A comparison of strength and power characteristics prior to anterior cruciate ligament rupture and at the end of rehabilitation in professional soccer players

Authors

Luca Maestroni MSc[ab], Anthony Turner PhD[b], Konstantinos Papadopoulos PhD[c], Daniel Cohen PhD[de,] Vasileios Sideris PhD[f], Philip Graham-Smith PhD[g], Paul Read PhD[h,i,j]

[a]ReAct, Via Madonna della Neve, 24, 24121 Bergamo (BG), Italy

[b]London Sport Institute, School of Science and Technology, Middlesex University, Greenlands Lane, London, United Kingdom

[c] School of Allied Health and Community, University of Worcester, UK

[d]Masira Research Institute, Faculty of Health Sciences, University of Santander (UDES), Bucaramanga 680005, Colombia

[e]Mindeporte (Colombian Ministry of Sport) High Performance Centre, Bogota 111071, Colombia

[f]Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

[g]Aspire Academy, Doha, Qatar

[h]Institute of Sport, Exercise and Health, London, United Kingdom

[i] Division of Surgery & Interventional Science, University College London, UK

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

Corresponding author

Luca Maestroni

ReAct, Via Madonna della Neve, 24, 24121 Bergamo (BG), Italy

London Sport Institute, School of Science and Technology, Middlesex University, Greenlands Lane, London, United Kingdom

Email: lucamae@hotmail.it

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LM and PR: concept, design and writing the first version of the manuscript. LM, PR and AT: statistical analysis. KP,VS, DC, PGS and AT: writing and editing of the manuscript.

ABSTRACT

Background: Strength and power is often reduced on the involved vs. contralateral limb and healthy controls following anterior cruciate ligament (ACL) reconstruction but no study has compared to pre-injury values at the time of return to sport (RTS).

Hypothesis: Divergent recovery patterns in strength and power characteristics will be present at RTS relative to pre-injury baseline data and healthy matched controls.

Study design: Cohort study

Level of evidence: Level 3

Methods: Isokinetic strength tests, bilateral and single leg countermovement jumps (CMJ; SLCMJ) were measured prior to ACL rupture in 20 professional soccer players. These then had surgical reconstruction (ACL group) and completed follow up testing prior to RTS. Healthy controls (uninjured group) were tested at the same time as the ACL group pre-injury.

Values recorded at RTS of the ACL group were compared to pre-injury. We also compared the uninjured and ACL groups at baseline and RTS.

Results: Compared to pre-injury, ACL normalised quadriceps peak torque of the involved limb (% difference = -7%), SLCMJ height (% difference = -12.08%) and Reactive Strength Index modified (RSImod) (% difference = -5.04%) were reduced following ACL reconstruction. No significant reductions in CMJ height, RSImod and relative peak power were indicated at RTS in the ACL group when compared to pre-injury values but deficits were present relative to controls. The uninvolved limb ~~significantly~~ improved quadriceps (% difference = 9.34%) and hamstring strength (% difference = 7.36%) from pre-injury to RTS. No significant differences from baseline were shown in SLCMJ height, power and reactive strength of the uninvolved limb following ACL reconstruction.

Conclusion: Strength and power in professional soccer players at RTS following ACL reconstruction were often reduced compared to preinjury values and matched healthy controls.

Clinical relevance: Deficits were more apparent in the SLCMJ suggesting dynamic and multijoint unilateral force production is an important component of rehabilitation. Use of the uninvolved limb and normative data to determine recovery may not always be appropriate.

KEYWORDS

Anterior cruciate ligament, strength, power, reactive strength, soccer

INTRODUCTION

Anterior cruciate ligament (ACL) injuries in elite soccer players incur a high burden [2], with substantial time-loss and economic cost [10]. This traumatic event often results in surgical reconstruction and return to sport (RTS) time is on average ~ 8 months [37]. Although most elite athletes (83%) return to their pre-injury level of competition following ACL reconstruction [22], this is often accompanied by an increased risk of ipsilateral [17] and contralateral [18] injury, early onset of posttraumatic osteoarthritis, and sports performance deterioration [8,22-24].

Strength and power are reduced following ACL reconstruction [29]. Strength assessment has commonly included isokinetic testing of knee extension and flexion peak torque, with established excellent reliability scores documented [1,14,38]. Deficits in peak knee extension and flexion torque are commonly displayed in the ACL reconstructed limb compared to the uninvolved side and healthy controls after rehabilitation at the time of RTS [15,29]. In addition, jump performance is often used to quantify dynamic multijoint force production and can discriminate rehabilitation status [31,32]. Countermovement jump (CMJ) performance variables can help practitioners to quantify neuromuscular qualities that underpin movements inherent to soccer such as sprinting, jumping, and change of direction [13]. However, it has been suggested that single leg dynamic tasks are more representative of limb strength due to their higher relative force demands[7], whereas bilateral jumping and landing tasks occur at a higher velocity. Furthermore, compensation strategies are restricted to interjoint in unilateral movements, whereas bilateral jumping can provide more options to unload the ACL reconstructed limb via both interjoint and interlimb [28]. The differing demands of the bilateral and unilateral tasks may reveal specific deficits, warranting the inclusion of both in the assessment of neuromuscular performance for athletes during rehabilitation aiming to return to a high level of competition.

Research [16-20,31,32,34,35] assessing strength and power characteristics in athletes following ACL reconstruction has been limited mostly to cross-sectional studies at single time points or around the time of RTS. Residual deficits in vertical jump height, lower limb power, and reactive strength appear to be present following ACL reconstruction [27,32,34]. Lower quadriceps strength and reduced plyometric ability have also displayed associations with increased risk of contralateral reinjury [17,18]. However, the available research has used the contralateral limb or values from matched controls to determine if deficits are present. There is potential for deterioration of the uninvolved contralateral limb following surgery due to deconditioning/lack of exposure [44]. Without pre-injury baseline physical characteristics, it is impossible to determine if athletes have returned to previous strength and jump performance values. It is also unknown if matched controls provide an accurate representation of baseline / pre-injury performance. A prospective study monitoring strength and power qualities from tests that are commonly used as part of RTS assessment in elite soccer players before and after ACL rupture and reconstruction may help guide performance recovery and determine the accuracy of proxy measures, including the uninvolved limb and comparison values of healthy controls.

Our aim was to examine changes in strength and power performance following the completion of rehabilitation at the time of RTS compared to pre-injury baseline data and compared to healthy matched controls. Using these data, we examined how pre-injury benchmark data can be used to guide performance recovery and inform physical readiness as part of RTS decision making. Our specific research questions included: 1) to what extent performance metrics are recovered at the time of RTS following ACL reconstruction; and 2) how accurate is the use of; a) the contralateral limb; and b) group / control normative data as proxy measures for determining performance recovery when pre-injury data exist.

METHODS

Participants

Twenty soccer players (24.7 ± 3.4 years; height = 175.3 ± 7.0 cm; weight =69.5 ± 10.7 kg) participating in the Qatar Stars and Gas Leagues attended a periodic health evaluation between 2017 and 2019, and subsequently went on to sustain an ACL rupture before undergoing ACL reconstruction (ACL group). The majority of ACL grafts were bone-patella-tendon bone (80%), with the remaining players (20%) all semitendinosus and gracilis hamstring tendon grafts. Only participants with no history of previous ACL injury / surgery, or other knee ligament or cartilage injury / surgery of either the operated or non-operated leg at the time of the periodic health evaluation were included. All athletes were treated at the same Orthopaedic and Sports Medicine Hospital. Rehabilitation was delivered 5 days per week and 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 were 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.

We also recruited thirty-five (uninjured) controls (23.8 ± 2.8 years; height = 173.8 ± 5.4 cm; weight = 71.6 ± 6.3 kg) from the same leagues who attended pre-season screening at the national sports medicine institution and were randomly selected from a pool of 300 athletes. Inclusion was based on having no history of ACL injury and being free from any severe injury (defined as > 28 days' time-loss) in the previous 12 months, verified via a national injury audit. Clubs competing in the stated leagues within Qatar regularly complete formalised strength and conditioning including resistance training, speed, agility and plyometrics. Before participating, all participants provided informed written consent and ethical approval was provided (IRB: F2017000227).

Experimental approach to the problem

To address our stated aims, we separated the study into 4 components. ***In part 1,*** we compared strength and power characteristics of the ACL group to the uninjured group using both the pre-injury (baseline) data and performance following the completion of rehabilitation of the ACL group. Pre-injury baseline data are not commonly available, forcing clinicians to instead use either peers/published data and or the contralateral limb as proxy benchmarks following ACL reconstruction [29], but the former has not been explored. In ***part 2***, we monitored the trajectory of strength and power performance of the uninvolved limb in the ACL group by comparing isokinetic and SLCMJ assessment scores at two time points: pre-injury and at the end of rehabilitation prior to RTS. Conflicting evidence is available about the detrimental effect of ACL reconstruction and subsequent deconditioning on the uninvolved limb [26,36,44]. Currently, no study has conducted an assessment of strength and power characteristics of the uninvolved limb before and after ACL reconstruction following structured full time rehabilitation. In ***part 3,*** we measured the effect of ACL reconstruction and rehabilitation on the injured limb by comparing isokinetic and SLCMJ performance scores at two time points: pre-injury and at the end of rehabilitation, following sports specific reconditioning prior to RTS. Finally, in ***part 4***, we investigated the effect of ACL reconstruction on bilateral CMJ performance by comparing pre-injury and RTS values.

Procedures

A schematic diagram of our study is represented in Figure 1. A test battery consisting of isokinetic strength assessment, CMJ, and SLCMJ was performed. The ACL reconstructed cohort was screened 33.9 ± 29.6 weeks before the ACL rupture, and assessed at the end of rehabilitation prior to RTS (30.3 ± 7.2 weeks post-surgery). Players completed a standardized warm up consisting of 5 minutes on a cycle ergometer, bilateral and unilateral bodyweight squats, and bilateral CMJs at 50, 75 and 100% maximum effort [33]. Test conditions and procedures were replicated at each assessment.

*****INSERT FIGURE 1 NEAR HERE*****

Isokinetic knee extension and flexion strength

Maximal quadriceps knee extension peak torque (Quad PT Rel) and hamstring flexion peak torque (HS PT Rel) relative to body mass (N.m.kg^{-1}) were measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, New York, USA). Players were in a seated position with the hip flexed to 90°. Five repetitions of concentric knee extension and flexion were performed at 60°/s with the highest peak torque value recorded [42]. Peak torque values were reported as a percentage of the individual's body mass. Procedures were explained to participants following which they completed 3 practice repetitions. Testing then commenced after 60s. Limb order was randomized. The dominant limb of healthy controls was defined as the preferred kicking leg. Standardized, vigorous verbal encouragement was provided throughout. Each participant had previous experience of isokinetic testing and all tests were conducted by the same physiotherapist with > 5 years experience in the relevant test procedures.

Countermovement Jump (bilateral/single)

Participants were instructed to stand fully upright, hands on hips, and align their feet on a synchronized dual force plate system (ForceDecks v1.2.6109, Vald Performance, Albion, Australia). Prior to the initiation of the test, each individual was instructed to remain motionless for a minimum of three seconds to ensure a stable baseline of force at body weight was obtained. Players then performed a downward motion (descent phase) until they reached their preferred self-selected depth, before rapidly reversing the motion by triple extending at the hip, knee, and ankle. The aim of the task was to achieve their maximal vertical displacement of the centre of mass. Hands remained on hips throughout and no bending of the knees was permitted whilst airborne. The procedures were replicated for the the SLCMJ, except the non-test leg was positioned with the hip and knee at 90º and no obvious swinging was allowed to minimize contralateral propulsion. Limb order was randomized. Two trials were performed with a 30 s rest period between each jump, with the best trial recorded for statistical analysis.

All data were recorded at a sampling rate of 1000 Hz. The initiation of the jump was defined by a 20 N change from body weight calculated during the quiet standing period and the instant of take-off, when the total vertical force dropped below 20 N. We selected three outputs, which are commonly reported in jump performing testing of healthy athletes and which can also be estimated using other lower cost technologies than force platform. Jump height was calculated from the impulse-momentum relationship derived take off velocity and equation of constant acceleration (velocity at take-off squared divided by 2*9.81 ($v^2/2g$). Peak power was measured and normalized to bodyweight Watt$^{\cdot kg-1}$ (Peak Power Rel) during the propulsion phase. Reactive strength index modified (RSImod) was calculated by dividing jump height by contraction time (determined from movement onset to time to take off [39].

Intraday reliability analysis was conducted on baseline pre-injury scores of the ACL group. The between trial reliability was analyzed using a 2-way random effects intraclass correlation coefficient [ICC(2,1)] [21] with 95% confidence intervals (CI). The ICCs were analyzed as single measures. Coefficient of variation (CV%) and 95% confidence intervals (95%CI) and Standard error of measurement (SEM) were also calculated. Reliability scores were categorized as acceptable if the CV was ≤ 10% [40], and were further categorized as "excellent" if ICC was > 0.90, "good" between 0.75 and 0.90, "moderate" between 0.50 and 0.75, and "poor" < 0.50 [21].

CMJ height, relative peak power and reactive strength displayed "excellent" reliability with ICC ranging from 0.945 to 0.978, and CV between 2.1 and 8.6% (Table 1). SLCMJ height, RSImod and jump height symmetry displayed "excellent" reliability, with ICCs ranging from 0.901 to 0.960 and CV between 4.2 and 5.9 (Table 1). Relative peak power showed CV < 10%, and ICC between 0.781 and 0.860.

***** INSERT TABLE 1 NEAR HERE *****

Statistical analysis

The distribution of the data were checked using the Shapiro-Wilk normality test. Descriptive statistics (mean ± SD) for all variables were calculated. Percentage changes from pre-injury to post ACL reconstruction were calculated for each player using the percentage difference and then averaged.

In ***part 1***, an independent samples *t*-test or Mann–Whitney U tests were used to examine differences in anthropometrics and physical performance variables between ACL and uninjured group.

For ***parts 2, 3, and 4*** paired-samples tests or Wilcoxon Rank Sum Test were used to detect statistical differences between pre-injury and post-surgery physical performance variables. The Two-way repeated measures ANOVA was used to examine the influence and interaction of time and/or injury (performance on the injured limb) for each test variable in the ACL group.

In all parts, Bonferroni correction was applied to reduce the risk of type I error with multiple statistical tests (adjusted $\alpha = 0.025$ and $\alpha = 0.017$ for isokinetic dynamometry and dual force plate system derived variables respectively). Hedges *g* 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 [41]. Significance was set at $p < 0.05$. Data processing and descriptive statistics were processed using SPSS® (V.25. Chicago Illinois).

RESULTS

Part 1: strength and power characteristics of the ACL reconstructed group vs healthy matched controls

Baseline (pre-injury) anthropometric, strength and power characteristics of the ACL reconstructed group were not significantly different to healthy matched controls (see Table 2).

***** INSERT TABLE 2 NEAR HERE *****

Normalised quadriceps and hamstring peak torque were significantly higher in the uninvolved limb of the ACL group prior to RTS compared to those who were uninjured ($g = 0.77$, 95%CI [0.19, 1.36]; $p = 0.018$, and $g = 0.77$, 95%CI [0.19, 1.35]; $p = 0.005$ respectively). There were no significant differences in SLCMJ height, RSImod and relative peak power between the uninvolved limb of the ACL group and uninjured controls (Table 3).

Normalised hamstring peak torque was significantly higher in the reconstructed limb of the ACL group following rehabilitation compared to uninjured controls ($g = 1.32$, 95%CI [0.70, 1.93]; $p \leq 0.0001$), whereas there were no significant between-group differences in normalised quadriceps peak torque (Table 4).

There were large significant differences between the ACL group following surgery and uninjured controls in SLCMJ height ($g= -1.64$, 95%CI [-2.28, -0.99]; $p \leq 0.0001$), RSImod ($g = -0.93$, 95%CI [-1.52, -0.34]; $p = 0.004$), and jump height symmetry ($g = -1.51$, 95%CI [-2.14, -0.87]; $p \leq 0.001$) (Table 4).

There were large significant differences between the ACL group following surgery and uninjured controls in CMJ height ($g= -1.17$, 95%CI [-1.77, -0.56]; $p \leq 0.0001$) and RSImod ($g = -0.89$, 95%CI [-1.48, -0.30]; $p = 0.001$). Moderate differences in relative peak power ($g = -0.76$, 95%CI [-1.34, -0.18]; $p = 0.008$) were also present between groups (Table 5).

***** INSERT TABLES 3, 4 and 5 NEAR HERE *****

Part 2: the effect of ACL reconstruction on the uninjured limb

Uninvolved limb pre-injury and post ACLR performance for each of the participants is shown in figures 2b, 3b and 4b). There was no significant main effect of time (F(1,19) = 0.43, $p = 0.838$), but there was a significant main effect of injury on normalised quadriceps peak torque (F(1,19) = 7.996, $p = 0.011$). A significant interaction effect between time and injury was present (F(1,19) = 32.8, $p \leq 0.001$), showing an increase in normalised quadriceps peak torque in the uninvolved limb. No main effect of injury was observed for normalised hamstring peak torque (F(1,19) = 0.47, $p = 0.5$) and no significant interaction effect between time and injury (F(1,19) = 3.8, $p = 0.065$). There was only a significant main effect of time on normalised hamstring peak torque (F(1,19)= 7.35, $p = 0.014$), which showed improvements in normalised hamstring peak torque in the uninvolved limb attributable to the passage of time only following surgery.

There were no significant main or interaction effects of time and/or injury on SLCMJ jump height, relative peak power and RSI Mod in the uninvolved limb.

Moderate effect size differences in normalised quadriceps peak torque were observed post ACL reconstruction in comparison to pre-injury values ($g = 0.57$, 95%CI [-0.08, 1.23]; $p \leq 0.021$), whereas there were no significant differences in normalised hamstring peak torque (Table 3).

Part 3: the effect of ACL reconstruction on the injured limb

Involved limb pre-injury and post ACLR performance for each of the participants is shown in figures 2a, 3a and 4a. There was no significant main effect of time (F(1,19) = 0.43, $p = 0.838$), but there was a significant main effect of injury on normalised quadriceps peak torque (F(1,19) = 7.996, $p = 0.011$). A significant interaction effect between time and injury was present (F(1,19) = 32.8, $p \leq 0.001$), showing deterioration in normalised quadriceps peak torque in the ACL reconstructed limb. No main effect of injury was observed for normalised hamstring peak torque (F(1,19) = 0.47, $p = 0.5$) and there was no significant interaction effect between time and injury (F(1,19) = 3.8, $p = 0.065$). A significant main effect of time on normalised hamstring peak torque (F(1,19)= 7.35, $p = 0.014$) was shown, which indicates improvements in normalised hamstring peak torque in the ACL reconstructed limb following surgery.

There was a significant main effect of time (F(1,19)= 5.28, p = 0.033) and injury (F(1,19) = 49.56, p ≤ 0.001) on SLCMJ height, relative peak power (F(1,19) = 31.75, p ≤ 0.001), and RSImod (F(1,19) = 45.42, p ≤ 0.001) in the ACL reconstructed limb. A significant interaction effect was present between time and injury in jump height (F(1,19) = 11.53, p = 0.003), relative peak power (F(1,19) = 5.86, p = 0.026), and RSImod (F(1,19) = 8.02, p = 0.011), indicating SLCMJ performance had not returned to baseline. Conversely, normalised hamstring peak torque was significantly higher following ACL reconstruction compared to pre-injury values ($g = 0.90$, 95%CI [0.23, 1.58]; $p \leq 0.0001$). No significant differences in normalised quadriceps peak torque were present (Table 4).

***** INSERT FIGURES 2, 3 and 4 NEAR HERE *****

Part 4: the effect of ACL reconstruction on CMJ performance

Pre-injury and post ACLR CMJ height for each of the participants is shown in figure 5. No significant reductions in CMJ RSImod were present between the ACL reconstructed group before ACL rupture and after reconstruction at the time of RTS. Although not achieving our determined alpha level, moderate differences in CMJ jump height (*g* = 0.54, 95%CI [-0.12, 1.19]; *p* = 0.042) and relative peak power (*g* = 0.53, 95%CI [-0.12, 1.19]; *p* = 0.042) were present between the ACL reconstructed group before injury and after reconstruction at the end of rehabilitation around at the time of RTS (Table 5).

***** INSERT FIGURES 5, 6 and 7 NEAR HERE *****

DISCUSSION

Our aim was to examine how pre-injury data can be used to guide performance recovery and inform physical readiness as part of RTS decision making. Cumulatively, the results indicate that residual deficits in strength and power are present following ACL reconstruction (7.6 ± 1.8 months post-surgery) and the pattern of recovery is diverse across tests and metrics selected. Use of both the uninvolved limb and normative data of matched controls as a proxy measure to determine the level of performance recovery may not always be appropriate to estimate the degree of recovery and practitioners are encouraged to collect routine pre-injury data where possible to most accurately assess physical readiness to RTS.

Recovery of involved limb and bilateral performance

Deficits in knee extension peak torque relative to controls have been documented in male multidirectional team sport athletes more than 6 months following surgery [29]. In our study, group mean values indicated normalised quadriceps strength levels in the ACL cohort at the time of RTS were in line with recommended thresholds (> 3.0 Nm/kg at 60°/s) [43], and did not significantly differ from the uninjured group indicating this should be the first rehabilitation target. However, there was some variability across participants (figure 3a), and normalised quadriceps strength of the involved limb post ACL reconstruction showed reduced values compared to those recorded pre-injury ($g = -0.48$, $p = 0.036$), suggesting that comparison with pre-injury values may add important information regarding strength recovery following ACL reconstruction. Our professional athletes completed a progressive strength training intervention during rehabilitation which has been shown to attenuate strength deficits following ACL rehabilitation [43]. However, normalised quadriceps strength on the involved limb was reduced compared to baseline values and substantially lower than the contralateral limb at the the end of rehabilitation. These data indicate that both individual limb torque scores need to be considered in RTS decision making, and when pre-injury data are available, assessment of symmetry may be secondary compared to attainment of the athletes own benchmark scores on each limb. Longer rehabilitation periods (≥ 9 months) may also be needed to recover knee extensor torque deficits [3]. Optimal knee extension strength recovery is associated with reduced risk of future knee injury [12] and osteoarthritis [9], greater subjective knee functional scores (IKDC) [6], articular cartilage status [11], and reduced inter-limb and intralimb maladaptive compensation strategies during unilateral and bilateral jumping and landing tasks [28]. Targeted interventions with a maximal strength emphasis should be integral components of rehabilitation until at the very least normative values (>3.0 Nm/Kg) are met.

Our study revealed a significant reduction in CMJ height, RSImod and relative peak power in ACL reconstructed players in comparison to baseline pre-injury performance (CMJ height $g = - 0.54, p = 0.042$; RSImod $g = - 0.39, p = 0.083$; relative peak power $g = - 0.53, p = 0.042$) and healthy controls (CMJ height $g = -1.17, p \leq 0.0001$; RSImod $g = - 0.89, p = 0.001$; relative peak power $g = - 0.76, p = 0.008$). For some indviduals, CMJ height was substantially lower than their pre-injury baseline (Figure 5). Other researchers have suggested that recovery of CMJ height is still incomplete at the time to RTS in comparison to healthy controls [35]. There was also evidence of large reductions in SLCMJ height ($g = -1.64, p \leq 0.0001$) and RSImod ($g = -0.93, p = 0.004$) on the involved limb, and this trend was consistent across most participants (Figure 2a). To execute a single leg jump, there is a higher relative force requirement compared to bilateral (estimated ~ 1.62 times of those in a CMJ) to displace body mass vertically, resulting in slower movement velocities[7]. We observed a greater reduction in SLCMJ (-12.08%, than CMJ height (-5.92%) following ACL reconstruction (figure 6). Therefore, as the deficits in SLCMJ height were twice the magnitude of those in the CMJ, it could be suggested that SLCMJ height offers a better reflection of limb capacity compared to measurement of the same variable in a bilateral jump. The CMJ task allows athletes to re-distribute their impulse production via inter-limb compensations in an attempt to maintain similar jump heights [35]. These data can be derived from dual force platforms but such technology is not commonly available to clinicians. Measurement of SLCMJ height is obtainable using a variety measurement tools and may be a useful indicator to determine the recovery of limb capcity around the time of RTS.

Previous research has reported SLCMJ normative scores of > 17 cm in multidirectional field sport athletes at the late stages of rehabilitation [32]. These values are in line with the results of our study (figure 7) which included healthy professional soccer players. Therefore, ~ 18 cm may represent a realistic target to achieve by the end of rehabilitation for field sport athletes if pre-injury values are not available. However, as many athletes baseline scores were higher (figure 2a), this further highlights the importance of routine pre-injury data collection at regular intervals to ensure the most accurate benchmark is established. In addition, the ACL reconstructed limb showed reduced RSImod in comparison to the dominant limb of healthy controls (figure 7). Decreased stretch shortening cycle performance has been recently documented in similar cohorts [19,27,34] and is associated with higher risk of ipsilateral and contralateral ACL injury [17,18], as well as reduced sports performance [25,30]. Thus, increased emphasis on reconditioning strategies to recover ballistic performance needs to be embedded in the RTS pathway together with progressive strength training interventions [4,5].

The use of proxy measures in decision making

When making RTS decisions, comparison with preinjury is often impracticable. Our data suggest that in single leg jumping tasks, healthy matched controls including mean values for team mates or published data for a similar playing level could provide a suitable reference of the minimum target which should be achieved in monitoring the recovery of physical performance following ACL reconstruction. However, utilisation of strength scores in healthy controls may not follow the same pattern. Overestimation of functional improvements during rehabilitation have been reported previously when using pre-operative scores on the contralateral limb as a reference value at the time of RTS owing to a bilateral reduction in physical performance following ACL reconstruction [44] inflating limb symmetry indexes. In contrast, we observed that normalised quadriceps and hamstring strength improved from pre-injury following the completion of rehabilitation on the uninvolved limb in the ACL reconstructed group and scores were greater than matched controls (figure 7) suggesting an underestimation in the degree of recovery if the latter comparison was used. Conversely, involved limb reductions in quadriceps strength at the time of RTS were greater when compared to pre-injury data (7%) and healthy controls (2.6%) suggesting use of healthy control values would overestimate the degree of recovery for involved limb quadriceps strength. If the contralateral limb was used post injury, a larger between-limb difference was present (14%) and this would underestimate the degree of recovery. Our participants were full-time athletes attending rehabilitation 5 days per week, of which, knee extension and flexion strength were considered a priority. This suggests that when a comprehensive rehabilitation programme including progressive strength training is followed, comparison with matched controls alone is not enough, although it does represent the first achievable milestone to ensure strength recovery. However, it should be considered that training age and routine exposure to strength and conditioning of the healthy controls were not examined. Similarly, use of the contralateral limb may be misleading and can underestimate recovery when significant training adaptations have occured. Thus, proxy measures to determine the level of performance recovery may not always be appropriate.

Large performance reductions were observed in bilateral CMJ height and RSImod based on healthy controls values, but the corresponding deficits based on true benchmark values were classified as moderate, suggesting a potential underestimation of recovery of these metrics when using healthy control data. SLCMJ performance on the uninvolved limb showed no significant difference pre-injury vs. RTS although there was a slight reduction in jump height. Our data indicate that both healthy controls and the unaffected limb could be used as a references in monitoring SLCMJ performance recovery (i.e., achievement of pre-injury baseline values) on a group level, but caution should be applied as several athletes pre-injury SLCMJ scores were greater than these values.

Our data also suggests that a comprehensive rehabilitation program can mitigate reductions in contralateral knee strength and power secondary to surgery and reduced load exposure. Maintaining or even increasing quadriceps and plyometric qualities can have important implications in reducing subsequent ACL injury risk to the uninjured limb in male athletes following ACL reconstruction [18], and thus should be monitored during rehabilitation. Further research is encouraged to measure temporal recovery across multiple timepoints in these physical qualities to more accurately determine the trajectory of recovery.

Limitations

Changes from baseline pre-injury scores following ACL reconstruction should be interpreted relative to the measurement error in the metrics used (Table 1). CMJ height and relative peak power displayed CV values of 2.7 and 2.1% respectively. The corresponding % changes following ACL reconstruction and rehabilitation were 5.92 and 4.94% indicating a ‘real’change had occurred with differences larger than the observed measurement error. RSImod reduced by 5.51% but the CV value was 8.6% which suggests the observed differences were within the error range and could be considered less meaningful. Similarly, only SLCMJ height showed changes following ACL reconstruction larger than the measurement error (-12% reduction; CV: 5.2%), whereas RSImod and relative peak power had a greater CV% relative to the observed % change. In addition, we were not able to collect follow up data on the uninjured controls to determine what is ‘normal’ seasonal variation in these metrics.

Our sample size precluded us from conducting analysis based on graft type and this may have an effect on strength and power qualities. The majority of our players had a bone-patellar tendon-bone graft, which can explain the incomplete and delayed recovery of knee extensor and concentric jump outputs deficits, in comparison to similar cohorts with a semitendinosus/gracilis graft type[31]. Future research may wish to examine temporal recovery of physical qualities using benchmark pre-injury data considering different graft types. Finally, none of the assessments directly assessed eccentric qualities, which may show divergent recovery patterns and deficits, and therefore our conclusions should be considered to be principally related to concentric strength / jump outputs that ultimately reflect capacity to generate concentric impulse. Our data were limited to adult male professional football players. Therefore, generalisation of these results to pediatric, adolescent and female athletes requires caution. Although the involved surgeons and rehabilitation specialists belonged to the same Orthopaedic and Sports Medicine Hospital, potential variations in surgical techniques and rehabilitation strategies could have been present and should also be acknowledged.

CONCLUSION

The current study indicates that ACL reconstruction has a detrimental effect on strength and power characteristics in professional soccer players but the pattern was diverse. Peak knee extension strength, CMJ and SLCMJ height, RSImod, and relative peak power values at the end of rehabilitation prior to RTS remained below those recorded pre-injury. Furthermore, inspite of the fact that players approached strength values deemed sufficient in the ACL reconstructed limb and exceeded these criteria in the contralateral limb, large differences in SLCMJ height and RSImod were still evident on the ACL reconstructed limb in comparison to uninjured matched controls. These differences were smaller when assessed bilaterally (i.e., CMJ test), indicating that SLCMJ can be used to more closely evaluate the recovery of individual limb physical capacity. These data can be easily obtained using a variety of cost effective methods, especially compared to isokinetic assessments which require expensive equipment and are time in-efficicent.

Our findings are summarised in table 6, and have clinical implications to help guide the RTS process. Cumulatively, we suggest that an optimal approach to determine physical recovery at the time of RTS would include the following: 1) data collected as early as possible (baseline pre-injury if available or if not pre-operative values on the uninvolved limb) to inform readiness to RTS as this should be considered the gold standard reducing the need for proxy measures of limb recovery, which can overestimate or underestimate limb function; 2) consider both absolute scores on each limb and not just symmetry values; 3) in situations where baseline pre-injury data are not available, compare to uninjured matched controls to ensure minimum standards are met. In addition, we suggest to include both unilateral and bilateral assessments with a range of demands across the strength, power and velocity spectrum to ensure performance is measured under different task constraints.

FIGURES 2a, 2b, 3a, 3b, 4a, 4b, 5, and 7 and TABLES 1, 3, & 4 ONLINE ONLY

***** INSERT TABLE 6 NEAR HERE *****

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Figure 1 Schematic representation of the study design. Uninjured players (black). Injured players (grey).

Figure 2a Involved limb and **Figure 2b** uninvolved limb single leg countermovement jump (SLCMJ) height pre-injury and post anterior cruciate ligament reconstruction (ACLR). Centimeters (cm). Control group (CTRL)

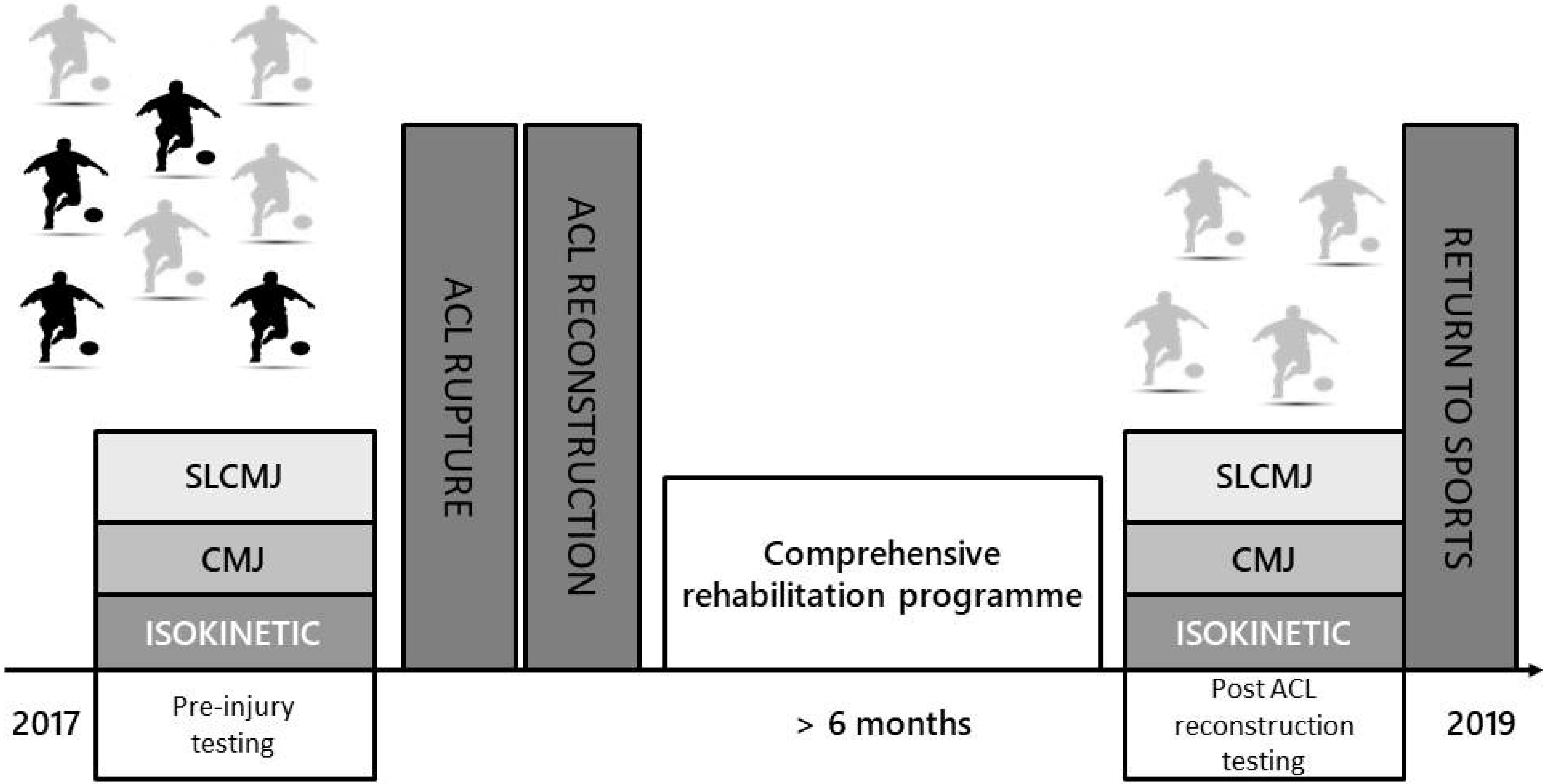
Figure 3a Involved limb and **Figure 3b** uninvolved limb knee extension strength pre-injury and post anterior cruciate ligament reconstruction (ACLR). Newton (N). Meter (m). Kilogram (kg). Control group (CTRL)

Figure 4a Involved limb and **Figure 4b** uninvolved limb knee flexion strength pre-injury and post anterior cruciate ligament reconstruction (ACLR). Newton (N). Meter (m). Kilogram (kg). Control group (CTRL)

Figure 5 Countermovement jump (CMJ) height pre-injury and post anterior cruciate ligament reconstruction (ACLR). Centimeters (cm). Control group (CTRL)

Figure 6 Percentage changes from pre-injury to post anterior cruciate ligament reconstruction of all variables analysed. Quadriceps relative peak torque (Quad PT Rel), Hamstrings elative peak torque (HS PT Rel), single leg countermovement jump (SLCMJ), reactive strength index modified (RSImod), relative peak power (peak power Rel), countermovement jump (CMJ), uninvolved (Uninv), involved (Inv)

Figure 7 Knee extension and flexion strength, single leg countermovement jump height, RSI and relative peak power. Newton (N). Meter (m). Centimetre (cm). Metre (m). Second (s). Kilogram (kg). Watt (W). RTS (return to sport)



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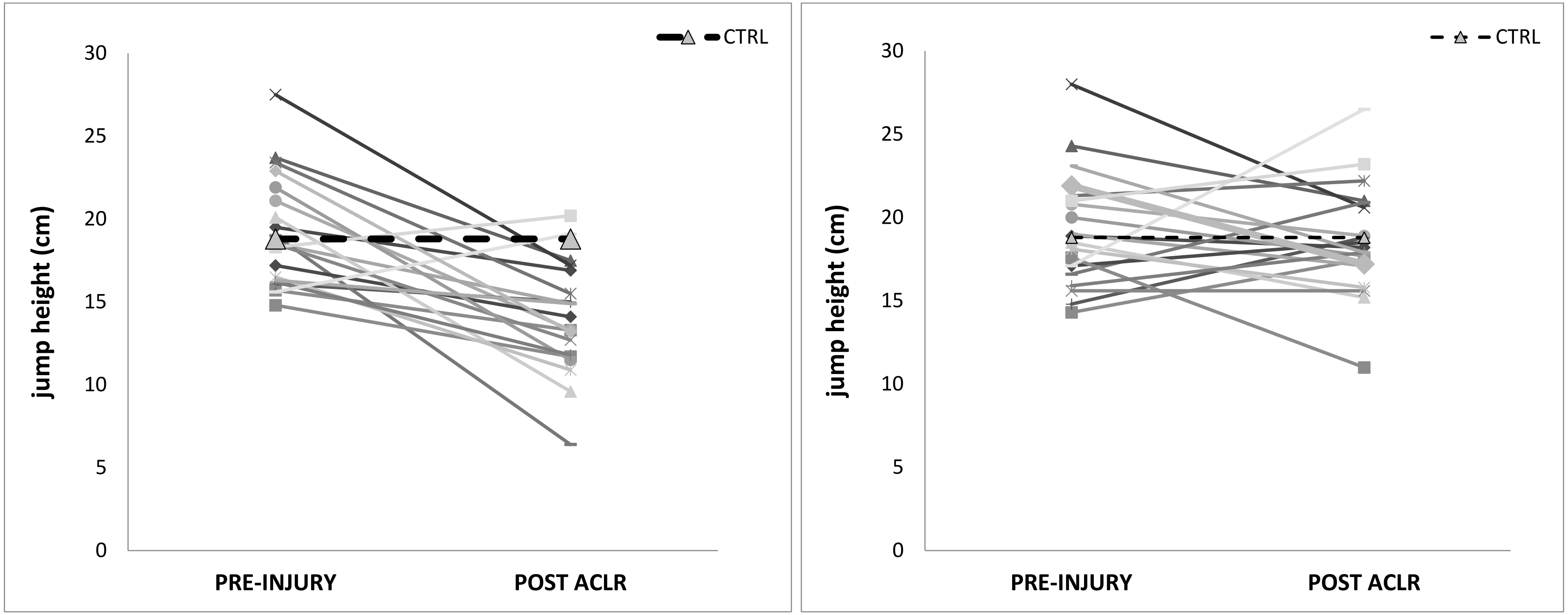

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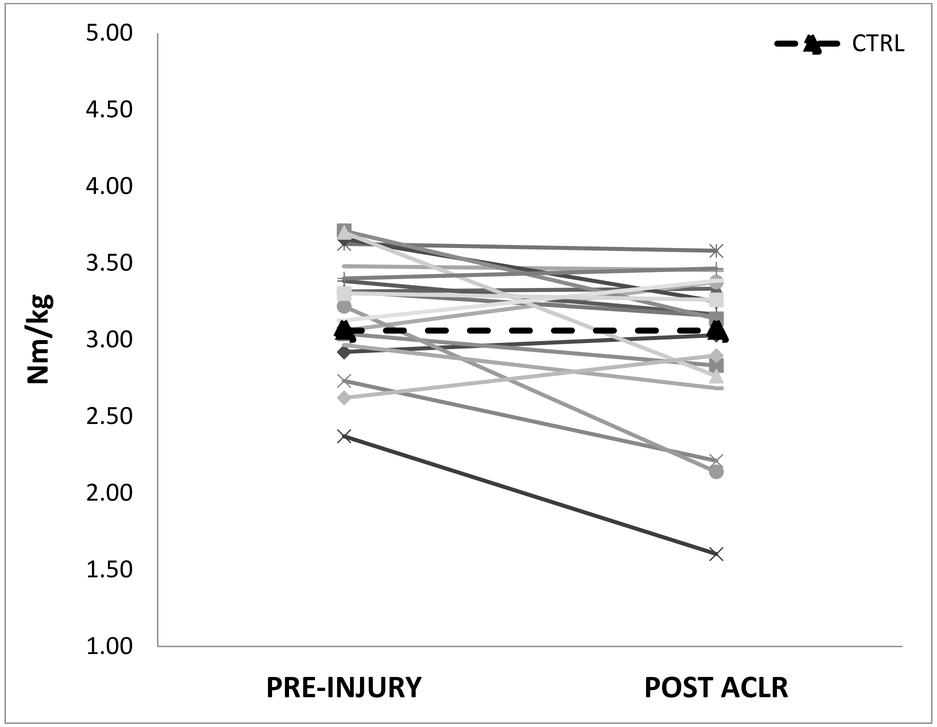

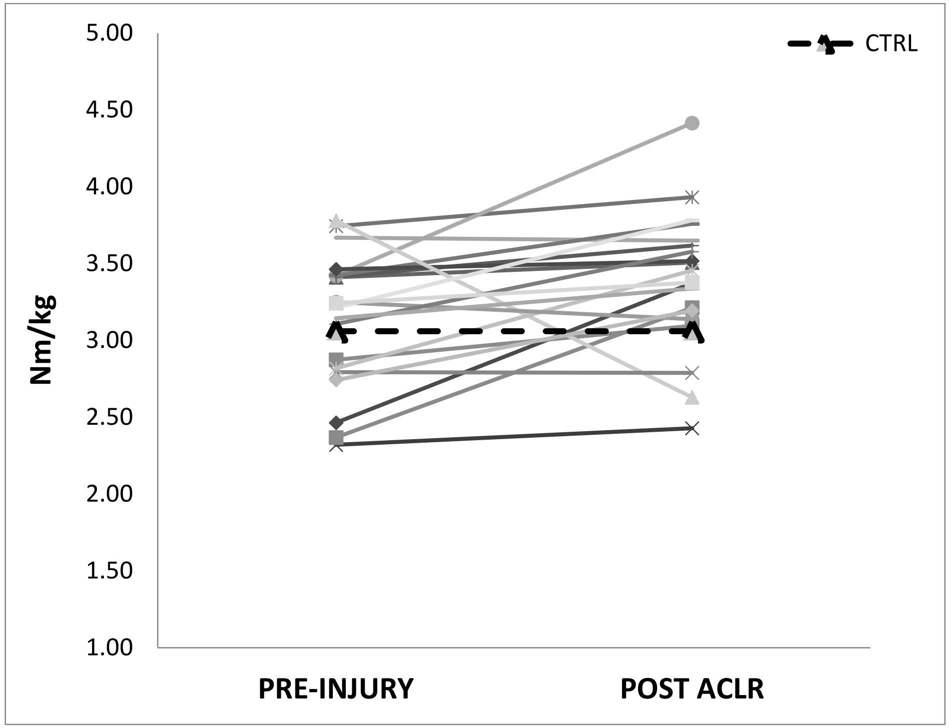

Figure 3a Involved limb and **Figure 3b** uninvolved limb knee extension strength pre-injury and post anterior cruciate ligament reconstruction (ACLR). Newton (N). Meter (m). Kilogram (kg). Control group (CTRL)

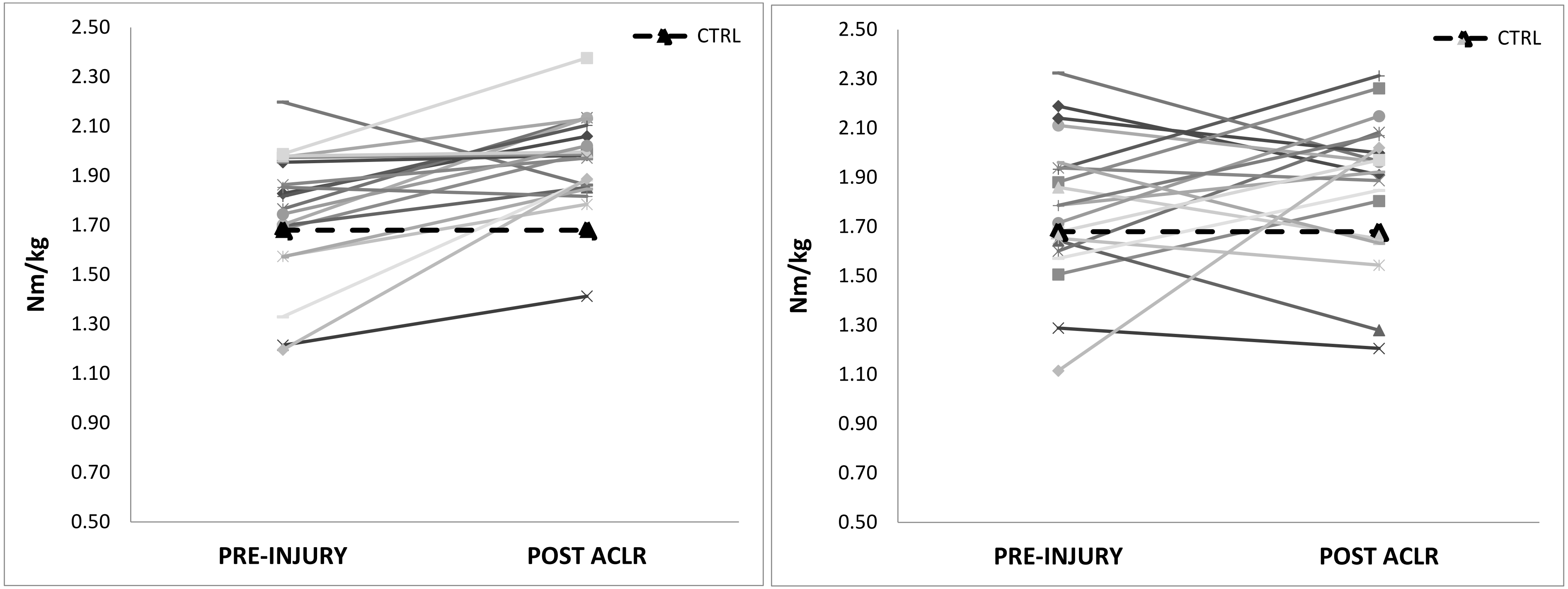

Figure 4a Involved limb and **Figure 4b** uninvolved limb knee flexion strength pre-injury and post anterior cruciate ligament reconstruction (ACLR). Newton (N). Meter (m). Kilogram (kg). Control group (CTRL)

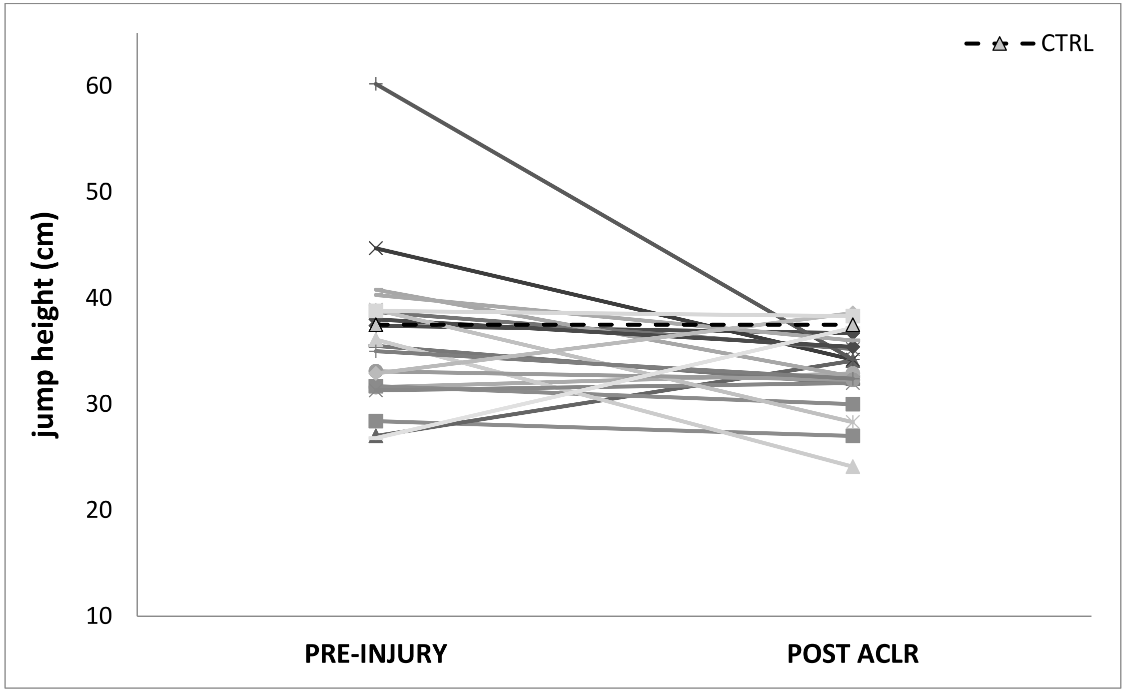

Figure 5 Countermovement jump (CMJ) height pre-injury and post anterior cruciate ligament reconstruction (ACLR). Centimeters (cm). Control group (CTRL)

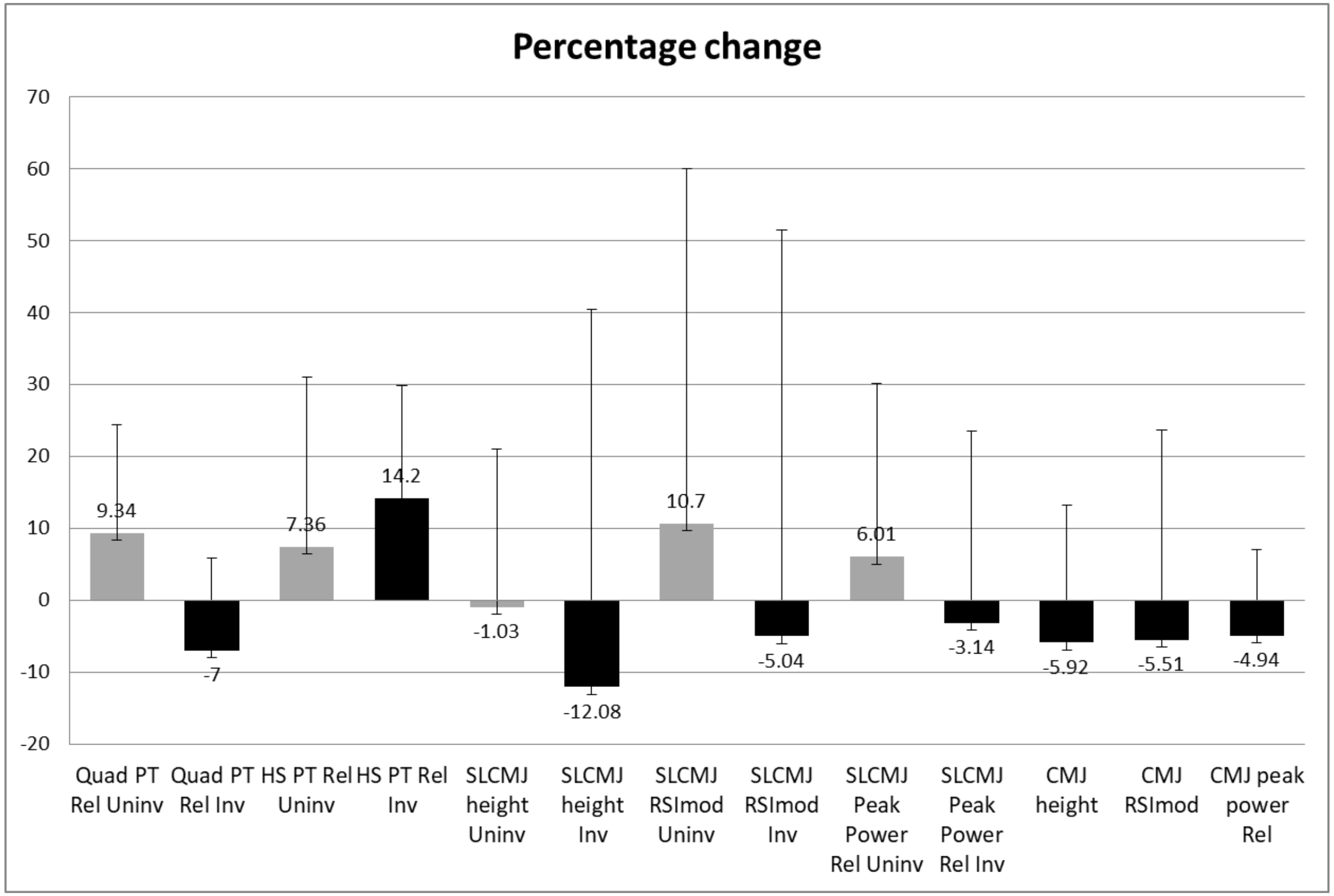

Figure 6 Percentage changes from pre-injury to post anterior cruciate ligament reconstruction of all variables analysed. Quadriceps relative peak torque (Quad PT Rel), Hamstrings relative peak torque (HS PT Rel), single leg countermovement jump (SLCMJ), reactive strength index modified (RSImod), relative peak power (peak power Rel), countermovement jump (CMJ), uninvolved (Uninv), involved (Inv)

Table 1 Intra-class correlation coefficients (ICC), coefficient of variation (CV%) and standard error of measurement (SEM) of the performance variables assessed during the bilateral countermovement jump (CMJ) and single leg countermovement jump (SLCMJ)

Test	Variable	CV % (95%CI)	ICC (2,1) (95% CI)	SEM
CMJ	Jump Height	2.7 (1.6 -3.8)	0.978 (.922- .994)	1.4
CMJ	Peak Power Rel	2.1 (1.2 – 3.0)	0.966 (.883- .991)	1.4
CMJ	RSI Mod	8.6 (5.0 – 12.2)	0.945 (.875-.976)	0.0
SLCMJ	Jump Height INV	5.2 (3.2 – 7.1)	0.96 (.876- .988)	1.0
SLCMJ	Peak Power Rel INV	6.3 (3.9 – 8.7)	0.781 (.424- .928)	2.2
SLCMJ	RSI Mod INV	10.8 (6.6 – 14.9)	0.907 (.724- .971)	0.0
SLCMJ	Jump Height UNINV	5.9 (3.6 – 8.1)	0.933 (.802-.979)	1.0
SLCMJ	Peak Power Rel UNINV	4.0 (2.5 – 5.5)	0.860 (.612- .955)	1.4
SLCMJ	RSI Mod UNINV	8.0 (4.9 – 11.1)	0.893 (.686- .966)	0.0
SLCMJ	Jump height symmetry	4.2 (2.4 - 6.0)	0.901 (.713- .968)	4.6

INV (involved limb), UNINV (uninvolved limb)

Table 2 Isokinetic, single leg and bilateral countermovement jump (CMJ) results of each group

Test	**Group 1 Pre-Injury (n=20)**		**Group 2: Healthy Controls (n=35)**	**Pre-injury vs controls effect size (95%CI)**	**Pre-injury vs controls *P* value**
	Involved limb	Uninvolved limb	Dominant Limb		
Quad PT Rel (N.m.kg^{-1})	3.2±0.37	3.13±0.44	3.06±0.4	0.35 (-0.21 to 0.92)	0.200
HS PT Rel (N.m.kg^{-1})	1.75±0.26	1.79±0.3	1.68±0.22	0.29 (-0.27 to 0.86)	0.335
SLCMJ Jump Height (cm)	18.5±4.4	19.2.2±3.4	18.8±2.3	-0.09 (-0.65 to 0.47)	0.787
SLCMJ RSI Mod	0.22±0.08	0.24±0.07	0.24±0.05	-0.25 (-0.82 to 0.31)	0.510
SLCMJ Peak Power Rel (W/Kg)	31.7±4.3	32.7±4.4	31.9±4.2	-0.05 (-0.61 to 0.52)	0.855
CMJ Jump Height (cm)	36.4±7.4		37.5±3.6	-0.22 (-0.78 to 0.35)	0.231
CMJ RSI Mod	0.46±0.11		0.49±0.07	-0.30 (-0.86 to 0.27)	0.354
CMJ Peak Power Rel (W/Kg)	52.1±6.3		52.8±4.9	-0.13 (-0.69 to 0.44)	0.695

PT (peak torque), Rel (relative to body mass), N (Newtons), m (meters), kg (kilograms), W (Watts), cm (centimeters)

Table 3 Isokinetic and single leg countermovement jump (SLCMJ) results of the uninvolved limb of the injured group and healthy matched controls

Test	**Group 1 Pre-Injury (n=20)**	**Group 1 Post-Injury (n=20)**	**PRE vs POST effect size (95%CI)**	**PRE vs POST P value**	**Pre-Post Percentage difference (95%CI)**	**Group 2: Healthy Controls (n=35)**	**Post-injury vs controls effect size (95%CI)**	**Post-injury vs controls *P* value**
	Uninvolved limb	Uninvolved limb						
Quad PT Rel (N.m.kg^{-1})	3.13±0.44	3.39±0.45	-0.57 (-1.23 to 0.08)	0.021	9.34% (6.45 to 12.23)	3.06±0.4	0.77 (0.19 to 1.36)	**0.018**
HS PT Rel (N.m.kg^{-1})	1.79±0.3	1.87±0.29	-0.27 (-0.91 to 0.38)	0.261	7.36% (5.08 to 9.64)	1.68±0.22	0.77 (0.19 to 1.35)	**0.005**
SLCMJ Jump Height (cm)	19.2.2±3.4	18.6±3.3	0.18 (-0.47 to 0.82)	0.517	-1.03% (-1.35 to -0.71)	18.8±2.3	-0.08 (-0.64 to 0.48)	0.568
SLCMJ RSI Mod	0.24±0.07	0.24±0.06	-0.03 (-0.67 to 0.61)	0.900	10.7% (7.38 to 14.02)	0.24±0.05	0.10 (-0.46 to 0.66)	0.987
SLCMJ Peak Power Rel (W/Kg)	32.7±4.4	33.0±3.9	0.17 (-0.47 to 0.82)	0.232	6.01% (4.15 to 7.87)	31.9±4.2	0.25 (-0.31 to 0.82)	0.385

PT (peak torque), Rel (relative to body mass), N (Newtons), m (meters), kg (kilograms), W (Watts), cm (centimeters)

Table 4 Isokinetic and single leg countermovement jump (SLCMJ) results of the involved limb of the injured group and healthy matched controls

Test	**Group 1 Pre-Injury (n=20)**	**Group 1 Post-Injury (n=20)**	**PRE vs POST effect size (95%CI)**	**PRE vs POST P value**	**Pre-Post Percentage difference (95%CI)**	**Group 2: Healthy Controls (n=35)**	**Post-injury vs controls effect size (95%CI)**	**Post-injury vs controls *P* value**
	Involved limb	Involved limb						
Quad PT Rel (N.m.kg^{-1})	3.2±0.37	2.98±0.51	0.48 (-0.17 to 1.13)	0.036	-7% (-9.2 to -4.8)	3.06±0.4	-0.18 (-0.74 to 0.39)	0.993
HS PT Rel (N.m.kg^{-1})	1.75±0.26	1.96±0.19	-0.90 (-1.58 to -0.23)	**≤0.0001**	14.2% (9.8 to 18.6)	1.68±0.22	1.32 (0.70 to 1.93)	**≤0.0001**
SLCMJ Jump Height (cm)	18.5±4.4	14.6±2.9	1.03 (0.34 to 1.71)	**0.005**	-12.08% (-16.54 to -9.06)	18.8±2.3	-1.64 (-2.28 to -0.99)	**≤0.0001**
SLCMJ RSI Mod	0.22±0.08	0.18±0.06	0.50 (-0.16 to 1.15)	0.099	-5.04% (-6.6 to -3.48)	0.24±0.05	-0.93 (-1.52 to -0.34)	**0.004**
SLCMJ Peak Power Rel (W/Kg)	31.7±4.3	30.2±7	0.25 (-0.39 to 0.90)	0.411	-3.14% (-3.61 to -2.67)	31.9±4.2	-0.31 (-0.88 to 0.25)	.325

PT (peak torque), Rel (relative to body mass), N (Newtons), m (meters), kg (kilograms), W (Watts), cm (centimeters)

Table 5 Countermovement Jump test results of each group

Test	Group 1 Pre-Injury (n=20)	Group 1 Post-Injury (n=20)	PRE vs POST effect size (95%CI)	PRE vs POST P value	Pre-Post Percentage difference (95%CI)	Group 2: Healthy Controls (n=35)	Post-injury vs controls effect size (95%CI)	Post-injury vs controls *P* value
CMJ Jump Height (cm)	36.4±7.4	33.2±3.7	0.54 (-0.12 to 1.19)	0.042	-5.92% (-7.76 to -4.08)	37.5±3.6	-1.17 (-1.77 to -0.56)	**≤0.0001**
CMJ RSI Mod	0.46±0.11	0.42±0.09	0.39 (-0.26 to 1.04)	0.083	-5.51% (-7.22 to -3.8)	0.49±0.07	-0.89 (-1.48 to -0.30)	**0.001**
CMJ Peak Power Rel (W/Kg)	52.1±6.3	49.1±4.6	0.53 (-0.12 to 1.19)	0.042	-4.94% (-6.47 to -3.41)	52.8±4.9	-0.76 (-1.34 to -0.18)	**0.008**

W (Watts), cm (centimeters), kg (kilograms)

Table 6 Summary table

Research question	**Significant findings**
Do the strength and power characteristics differ in soccer players who sustained an ACL injury and underwent subsequent reconstructive surgery to those of uninjured players?	No difference between groups in strength, power and reactive strength characteristics at baseline assessment, but lower performance was indicated in ACL reconstructed players at the end of rehabilitation
How does ACL reconstruction effect isokinetic knee extension / flexion strength and SLCMJ performance on the ***un-involved limb***?	Increase in quadriceps and hamstring strength from pre-injury to RTS. No significant differences from pre-injury in SLCMJ height, power and reactive strength following ACL reconstruction
How does ACL reconstruction effect isokinetic knee extension / flexion strength and SLCMJ performance on the ***involved limb***?	Increase in hamstring strength from pre-injury to RTS Decrease in quadriceps strength, SLCMJ height and reactive strength following ACL reconstruction
How does ACL reconstruction effect ***CMJ performance***?	Decrease in jump height, reactive strength and power following ACL reconstruction