increased when compared with healthy matched controls, suggesting a reduction in performance and function on the non-reconstructed limb, further highlighting limitations in using the non-involved limb for the purpose of benchmarking to determine return-to-sport readiness as it can overestimate performance. The observed residual deficits indicate incomplete restoration of knee function which may be due to a reduction in quadriceps strength, alterations in muscle activity, and a long duration of absence from high-performance training and competition. Further research is required to more clearly elucidate the underpinning mechanisms and investigate whether these differences are associated with an increased risk of reinjury.

Longitudinal analysis showed that RSI was the only variable to change significantly on the involved limb across the 2 measured time points, but improvements in the RSI score were not reflective of changes in drop jump ground reaction force characteristics and SSC function. Thus, RSI should not be the only metric recorded, and assessment of ground reaction force variables could be considered as an important component of future return-to-play criteria, providing a more comprehensive evaluation of readiness to reperform. These data suggest that targeted exercise prescription is necessary to restore SSC function after ACL reconstruction. An effective method to increase this physical quality is plyometric training (6,19). Plyometric training is used sparingly during ACL rehabilitation (13), which may be in part due to fear of high intensity loading. Evidence indicates that both low-intensity and high-intensity plyometric exercise can induce positive changes in knee function and psychological status after ACL reconstruction (6). Thus, lower-intensity rebound activities characterized by less eccentric loading can confidently be introduced earlier into rehabilitation programs to provide an appropriate stimulus and develop neuro muscular mechanisms that may be inhibited during more demanding tasks (36). A progressive sequence may initially involve tasks, which focus on force attenuation over a larger displacement, before moving on to the hopping protocols adopting spring-like behaviour (but with a compliant spring, using large displacement). Stiffer spring-like tasks can then be introduced, and increases in eccentric loading (e.g., greater drop heights and emphasis in shorter ground contact times) can then be incrementally applied in the later stages of rehabilitation. A large emphasis on resistance training and dynamic stabilization is also encouraged. Residual strength deficits in strength are common after ACL reconstruction (31,41), and this physical capacity provides the foundation for SSC function and should be prioritized in the earlier stages of rehabilitation, with plyometric ability shown to improve after a period of resistance training (10).

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