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Single leg drop jump is affected by physical capacities in male soccer players following ACL reconstruction

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ABSTRACT

Single leg drop jump (SLDJ) assessment is commonly used during the later stages of rehabilitation to identify residual deficits in reactive strength but the effects of physical capacity on kinetic and kinematic variables in male soccer players following ACL reconstruction remain unknown. Isokinetic knee extension strength, kinematics from an inertial measurement unit 3D system and SLDJ performance variables and mechanics derived from a force plate were measured in 64 professional soccer players (24.7 ± 3.4 years) prior to return to sport (RTS). SLDJ between-limb differences was measured (part 1) and players were divided into tertiles based on isokinetic knee extension strength (weak, moderate and strong) and reactive strength index (RSI) (low, medium and high) (part 2). Moderate to large significant differences between the ACL reconstructed and uninjured limb in SLDJ performance (d = 0.92–1.05), kinetic (d = 0.62–0.71) and kinematic variables (d = 0.56) were evident. Stronger athletes jumped higher (p = 0.002; d = 0.85), produced greater concentric (p = 0.001; d = 0.85) and eccentric power (p = 0.002; d = 0.84). Similar findings were present for RSI, but the effects were larger (d = 1.52–3.84). Weaker players, and in particular those who had lower RSI, displayed landing mechanics indicative of a 'stiff' knee movement strategy. SLDJ performance, kinetic and kinematic differences were identified between-limbs in soccer players at the end of their rehabilitation following ACL reconstruction. Players with lower knee extension strength and RSI displayed reduced performance and kinetic strategies associated with increased injury risk.

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ACL recontruction; drop jump; soccer

Introduction

Residual deficits in strength and power qualities have been identified in multidirectional field sport athletes in the later stages of rehabilitation and at the point of return to sport (RTS) following anterior cruciate ligament (ACL) reconstruction (King et al. 2018, 2021b; Lloyd et al. 2020; Read et al. 2020, 2020; Maestroni et al. 2021). The ability to rapidly transition from eccentric to concentric muscle actions is commonly assessed using the reactive strength index (RSI) in rebound tasks (Flanagan and Comyns 2008). RSI has been used to determine plyometric capabilities in athletic cohorts after ACL reconstruction, with significant between-limb and group (compared with healthy controls) differences (King et al. 2018; Lloyd et al. 2020; Read et al. 2020, 2022; Kotsifaki et al. 2022), and associations with increased risk of ipsilateral re-injury and contralateral ACL injury (King et al. 2021a, 2021b). Recent findings (Read et al. 2022) also showed that, from mid to late stage of rehabilitation, a trend was evident of improved single-leg drop jump (SLDJ) performance (RSI) and ground reaction force characteristics. However, RSI was the only variable to change significantly on the involved limb across the two time points. Therefore, changes in RSI may not be reflective of alterations in ground reaction force characteristics (Read et al. 2022), and are unaffected by whether individuals possess spring-like characteristics (Pedley et al. 2020). Maladaptive functioning of the above dampening mechanisms has been demonstrated following ACL reconstruction (Read et al. 2022). This can impair force attenuation in the short timeframes required, exposing athletes to large impact forces during fast sporting actions such as jumping, landing, and change of direction, which are commonly associated with high peak ACL strain (Fox 2018; Dos'Santos et al. 2019).

Recent evidence has examined performance and kinetic variables during the SLDJ in athletic cohorts following ACL reconstruction (King et al. 2018; Birchmeier et al. 2019; Crotty et al. 2022; Read et al. 2022). Less data is available to describe SLDJ kinematics. Current findings (King et al. 2018; Kotsifaki et al. 2022) indicate that during the stance and propulsion phase, the ACL reconstructed limb displays greater hip and trunk flexion angles, but reduced knee flexion angles in comparison to the uninvolved limb. These studies used three-dimensional motion capture (Marshall et al. 2014; King et al. 2018), which is considered the gold standard for assessing athletes' movement quality but is expensive, requires technical expertise and large periods of time for data collection.

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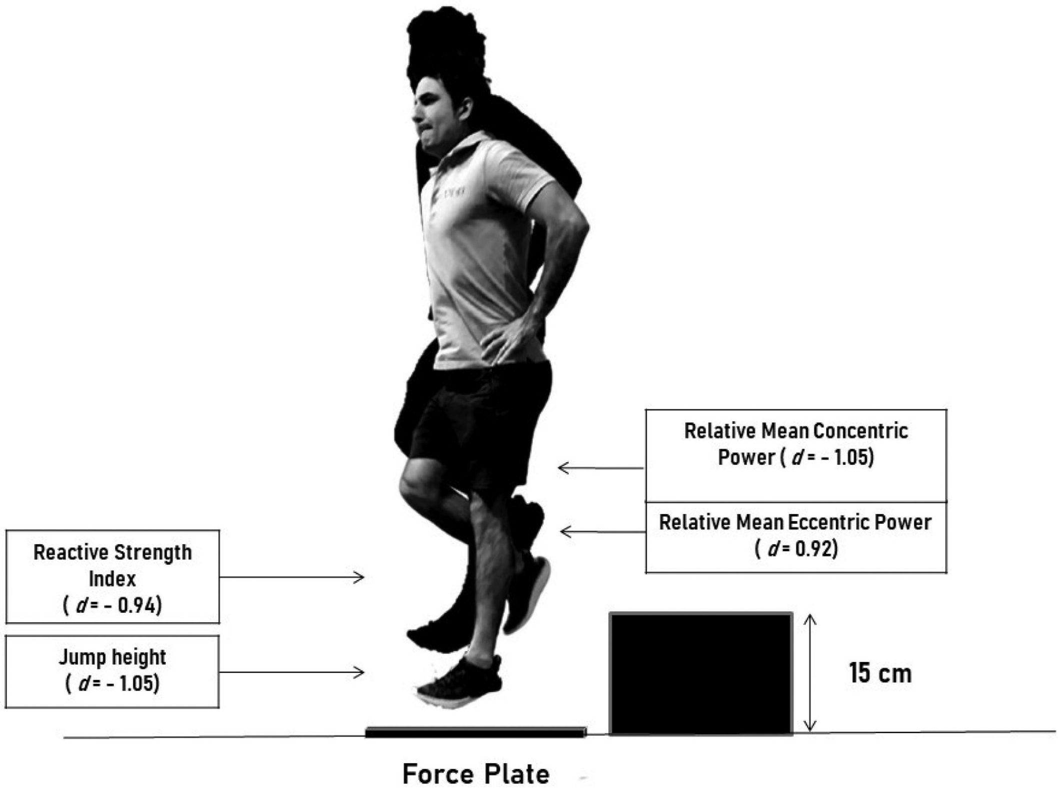

Figure 1. Single leg drop jump performance variables of the ACL reconstructed limb (grey) in comparison with the uninvolved limb (black).

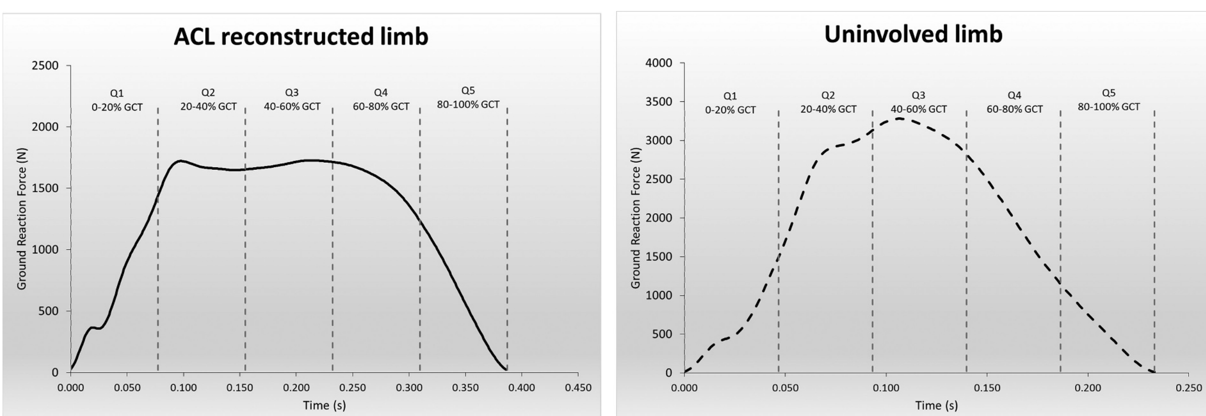

Figure 2. Example of a single leg drop jump force-time curve of the ACL reconstructed and uninvolved limb.

Wearable technology has been recently proposed as a more clinically viable alternative (Marques et al. 2022). Sensors can easily be attached to specific anatomical locations, and preliminary data suggests they can be used to identify between-limb kinetic and kinematic differences following ACL reconstruction (Marques et al. 2022). There is an absence of research to examine movement tasks associated with prospective injury risk measured using wearable technology, and no data in adult male multidirectional field sports athletes.

To enhance our knowledge of factors that underpin performance and movement strategy used during RTS tests, a clear understanding of the influence of physical capacities on SLDJ mechanics is warranted. A recent study including male multidirectional field sports athletes at the time of RTS following ACL reconstruction indicated that knee extension strength explained a third of the variance in SLDJ RSI ($R^2 = 33\%$, $p < 0.001$) (Crotty et al. 2022). However, ground reaction force and kinematic variables were not examined. Birchmeier et al (Birchmeier et al. 2019). reported that RSI measured during a SLDJ, peak knee extension torque, and rate of torque development explained two thirds of the variance in triple hop distance ($R^2 = 61.8\%$, $p < 0.001$) in male and female athletes. SLDJ ground reaction force characteristics and kinematics were not measured, no associations between knee extension strength and SLDJ mechanics were examined, and the relationship between RSI and performance was assessed in the triple hop only. Considering that quadriceps strength plays a key role in attenuating force during the deceleration phase of ground

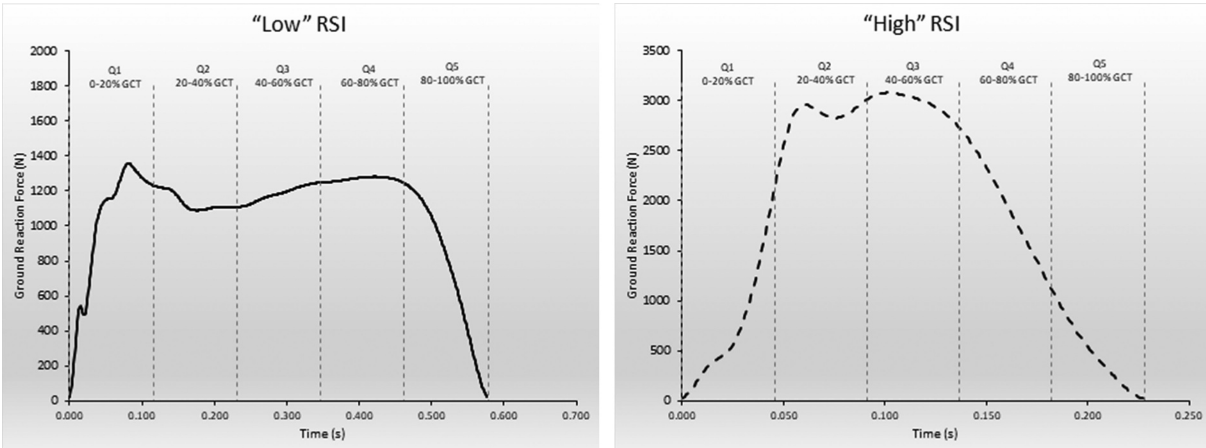

Figure 3. Example of a single leg drop jump force-time curve of a player displaying 'low' and 'high' RSI.

contact (Ward et al. 2018; He et al. 2022), more data are required to examine if there are differences in SLDJ kinetics and kinematics depending on a soccer players level of physical capacity including knee extension strength and RSI.

This study aimed to 1) investigate performance, kinetic and kinematic differences between the ACL reconstructed and the uninvolved limbs using practically viable methods which do not require a biomechanics laboratory enhancing utility in the field; and 2) examine if there are differences in SLDJ performance and mechanics in soccer players with heightened isokinetic knee extension and reactive strength.

Materials and methods

Participants

Sixty-four male soccer players participating in the Qatar Stars and Qatar Gas Leagues (22.6 ± 3.7 years; 174 ± 7.0 cm; 70 ± 10.2 kg) at an average of 8.3 (±1.9) months post ACL reconstruction (bone-patella-tendon bone (78%), with the remaining players (22%) all semitendinosus and gracilis hamstring tendon grafts), volunteered to take part in this study. Players competing at a registered club in Qatar are provided the opportunity to undergo surgery and rehabilitation at the specialist Orthopaedic and Sports Medicine centre which was the designated research site for the study. Inclusion criteria required players to have no history of previous ACL injury/surgery, or other knee ligament or cartilage injury/surgery of either the operated or non-operated leg. Players were excluded if they reported previous ACL injury/surgery or other knee ligament or cartilage injury/surgery of the operated or nonoperated leg.

All participants were involved in an intensive rehabilitation programme (5 days per week) (Kyritsis et al. 2016) at the same Orthopedic and Sports Medicine Hospital by a specialist team of sports physiotherapists who only treat ACL-injured patients. Three surgeons were involved in the study, and they were selected due to their appointment as resident orthopaedic surgeons who specialise in ACL reconstruction surgery.

Immediately after surgery, players were advised to weight bear as tolerated and no brace was used. Rehabilitation was divided into early, intermediate, and advanced phases. The focus of the early phase was on controlling swelling, restoring range of motion and activation of the knee extensor and flexor muscles. The goal of the intermediate and advanced phases was to optimise muscle strength, proprioception, and neuromuscular control, and complete a phased running progression program. On completion of these phases, players took part in an on-field sports specific training and conditioning block. Routine testing and monitoring were completed during rehabilitation by an independent assessment unit to remove the potential for clinician bias. Jump monitoring commenced ~5 months post-surgery, following clearance from the treating physiotherapist.

Informed written consent was obtained prior to participation. This study was approved by the Institutional Review Board (IRB: F2017000227) and Research Ethics Committee (REC: 14326).

Experimental design

To address our stated aims, we separated our cross-sectional study into two components. ***In part 1,*** we compared SLDJ performance, kinetic and kinematic variables between the ACL reconstructed and uninjured limb. In ***part 2***, we examined the effect of isokinetic strength of the quadriceps and reactive strength on drop jump mechanics. For this analysis, both limbs were analysed providing the following sample size ($n = 128$ kinetic and $n = 66$ kinematic). There were fewer kinematic data available as the measurement system was introduced at a later date following the onset of data collection for this study.

All participants were familiar with the test procedures, and we included a standardised warm-up. Each player completed 5 minutes of pulse raising activity (stationary cycling performed at 60% of maximum perceived effort) followed by ten body weight squats (bilateral and unilateral), lunges and step ups. This was supervised by a member of the research team. Countermovement jumps were then completed at 50, 75 and 90% of perceived maximum, prior to the single leg drop jumps. Isokinetic assessments were completed ~ 5 minutes after the completion of the SLDJ assessment, allowing time for participant set up and practice trials. The assessment was conducted under the supervision of an experienced investigator (>5 years using the stated test methodology).

Procedures

Isokinetic knee extension strength

Maximal quadriceps knee extension peak torque (Quad PT Rel) relative to body mass (N.m.kg^{-1}) was measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, New York, USA). Players were in a seated position with the hip flexed to 90°. The rotational axis of the dynamometer was aligned to the lateral femoral epicondyle, and the lower leg was attached to the dynamometer lever arm just above the medial malleolus. Procedures were explained to participants following which they completed three practice repetitions. Testing then commenced after 60s. Five repetitions of concentric knee extension were performed at 60°·s^{-1} with the highest peak torque value recorded (Undheim et al. 2015). Limb order was randomized. Standardized, vigorous verbal encouragement was provided throughout.

Single leg drop vertical jump

Athletes began in a unilateral stance and then stepped directly off a 15-cm box, landing with the same leg on a force plate (ForceDecks v1.2.6109, Vald Performance, Albion, Australia). Following ground contact, a vertical rebound jump was immediately performed. Instructions were to minimize the time spent on the ground and jump as high as possible. Hands remained on hips throughout the test. Bending of the test leg whilst airborne was not permitted. Three practice attempts were performed on each limb followed by a 60 s rest period. Players then completed three recorded trials with 30s of rest between each. The limb order was randomized. Except for jump height and RSI in which the best score was retained, mean scores were used for the analysis.

Ground reaction force data were sampled at 1000 Hz and smoothed using a fourth order recursive low-pass Butterworth filter with a cut off of 30 Hz built into a customized Microsoft Excel® (v16.0) spreadsheet. The description and method of calculation used for each variable included in this study are summarised in Table 1.

To measure kinematics, inertial measurement unit (IMU) sensors (Noraxon myoMOTION™ System, Scottsdale, USA) sampling at a rate of 200 Hz were placed according to the rigid body model used in the Noraxon MR3 software (Noraxon myoMOTION™ System, Scottsdale, USA). Sensor placement locations included the pelvis (body are of the sacrum), and bilaterally on the lateral thighs (distal half where there is a lower amount of muscle development), shanks (front and slightly medial along the tibia) and mid-foot in accordance with the manufacturer guidelines. With use of the pelvic sensor, any distal sensor can be mounted to any position of the selected segment. Using this mode, the distance of a given sensor to the joint center does not influence the angular calculations, but the contralateral sensors should be placed at equal distance from the joint center. The X-coordinate on the sensor label displayed a superior orientation (showing up to the sky/ceiling), except for the foot sensors, where the X-coordinate was pointing distally (toward the toes). Velcro straps and tape were used to fix the sensors. The upright position was used to carry out the calibration of the model using the neutral/zero method which assumes that all joints are at zero position in a normal upright standing pose. Joint and individual sensor orientation angles and angular velocities were recorded and further processed using MR3 software. Peak flexion angles of the ankle, knee and hip and peak thigh angular velocity during the eccentric phase of the first landing were extracted by identifying the first eccentric peak after initial contact over the sagittal plane motion data (Tamura et al. 2017; Pratt and Sigward 2018a, 2018b).

Two objective criteria were used to determine stretch-shortening cycle (SSC) classification: 1) the presence of an impact peak in the athletes force-time profile (defined as the highest transient, visible force peak occurring during the first 20% of ground contact) (Pedley et al. 2020); and 2) whether they displayed spring-like behavior (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 < -0.80) (Padua et al. 2005). A classification of 'good' was provided when no impact peak was present and the correlation displayed a spring-like behavior ($r \geq -0.80$). Players were deemed 'moderate' if there was an impact peak but still spring-like, *or* no

Table 1. Description of variables examined.

Variable	Measurement unit	Description
Jump Height	cm	Maximal jump height computed using impulse-momentum method
RSI	m·s^{-1}	Jump height divided by contact time
Relative Mean Concentric Power	W·kg^{-1}	Mean power per kilogram during the concentric phase
Relative Mean Eccentric Power	W·kg^{-1}	Mean power per kilogram during the eccentric phase
Concentric Impulse	N·s	Concentric force exerted multiplied by time taken
Eccentric Impulse	N·s	Eccentric force exerted multiplied by time taken
Force at Peak CoM Displacement	N	Force recorded at the lowest CoM position
Peak CoM displacement	m	The distance travelled by the athlete's CoM downwards during the contact time
Peak Force 1st landing	N	Highest transient, visible force peak during the landing phase
Time of Landing Peak	s	Time taken to achieve force peak during the landing phase
Time of peak CoM displacement	%	Time taken to reach the lowest CoM position
Peak ankle flexion	deg	Maximum flexion angle reached by the ankle
Peak hip flexion	deg	Maximum flexion angle reached by the hip
Peak knee flexion	deg	Maximum flexion angle reached by the knee
Thigh angular velocity	deg·s^{-1}	Rate of change of thigh angular displacement

(RSI) reactive strength index, (CoM) center of mass, (N) Newton, (cm) centimeter, (m) meter, (W) watt, (s) second, (kg) kilogram, (deg) degree.

impact peak was present but did not display a spring like behavior). Finally, a classification of 'poor' was given when there was an impact peak and they were not spring-like in accordance with previous research (Pedley et al. 2020).

Statistical analysis

The distribution of the data was checked using the Shapiro-Wilk normality test.

In ***part 1***, paired-samples tests or Wilcoxon Rank Sum Tests were used dependent on whether the data were normally distributed to examine differences in performance, kinetic and kinematic variables between the ACL reconstructed and uninjured limb. Bonferroni correction was applied to reduce the risk of type I error with multiple statistical tests. Chi-squared (χ^2) analysis was used to investigate the interaction between limbs and SSC category.

For ***part 2,*** strength and RSI thresholds were computed across players by dividing the data into tertiles, creating three groups (according to strength level: tertile 1 = 'weak', tertile 2 = 'moderate', and tertile 3 = 'strong'; according to RSI level: tertile 1 = 'low', tertile 2 = 'medium', and tertile 3 = 'high'). A one-way analysis of variance (ANOVA or Kruskal – Wallis) was conducted to determine differences in SLDJ performance, and kinetic and kinematic variables between groups split according to strength levels. The same analysis was repeated with groups split according to RSI levels. Bonferroni post hoc test was used to determine pairwise differences between tertiles in the physical capacity level examined. Chi-squared (χ^2) analysis was used to investigate the interaction between groups and SSC category.

In all parts, Cohen's d effect sizes (ES) with 95% confidence intervals were calculated to interpret the magnitude of these differences with the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for small, moderate, and large effect sizes, respectively (Turner et al. 2021). Significance was set at $p < 0.05$. All data were computed through Microsoft Excel®2010. Data processing and descriptive statistics were processed using SPSS® (V.25. Chicago Illinois).

Results

Part 1: performance, and kinetic and kinematic differences between the ACL reconstructed and uninjured limb

There were large significant differences between the ACL reconstructed and uninjured limb in SLDJ height ($d = -1.05$, 95%CI [−1.42, −0.67]; $p \leq 0.0001$), RSI ($d = -0.94$, 95%CI [−1.31, −0.57]; $p \leq 0.0001$), relative mean concentric power ($d = -1.05$, 95%CI [−1.43, −0.68]; $p \leq 0.0001$) and relative mean eccentric power ($d = 0.92$, 95%CI [0.55, 1.28]; $p \leq 0.0001$) (Table 2, Figure1). With the exception of concentric impulse and peak force at 1st landing, all kinetic variables displayed significant between-limb differences with effect sizes ranging from moderate ($d = -0.71$) to small ($d = -0.42$) (Table 2, Figure 2).

Table 2. Performance and kinetic differences between the ACL reconstructed and uninvolved limb.

Variable	ACL reconstructed limb	Uninvolved limb	Between limbs differences: effect size (95%CI) and P value
Performance			
Jump Height (m)	0.12 ± 0.019	0.14 ± 0.019	−1.05 (−1.42 to −0.67) p <0.0001
Reactive Strength Index	0.299 ± 0.07	0.369 ± 0.078	−0.94 (−1.31 to −0.57) p <0.0001
Relative Mean Concentric Power (W·kg^{-1})	16.67 ± 2.11	18.87 ± 2.04	−1.05 (−1.43 to −0.68) p <0.0001
Relative Mean Eccentric Power (W·kg^{-1})	−16.59 ± 2.56	−18.94 ± 2.52	0.92 (0.55 to 1.28) p <0.0001
Kinetic			
Concentric Impulse (N·s)	281 ± 82	274 ± 61	0.09 (−0.26 to 0.44) $p = 0.110$
Eccentric Impulse (N·s)	244 ± 57	251 ± 54	−0.14 (−0.49 to 0.21) $p = 0.002$
Force at Peak Centre of Mass Displacement (N)	1625 ± 413	1802 ± 435	−0.42 (−0.77 to −0.06) p <0.0001
Peak CoM displacement (m)	−0.18 ± 0.03	−0.20 ± 0.04	0.69 (0.33 to 1.05) p <0.0001
Peak Force 1st landing (N)	1953 ± 450	1996 ± 440	−0.09 (−0.44 to 0.26) $p = 0.147$
Time of Landing Peak (s)	0.084 ± 0.022	0.102 ± 0.028	−0.71 (−1.08 to −0.35) p <0.0001
Time of peak CoM displacement (%)	43.92 ± 3.74	45.93 ± 2.64	−0.62 (−0.98 to −0.26) p <0.0001
Kinematic			
Peak ankle flexion (deg)	14.15 ± 5.61	17.08 ± 4.69	−0.56 (−1.06 to − 0.06) $p = 0.0008$
Peak hip flexion (deg)	47.43 ± 11.90	44.18 ± 12.89	0.26 (−0.24 to 0.75) $p = 0.016$
Peak knee flexion (deg)	53.48 ± 11.85	57.68 ± 9.90	−0.38 (−0.88 to 0.12) $p = 0.0009$
Thigh angular velocity (deg·s^{-1})	203.21 ± 90.51	236.33 ± 83.61	−0.38 (−0.87 to 0.12) $p = 0.002$

Significant difference between limbs: $p < 0.003$.

All kinematic variables displayed significant between limbs differences, with the exception of peak hip flexion (Table 2). The effect size ranged from moderate ($d = -0.56$) to small ($d = -0.38$). Chi-squared analysis did not reveal any significant relationship between limbs and SSC category (χ^2 (Bhattacharyya 2017) = 3930, $p = 0.140$).

Part 2a: the effect of strength on SLDJ performance, kinetic and kinematic variables

According to strength tertiles, groups were split as follows: 'weak' = ≤ 2.86 N·m·kg^{-1}, 'moderate' = 2.87–3.22 N·m·kg^{-1}, and 'strong' ≥ 3.23 N·m·kg^{-1}. There were no significant differences between the 'weak' and 'moderate' and 'moderate' and 'strong' groups. There were large statistically significant differences between the 'weak' and 'strong' groups in SLDJ height ($d = -0.85$, 95%CI [−1.30, −0.40]; $p = 0.002$), RSI ($d = -0.93$, 95%CI [−1.38, −0.48]; $p = 0.002$), mean concentric ($d = -0.85$, 95%CI [−1.30, −0.40]; $p = 0.001$) and eccentric power ($d = 0.84$, 95%CI [0.40, 1.29]; $p = 0.002$) (Table 3). Moderate differences in time of peak CoM displacement ($d = -0.69$, 95%CI [−1.13, −0.25]; $p = 0.007$), peak CoM displacement ($d = 0.51$, 95%CI [0.081, 0.95]; $p = 0.03$) and time of landing peak ($d = -0.60$, 95%CI [−1.04, −0.16]; $p = 0.02$) were also observed (Table 3). No significant differences in any kinematic variable were present between the 'weak' and 'strong' groups in SLDJ (Table 3).

Owing to the expected count of 'poor' SSC function being less than 5, chi squared analysis could not be performed on three categories of SSC function. Therefore, frequency count of poor and moderate was combined to produce two categories of function. Chi-squared analysis did not reveal any significant relationship between strength level and SSC category (χ^2 (Bhattacharyya 2017) = 3873, $p = 0.144$), with no significant differences in the proportion of poor or moderate and good SSC category between groups.

Part 2b: the effect of reactive strength on SLDJ performance, kinetic and kinematic variables

According to RSI tertiles, groups were split as follows: 'low' = ≤ 0.29, 'medium' = 0.30–0.38, and 'high' ≥ 0.39. There were no statistically significant differences between the 'low' and 'medium' RSI groups, except for jump height ($d = -0.79$, 95%CI [−1.24, −0.34]; $p = 0.0007$). There were significant differences corresponding to a very large effect size between the 'medium' and 'high' RSI groups in relative mean concentric ($d = -2.89$, 95%CI [−3.51, −2.27]; $p = 0.002$) and eccentric power ($d = 3.36$, 95%CI [2.68, 4.03]; $p = 0.003$). Moderate differences were shown in force at peak CoM displacement ($d = -0.75$, 95%CI [−1.19, −0.30]; $p = 0.0008$)

There were statistically significant differences corresponding to a very large effect size between the 'low' and 'high' RSI group in SLDJ height ($d = -1.54$, 95%CI [−2.03, −1.05]; $p \leq 0.0001$), relative mean concentric ($d = -3.67$, 95%CI [−4.38, −2.96]; $p \leq 0.0001$) and eccentric power ($d = 3.94$, 95%CI [3.20, 4.68]; $p \leq 0.0001$), (Table 4).

Large differences in force at peak CoM displacement ($d = -1.30$, 95%CI [−1.77, −0.82]; $p \leq 0.0001$), concentric ($d = 0.91$, 95%CI [0.46, 1.36]; $p \leq 0.0001$) and eccentric impulse (d = 0.88, 95%CI [0.43, 1.33]; $p \leq 0.0001$) were evident between the two groups. Moderate and small differences were shown in time of landing peak ($d = -0.65$, 95%CI [−1.09, −0.21]; $p = 0.014$) and peak force 1st landing ($d = -0.49$, 95%CI [−0.92, −0.05]; $p = 0.005$) respectively (Table 4). No significant between groups differences were present in peak CoM displacement and time of peak CoM displacement (Figure 3).

Peak hip flexion showed large differences between groups ($d = 0.91$, 95%CI [0.28, 1.55]; ($p = 0.014$). No significant difference in any other kinematic variable was present between the 'low' and 'high' RSI groups in SLDJ (Table 4). Chi-squared analysis revealed a significant relationship between RSI level and SSC category (χ^2 (Bhattacharyya 2017) = 13713, $p = 0.001$). The 'high' RSI group had a greater proportion of 'good' SSC function (77%) in comparison with the 'low' RSI group (37%).

Discussion

The aims of this study were to 1) investigate performance, kinetic and kinematic differences between the ACL reconstructed limb and the uninvolved limb; and 2) examine the effect of knee extension isokinetic strength and reactive strength levels on single leg drop jump mechanics. The results showed that in the ACL reconstructed limb, all performance metrics were reduced and most kinetic and kinematic variables differed between limbs despite players being in the final stages of rehabilitation ~8 months post-surgery. Knee extension isokinetic strength level revealed large and moderate differences in performance metrics and kinetic variables respectively, whereas RSI level more clearly displayed performance and biomechanical variables typically associated with impaired SSC function and increased re-injury risk.

The inclusion of the SLDJ assessment in the late phase of rehabilitation has been suggested to better highlight deficits in knee function compared to single leg countermovement and horizontal jumps in male athletes at the time of RTS (King et al. 2018, 2019; Kotsifaki et al. 2022). Quantifying SSC performance can determine an athlete's ability to efficiently store and reutilise elastic energy during high eccentric stretch loads, such as landing and change of direction, which are crucial for sports performance across a range of field sports (Brughelli et al. 2008), and have also been identified as primary actions in non-contact ACL injuries (Dos'Santos et al. 2018; Fox 2018; Marques et al. 2019). Our results strengthen previous findings (King et al. 2018; Lloyd et al. 2020; Read et al. 2020; Kotsifaki et al. 2022), showing that jump height, reactive strength, and relative concentric and eccentric mean power are reduced in the ACL reconstructed limb in comparison to the uninvolved limb. We also observed kinetic and kinematic differences between limbs in SLDJ execution, typically associated with higher re-injury risk. In particular, CoM displacement was reduced and peak landing force occurred in the earlier stages of ground contact. This resulted in a lower thigh angular velocity, and peak ankle and knee flexion angles, thus adopting a 'stiff' knee movement strategy commonly documented in male athletes following ACL reconstruction and associated with higher risk of re-injury (Maestroni et al. 2021).

The reduction of thigh angular velocity observed suggests an intra-limb compensation strategy for lower peak power

Table 3. Performance, kinetic and kinematic differences between the 'weak', 'moderate' and 'strong' group.

Variable	Weak ($n = 43$)	Moderate ($n = 42$)	Strong ($n = 43$)	'Weak' vs 'Moderate' group differences: effect size (95%CI) and P value	'Moderate' vs 'Strong' group differences: effect size (95%CI) and P value	'Weak' vs 'Strong' group differences: effect size (95%CI) and P value
Performance						
Jump Height (m)	0.12 ± 0.02	0.13 ± 0.02	0.14 ± 0.02	−0.48 (−0.92 to −0.05) $p = 0.07$	−0.49 (−0.93 to −0.05) $p = 0.214$	−0.85 (−1.30 to −0.40) $p = 0.002$
Reactive Strength Index	0.30 ± 0.08	0.33 ± 0.07	0.37 ± 0.08	−0.40 (−0.83 to 0.04) $p = 0.458$	−0.58 (−1.02 to −0.14) $p = 0.027$	−0.93 (−1.38 to −0.48) $p = 0.002$
Relative Mean Concentric Power ($W{\cdot}kg^{-1}$)	16.84 ± 2.77	17.58 ± 1.75	18.88 ± 2.04	−0.32 (−0.75 to 0.12) $p = 0.371$	−0.70 (−1.14 to −0.25) $p = 0.023$	−0.85 (−1.30 to −0.40) $p = 0.001$
Relative Mean Eccentric Power ($W{\cdot}kg^{-1}$)	−16.78 ± 3.07	−17.43 ± 2.49	−19.08 ± 2.27	0.23 (−0.20 to 0.66) $p = 0.770$	0.69 (0.24 to 1.13) $p = 0.014$	0.84 (0.40 to 1.29) $p = 0.002$
Kinetic						
Concentric Impulse (N·s)	287 ± 102	281 ± 53	264 ± 45	0.07 (−0.36 to 0.50) $p = 0.654$	0.35 (−0.09 to 0.78) $p = 0.128$	0.29 (−0.14 to 0.72) $p = 0.228$
Eccentric Impulse (N·s)	244 ± 66	257 ± 55	241 ± 42	−0.21 (−0.64 to 0.22) $p = 0.229$	0.33 (−0.11 to 0.76) $p = 0.199$	0.06 (−0.37 to 0.49) $p = 0.935$
Force at Peak Centre of Mass Displacement (N)	1657 ± 415	1680 ± 380	1802 ± 489	−0.06 (−0.49 to 0.37) $p = 0.909$	−0.28 (−0.71 to −0.16) $p = 0.334$	−0.32 (−0.75 to 0.12) $p = 0.298$
Peak CoM displacement (m)	−0.18 ± 0.04	−0.20 ± 0.04	−0.2 ± 0.04	0.51 (0.08 to 0.95) $p = 0.019$	−0.00 (−0.43 to 0.43) $p = 0.799$	0.51 (0.08 to 0.95) $p = 0.03$
Peak Force 1st landing (N)	2033 ± 526	1908 ± 319	1980 ± 461	0.28 (−0.15 to 0.72) $p = 0.257$	−0.18 (−0.61 to 0.25) $p = 0.745$	0.11 (−0.32 to 0.54) $p = 0.487$
Time of Landing Peak (s)	0.084 ± 0.027	0.090 ± 0.027	0.100 ± 0.026	−0.22 (−0.65 to 0.21) $p = 0.343$	−0.37 (−0.81 to 0.06) $p = 0.744$	−0.60 (−1.04 to −0.16) $p = 0.02$
Time of peak CoM displacement (%)	43.48 ± 3.48	45.6 ± 3.36	45.7 ± 2.84	−0.61 (−1.06 to −0.17) $p = 0.016$	−0.03 (−0.46 to 0.40) $p = 0.732$	−0.69 (−1.13 to −0.25) $p = 0.007$
Kinematic						
Peak ankle flexion (deg)	14.31 ± 6.3	15.7 ± 4.6	16.83 ± 4.92	−0.25 (−0.86 to 0.36) $p = 1.000$	−0.23 (−0.84 to 0.38) $p = 1.000$	−0.44 (−1.05 to 0.18) $p = 0.365$
Peak hip flexion (deg)	48.77 ± 12.87	43.6 ± 11.3	45.03 ± 12.96	0.42 (−0.20 to 1.03) $p = 0.519$	−0.12 (−0.72 to 0.49) $p = 1.000$	0.28 (−0.33 to 0.90) $p = 0.965$
Peak knee flexion (deg)	52.39 ± 12.2	56.1 ± 9.3	58.26 ± 11.09	−0.34 (−0.95 to 0.28) $p = 0.132$	−0.21 (−0.82 to 0.40) $p = 0.392$	−0.49 (−1.11 to 0.12) $p = 0.132$
Thigh angular velocity ($deg{\cdot}s^{-1}$)	214.73 ± 105.99	212.3 ± 65.3	232.27 ± 90.85	0.03 (−0.58 to 0.64) $p = 0.597$	−0.25 (−0.86 to 0.36) $p = 0.606$	−0.17 (−0.78 to 0.44) $p = 0.644$

Significant difference between limbs: $p < 0.003$.

Table 4. Performance, kinetic and kinematic differences between the 'low', 'medium' and 'high' RSI group.

Variable	Low ($n = 43$)	Medium ($n = 42$)	High ($n = 43$)	'Low' vs 'medium' group differences: effect size (95%CI) and P value	'Medium' vs 'high' group differences: effect size (95%CI) and P value	'Low' vs 'high' group differences: effect size (95%CI) and P value
Performance						
Jump Height (m)	0.12 ± 0.02	0.13 ± 0.02	0.14 ± 0.02	−0.79 (−1.24 to −0.34) $p = 0.0007$	−0.67 (−1.12 to −0.23) $p = 0.006$	−1.52 (−2.20 to −0.83) $p < 0.0001$
Relative Mean Concentric Power (W·kg^{-1})	15.38 ± 1.54	17.60 ± 0.74	20.32 ± 1.09	−1.81 (−2.33 to −1.30) $p = 0.209$	−2.89 (−3.51 to −2.27) $p = 0.002$	−3.59 (−4.58 to −2.61) $p < 0.0001$
Relative Mean Eccentric Power (W·kg^{-1})	−14.86 ± 1.86	−17.60 ± 0.86	−20.83 ± 1.03	1.87 (1.35 to 2.39) $p = 0.140$	3.36 (2.68 to 4.03) $p = 0.003$	3.84 (2.81 to 4.87) $p < 0.0001$
Kinetic						
Concentric Impulse (N·s)	313 ± 98	275 ± 48	245 ± 35	0.47 (0.04 to 0.91) $p = 0.654$	0.72 (0.77 to 1.16) $p = 0.128$	0.88 (0.25 to 1.51) $p < 0.0001$
Eccentric Impulse (N·s)	272 ± 70	247 ± 47	224 ± 32	0.42 (−0.02 to 0.85) $p = 0.229$	0.58 (0.14 to 1.02) $p = 0.199$	0.85 (0.22 to 1.49) $p < 0.0001$
Force at Peak Centre of Mass Displacement (N)	1471 ± 309	1680 ± 340	1988 ± 466	−0.64 (−1.08 to −0.20) $p = 0.035$	−0.75 (−1.19 to −0.30) $p = 0.0008$	−1.30 (−1.97 to −0.64) $p < 0.0001$
Peak CoM displacement (m)	−0.20 ± 0.04	−0.20 ± 0.04	−0.18 ± 0.03	−0.02 (−0.46 to 0.41) $p = 1.000$	−0.53 (−0.97 to −0.09) $p = 0.174$	−0.55 (−1.16 to 0.06) $p = 0.069$
Peak Force 1st landing (N)	1892 ± 526	1905 ± 334	2125 ± 419	−0.03 (−0.46 to 0.40) $p = 0.257$	−0.57 (−1.01 to −0.13) $p = 0.745$	−0.48 (−1.09 to 0.13) $p = 0.005$
Time of Landing Peak (s)	0.085 ± 0.028	0.090 ± 0.023	0.103 ± 0.027	−0.19 (−0.63 to 0.24) $p = 0.157$	−0.51 (−0.95 to −0.07) $p = 0.250$	−0.64 (−1.26 to −0.02) $p = 0.014$
Time of peak CoM displacement (%)	44.48 ± 4.29	44.87 ± 3.42	45.41 ± 2.05	−0.10 (−0.53 to 0.33) $p = 1.000$	−0.19 (−0.62 to 0.24) $p = 1.000$	−0.27 (−0.87 to 0.34) $p = 0.623$
Kinematic						
Peak ankle flexion (deg)	14.72 ± 6.4	15.40 ± 5.19	17.01 ± 3.92	−0.11 (−0.72 to 0.49) $p = 1.000$	−0.34 (−0.95 to 0.27) $p = 0.856$	−0.42 (−1.03 to 0.19) $p = 0.464$
Peak hip flexion (deg)	51.33 ± 11.39	44.27 ± 13.16	41.03 ± 10.75	0.57 (−0.05 to 1.18) $p = 0.148$	0.26 (−0.34 to 0.87) $p = 1.000$	0.91 (0.28 to 1.55) $p = 0.014$
Peak knee flexion (deg)	57.90 ± 12.54	53.13 ± 9.78	55.38 ± 10.34	0.41 (−0.20 to 1.02) $p = 0.459$	−0.22 (−0.82 to 0.38) $p = 1.000$	0.21 (−0.39 to 0.82) $p = 1.000$
Thigh angular velocity (deg·s^{-1})	210.13 ± 99.05	204.33 ± 69.12	246.24 ± 89.67	0.07 (−0.54 to 0.67) $p = 0.597$	−0.52 (−1.13 to 0.09) $p = 0.606$	−0.37 (−0.98 to 0.23) $p = 0.078$

Significant difference between limbs: $p \leq 0.003$.

generation at the knee, concomitant with reduced knee flexion ROM excursion. Pratt et al (Pratt and Sigward 2018b). showed that peak thigh angular velocity was the best predictor of knee power absorption (R^2 = 66%) after initial ground contact during single limb loading. Cumulatively, this may indicate the need at the time of RTS of a more controlled active deceleration of the body's CoM, through enhanced pre-activation strategies and more efficient utilisation of stretch-reflexes (Gollhofer et al. 1984; Bhattacharyya 2017). Earlier activation of active constraints and enhanced neuromuscular control strategies may help to optimise the force-time profile, reducing the presence of an impact peak; thus, absorbing and recycling large peak braking forces more efficiently through the entire ground contact phase. Our analysis reinforced the notion that performance and biomechanical assessment of SLDJ provide useful information to assess knee function in the late stage of rehabilitation and at the time of RTS, with implications for sports performance readiness and rehabilitation status. In addition, wearable technology, such as IMUs used for this study, identified similar kinematic strategies recently reported using three-dimensional motion capture [3, 10]. This may aid in bridging the gap between lab and field-based methods; however, more research is needed to validate thigh angular velocity using IMU sensors during a SLDJ task following ACL reconstruction.

Deficits in peak knee extension torque are commonly displayed in the ACL reconstructed limb at the time of RTS (Johnston et al. 2020; Maestroni et al. 2021). The most common assessment mode includes the use of isokinetic peak torque at $60°{\cdot}s^{-1}$ (Undheim et al. 2015), with practice recommendations to restore knee extension strength >3.0 $N{\cdot}m{\cdot}kg^{-1}$, as minimum requirement of a rehabilitation programme (van Melick et al. 2016, 2022). Our results indicate that, players who produced lower peak knee extension torque (<2.86 $N{\cdot}m{\cdot}kg^{-1}$) displayed reduced SLDJ performance, shallower CoM displacement (d = 0.51) and peak knee flexion angles (d = −0.49), with peak landing force occurring earlier during the ground contact phase (d = −0.60) than stronger players >3.23 $N{\cdot}m{\cdot}kg^{-1}$. This movement strategy, characterized by an impaired capacity to effectively attenuate landing velocity in the lower extremity, has been associated with poorer tibio-femoral articular cartilage composition and matrix degeneration following ACL reconstruction (Pfeiffer et al. 2021; Brunst et al. 2022). Therefore, it appears that a 'stiff' knee movement strategy to offload the knee joint is more likely present in weaker than stronger athletes at the time of RTS, thus highlighting the importance of quadriceps strength recovery during rehabilitation.

Players with 'high' RSI scores (≥0.39) displayed greater performance metrics (i.e. jump height, relative concentric and eccentric power) and more advantageous biomechanical characteristics compared to players with 'low' RSI (≤0.29), suggesting larger magnitude differences in RSI affect ground reaction force and spring-like characteristics. Our tertiles categorization reflected values previously shown in 268 male soccer players (Read et al. 2020), and thus such cut-off can be used to benchmark SSC performance recovery. Higher SSC performance is associated with a reduced metabolic cost of running and enhanced change of direction performance (Maloney et al. 2017; Li et al. 2019), but also with a lower risk of ipsilateral and contralateral ACL injury (King et al. 2021a, 2021b). In our cohort, those displayng 'low' RSI scores appeared to show less frequently spring-like behavior, recorded a landing peak earlier during ground contact (d = −0.64), and absorbed less force in the eccentric phase, but over a longer contact time, which was evident in the higher eccentric impulse recorded (d = 0.85). This absorbing motion does not exploit the advantages of elastic energy and stretch reflexes during the initial phase of landing (Oh and Lee 2022), and occurred through higher deformation of the CoM coming from greater hip flexion angles (d = 0.91), which is a typical intra-limb compensation strategy adopted during single leg dynamic tasks in ACL reconstructed cohorts (Maestroni et al. 2021).

Our data were limited to adult male professional football players. Therefore generalisation of these results to pediatric, adolescent and female athletes requires caution. Our strength assessment did not include distal components nor closed chain tasks. Soleus contribution was recently found lower in ACL reconstructed male athletes during the propulsion phase of vertical jumps (Kotsifaki et al. 2022), and may be more strongly correlated with performance and biomechanics of fast SSC actions than quadriceps strength (Möck et al. 2018). Furthermore, there is potential for deterioration of the uninvolved contralateral limb following surgery due to deconditioning/lack of exposure (Wellsandt et al. 2017), which may overestimate rehabilitation status if symmetry scores are solely considered and a control group is not included. The main purpose of this study was to examine how differences in strength and RSI effect drop jump ground reaction force characteristics. We included kinematic data to provide further and more descriptive analysis. However, due to the reduced sample, our findings should be interpreted with caution (in particular when effect sizes are small) and warrants further research. In addition, although the IMU system has been validated for several single leg loading tasks (Pratt and Sigward 2018a, 2018b; Vervaat et al. 2022), confirmation of these findings during the SLDJ assessment warrants further investigation. In particular, IMU system measurement errors within the examined variables need to be established before concluding that meaningful differences have occurred.

Between-limb differences in SLDJ performance, kinetics and kinematics are present in the later stages of rehabilitation following ACL reconstruction. These deficits were more apparent in male soccer players who displayed lower isokinetic knee extension torque and SLDJ RSI. The involved limb displayed a 'stiff' knee movement strategy, characterised by lower thigh angular velocity, reduced CoM displacement, and peak landing force occurring in the earlier stages of ground contact, which is associated with higher risk of re-injury (Maestroni et al. 2021). Our findings suggest that targeted interventions to improve maximal strength and plyometric ability are needed at the appropriate stages during rehabilitation (Królikowska et al. 2019; Welling et al. 2019; Maestroni et al. 2020) to enhance the modulation of the SSC (Maloney et al. 2019; Haff and Nimphius 2012), and to improve eccentric force generation capacity. For example, single joint (e.g. leg extension) and multi joint exercises (e.g. split squat) can be utilised to normalise inter-limb asymmetries in force production. External load of strength exercises should be regularly progressed to optimise strength levels according with normative values (Welling et al. 2019; Oliveira et al. 2022). Likewise, plyometric training can be progressed according to the athlete's strength level, fatigue, technique competency and rehabilitation phase (Suchomel et al. 2019). The initial focus is placed on exercises that emphasise eccentric storage capacity while landing, prior to progression of rebound spring like actions with short ground contact times. Finally, practitioners may wish to select activities that utilise kinetic energy recycling with increasing intensities of the eccentric stimulus (Flanagan and Comyns 2008). Progressive plyometric training is performed both bilaterally and unilaterally in vertical, horizontal and lateral directions to match the braking, propulsive and medio-lateral forces typical of change of direction tasks and sprinting actions (Brughelli et al. 2008; Asadi et al. 2016; Maloney et al. 2017; Haugen et al. 2019). For detailed information regarding practical applications to return athletes to high performance we recommend recently published articles (Buckthorpe 2019; Buckthorpe and Della Villa 2019; Welling et al. 2019; Maestroni et al. 2020). Examples of progressive SSC drills that can be used according to rehabilitation stage, load tolerance and physical competencies can also be found in our recent article (Turner et al. 2022).

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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