Angle specific analysis of hamstrings and quadriceps isokinetic torque identify residual deficits in soccer players following ACL reconstruction: a longitudinal investigation

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ABSTRACT

Analysing the isokinetic curve is important following ACL reconstruction as there may be deficits in torque production at specific points throughout the range of motion. We examined isokinetic (60°.s-1) torque-angle characteristics in 27 male soccer players (24.5 ± 3.9 years) at 3 time-points (17 ± 5; 25 ± 6; and 34 ± 7 weeks post-surgery). Extracted data included knee flexor and extensor peak torque, conventional hamstrings: quadriceps (H/Q) ratio, and angle-specific torque using Statistical Parametric Mapping (SPM). There were significant involved limb increases in extension peak torque at each assessment ($p<0.001$); however, asymmetry favouring the un-involved limb was observed ($p<0.01$). Flexion peak torque was greater on the un-involved limb at assessments 1 and 2 only ($p<0.05$). The angle of peak torque was not significantly different at individual time-points or within-limbs across the 3 assessments. SPM revealed involved limb angle-specific reductions in extension torque across the full range of motion at time-points 1 and 2 ($p<0.001$) but only in angles [51-80°] at assessment 3 ($p<0.05$). Between limb H/Q angle differences [33-45°] were shown at assessments 2 and 3. The ratio ranged from 1.60-0.74 depending on the angle tested. Angle-specific moment curves are useful for monitoring patterns of strength development during rehabilitation.

KEYWORDS Torque; strength; statistical parametric mapping; ratio

INTRODUCTION

Quadriceps and hamstring strength deficits are common following anterior cruciate ligament (ACL) reconstruction. (Schmitt et al., 2012) Increased quadriceps strength is associated with lower asymmetry during landing activities characterized as high injury risk. (Schmitt et al., 2015) Strong positive associations have also been reported with self-reported knee function, (Pietrosimone et al., 2013) physical performance, (Maestroni et al., 2021) lower risk of re-injury (Grindem et al., 2016; Paterno et al., 2010), and the development of osteoarthritis. (Tourville et al., 2014)

Isokinetic dynamometry provides an objective measure of muscle strength and has been used frequently following ACL reconstruction. (Undheim et al., 2015) The most common isokinetic output variable is peak torque for each tested joint rotation velocity. (Undheim et al., 2015) However, torque production is affected by several factors, including the mode of contraction, angular velocity, range of motion (ROM), number of repetitions, and gravity correction. (Undheim et al., 2015)

A limitation with just examining peak torque is that it discards angle-specific moment generating capacity. Analysing the curve represents an individual's ability to generate torque throughout the entire ROM. This has increased importance following ACL injury and reconstruction as isokinetic torque curves may display inherent irregularities (Ayalon et al., 2002; Ikeda et al., 2002) and specific deficits can remain undetected without evaluation of the entire angle-moment profile. (Baumgart et al., 2018; Eitzen et al., 2010; Huang et al., 2017; Shirakura et al., 1992) Between-limb quadriceps muscle strength differences have been shown most significant at flexion angles <45° (14) or <40º (0º = full leg extension; Eitzen et al., 2010; Huang et al., 2017) in ACL-deficient knees. Conversely, in ACL reconstructed male and female athletes, reported differences between the operated and non-operated limb were larger at knee angles >50°, (Baumgart et al., 2018) indicating surgical intervention may induce different isokinetic moment curve deficits.

Concentric/concentric hamstring: quadriceps (H/Q) muscle strength ratios are also most commonly used to determine readiness to return-to-sport following ACL reconstruction. (Undheim et al., 2015) A conventional ratio 0.56–0.59 has been reported in professional soccer players depending on playing experience. (Fousekis et al., 2010) However, hamstrings and quadriceps peak torque are achieved at different angles and quadriceps weakness is a known outcome following ACL reconstruction, (Maestroni et al., 2021) altering the ratio in favour of the hamstrings. Continuous angle-specific analysis has been used in a mixed cohort of male and female athletes from different sports following ACL hamstring tendon graft reconstruction. (Baumgart et al., 2018) H/Q ratios ranged from 0.43 to 1.89 over the total ROM. Conventional isokinetic evaluation of H/Q ratio using peak torque may therefore be inappropriate to determine antagonist to agonist muscle balance (Ruas et al., 2019), which can have implications for return-to-play decision-making. (Undheim et al., 2015)

Statistical Parametric Mapping (SPM) is a method that has been developed to consider the entire torque curve without reducing its dimensionality to a single point. (Alhammoud et al., 2019) To our knowledge, no studies have included male soccer players following ACL reconstruction, and more importantly, longitudinal data including angle-specific analysis at different stages of rehabilitation. This information may assist clinicians in understanding muscle adaptations that occur during the rehabilitation process and provide targeted exercise prescription with the aim of restoring full knee function prior to return-to-sport.

The aim of this study was to examine the longitudinal strength characteristics of soccer players at different stages of rehabilitation following ACL reconstruction. We included both commonly used protocols (assessment of peak torque) and SPM to analyse isokinetic strength parameters throughout the entire range of motion. It was hypothesized that SPM would both reveal and characterise the presence of residual deficits in knee extensor strength that are not readily apparent with traditional metrics alone such as the maximal peak torque and this may help guide rehabilitation.

MATERIALS AND METHODS

This study employed a single cohort, repeated measures design. Following ACL reconstruction, participants attended at three timepoints during their rehabilitation. The isokinetic test formed part of a battery of assessments including patient reported outcomes, clinical assessment, and movement screening. Isokinetic dynamometry was performed following clinical assessment and movement screening. Test order and all procedures including time of day were standardized at each assessment.

Participants

27 male soccer players (24.5 ± 3.9 years; height = 174.5 ± 7.1 cm; mass = 72.2 ± 10.2 kg) competing in one of the recognized leagues within the Qatar Football Association prior to their injury. The majority of participants underwent a bone-patellar tendon-bone (70%) vs. hamstring (30%) autograft. Mean time post-surgery was 17 ± 5 weeks; 25 ± 6 weeks; and 34 ± 7 weeks at assessments 1, 2, and 3, respectively. 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. All players attended the same Orthopaedic and Sports Medicine centre throughout the duration of the study. They completed a criteria-based rehabilitation programme (van Grinsven et al., 2010) in addition to a sports-specific phase of reconditioning. Informed written consent and ethical approval were obtained prior to commencement of testing. This study was approved by the institutional review board (IRB: F2017000227).

Procedures

Isokinetic assessment

Players completed a standardized warm up consisting of 5 minutes on a cycle ergometer, 10 bilateral and unilateral bodyweight squats, and bilateral countermovement jumps at 50, 75, and 100% of maximal effort. Knee extension and flexion strength were measured using an isokinetic dynamometer (Biodex System 4 Pro™, Biodex Medical Systems, Shirley, New York, USA). Players were set up according to the manufacturers guidelines and tested in a seated position with the hip flexed to 90° and hands by their sides. Gravity correction was performed prior to each test with the mass of the limb taken at 20º of knee flexion. Procedures were explained to participants, following which they completed three practice repetitions. Testing then commenced after 60s. Isokinetic assessment included five repetitions of concentric knee extension and flexion, respectively, at $60°.s^{-1}$. Standardized, vigorous verbal encouragement was provided throughout, and players were instructed to "kick up" and "pull back" as hard and fast as possible. The un-involved limb was tested first, followed by the involved limb. Each participant had previous experience of isokinetic testing, and all tests were conducted by an experienced physiotherapist (> 5 years) in the relevant test procedures.

Data extraction

The torque-angle series were extracted from the original torque dataset recorded at 100 Hz using custom routines in Matlab (version 2017a, MathWorks, Natick, MA, USA). Angles were low-pass filtered (fourth-order Butterworth, cut-off frequency at 10 Hz), and contractions were separated based on the sign inversion of the angle derivate. Torque was low-pass filtered (fourth-order Butterworth, cut-off frequency at 6 Hz) and resynchronized per degree of knee angle with a linear interpolation fitting to the raw torque values. The first and last contractions of each series were discarded from the analysis (repetitions 1 and 5) as well as abnormal curves after visual inspection. For the SPM analysis, the mean of the three remaining curves for each leg was used for subsequent statistical analysis of the 27 participants. Torque-angle curves for quadriceps and hamstrings were constructed through the isovelocity period using a [28–81°] range of motion (0º representing full leg extension). (Baltzopoulos & Brodie, 1989) The angle-specific H/Q ratio was continuously calculated by dividing hamstrings torque by quadriceps torque at the same knee angle. (Alhammoud et al., 2019)

Scaler data were also extracted including peak torque (N. m) of the quadriceps and hamstrings muscles defined as the highest torque output during the three recorded trials in addition to the angle at which this was recorded. To provide a relative measure, torque was normalized to body mass (N.m. kg−1). The limb symmetry index was calculated as a percentage (involved/un-involved*100) as well as the conventional non-angle-specific maximal H/Q ratio by dividing the hamstrings by quadriceps concentric maximal torque. This method of calculation was included as its most commonly used to assess limb symmetry following ACL reconstruction. (Undheim et al., 2015)

Statistical analyses

Comparative angle-specific torque analysis was conducted for the entire time-dependent torque signal using SPM-1D (© Todd Pataky, 2014, version M0.4), (Trama, 2021) an open-access package that performs SPM using a non-parametric approach called permutation tests. (Nichols & Holmes, 2002) We performed two-way ANOVA SPM{F} on the torque and ratio time-series to determine the main effects of time (first, second, third tests) and injury leg status (involved/un-involved) as well as the interaction between these factors. A two-way ANOVA was also completed for the scalar analysis. Then, *post hoc* tests were conducted on each vector component separately with two-sided paired samples t-tests SPM{t. (Pataky et al., 2015) A p-value with Bonferroni correction was calculated for each cluster crossing the critical threshold, with significance set at $p < 0.05$. Paired samples t-tests were also performed where appropriate when significant mean differences were identified following the completion of the two-way ANOVA used to perform the scalar analysis. Hedge's *g* effect sizes were evaluated as trivial (<0.20), small (0.20–0.49), medium (0.50–0.79), and large (≥0.80). (Kelley, 2005)

RESULTS

Peak torque

Knee extension and flexion peak torque, normalised torque, limb symmetry, H/Q ratio, and angle of peak torque descriptive statistics at each assessment are displayed in Table 1. Extension peak torque showed an effect of both time ($p < 0.001$; $g = 0.39$) and injury ($p < 0.001$; $g = 0.62$), and there was a signification interaction of these factors ($p < 0.001$; $g = 0.30$). Post hoc analysis indicated significant increases in extension peak torque across the three assessments on the involved limb only ($p < 0.001$; $g = 0.47$ to 0.57). Greater limb symmetry was shown at each assessment ($p < 0.001$; $g = 0.34$); however, significant between limb differences were observed at each time-point ($p < 0.01$; $g = 0.65$ to 1.52).

There were no main effects of time or injury on flexion torque ($p < 0.05$; $d < 0.2$) but an interaction was observed for time x injury ($p < 0.01$; $g = 0.18$). Post hoc analysis indicated that flexion torque was greater on the un-involved limb at assessments 1 ($p < 0.01$; $g = 0.49$) and 2 ($p < 0.05$; $g = 0.33$) respectively, but not at the third assessment. An effect of time was observed for LSI, with a significant increase in symmetry observed between assessments 2 and 3 ($p < 0.05$; $g = 0.48$). There were no main effects or interaction observed in the angle of peak torque for both extension and flexion ($p > 0.05$; $d < 0.2$).

No main effect of time ($g = 0.28$) and injury ($g = 0.44$) in H/Q ratio ($p < 0.001$) were observed. There was also a significant interaction effect ($p < 0.001$; $g = 0.19$). Post hoc analyses showed that the ratio on the injured leg significantly reduced at each assessment ($p < 0.05$; $g = 0.42$ to 0.54). No significant changes were observed on the un-involved limb. There was also a significant between-limbs difference at each time point ($p < 0.001$; $g = 0.87$ to 1.26), with a higher ratio consistently observed on the injured leg.

Table 1 Descriptive isokinetic statistics for each assessment.

	Assessment 1		Assessment 2		Assessment 3	
	Involved	un-involved	Involved	un-involved	Involved	un-involved
Quadriceps peak torque N.m	144 ± 42	212 ± 45	168 ± 42	215 ± 47	189 ± 48	219 ± 45
Quadriceps peak torque (N.m/kg)	1.99 ± 0.53	2.92 ± 0.53	2.30 ± 0.47	2.95 ± 0.52	2.58 ± 0.55	3.00 ± 0.51
Quadriceps peak torque LSI%	69.4 ± 21.8		79.4 ± 19.2		87.7 ± 22.8	
Quadriceps angle of peak torque	67 ± 8	68 ± 4	65 ± 7	68 ± 5	67 ± 7	67 ± 5
Hamstrings peak torque N.m	112 ± 26	124 ± 23	116 ± 27	124 ± 21	120 ± 26	119 ± 26
Hamstrings peak torque (N.m/kg)	1.55 ± 0.34	1.70 ± 0.26	1.60 ± 0.32	1.71 ± 0.25	1.64 ± 0.29	1.63 ± 0.33
Hamstrings peak torque LSI%	91.3 ± 16.4		93.6 ± 13.9		105.0 ± 30.7	
Hamstrings angle of peak torque	31 ± 8	30 ± 7	29 ± 9	28 ± 5	29 ± 13	27 ± 6
H/Q ratio	0.82 ± 0.24	0.59 ± 0.09	0.71 ± 0.16	0.59 ± 0.09	0.65 ± 0.12	0.55 ± 0.11

Non-parametric statistical inference

There was a main effect of time and injury on the overall [28– 81°] knee extension torque-angle curve ($p < 0.001$), as well as an interaction effect for time x injury on [29–81°] ($p < 0.001$). Post hoc analysis revealed that extension torque of the involved limb increased with time ($p < 0.05$), whereas the un-involved limb did not (Figure 1). Thus, the involved limb displayed lower torques than the un-involved limb over the entire [28–81°] ROM during the first test, but this difference was reduced to [32–81°] during the second test and [51–80°] during the third assessment ($p < 0.05$, Figure 1).

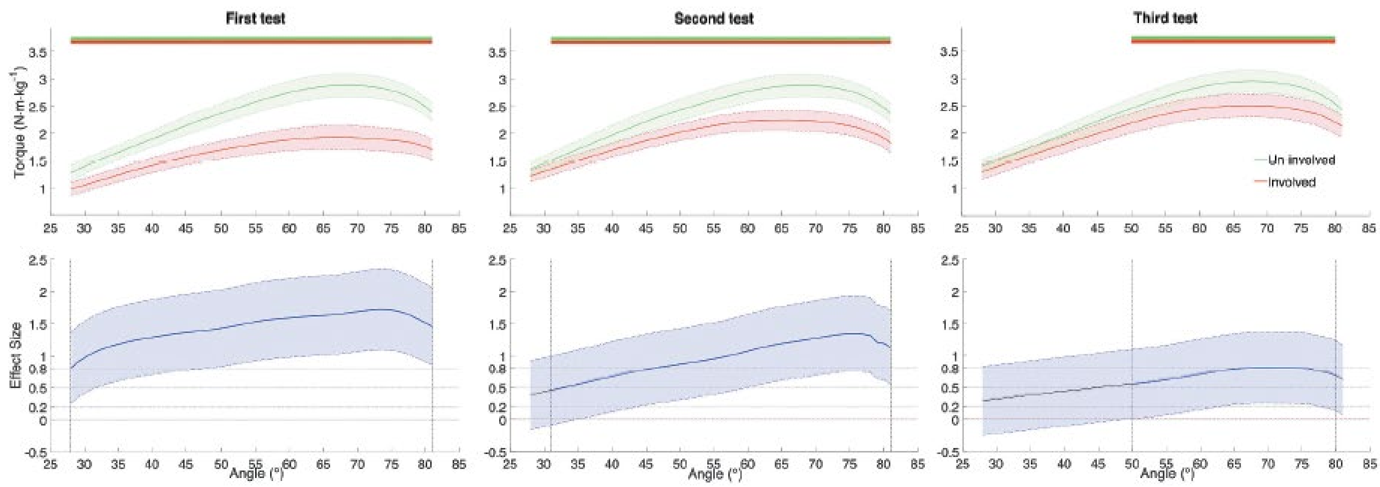

Figure 1 Mean ± 95% confidence interval extension torque angle-series at each time point separated for the involved and un-involved leg (upper panel) and their corresponding effect sizes.

No main effect of time was shown through the overall [28–81°] knee flexion torque-angle curve ($p > 0.05$), but there was a main effect of injury with higher values in the un-involved leg on [70–81°] ($p < 0.001$, Figure 2). There was a significant interaction effect on [36–63°] ($p < 0.001$, Figure 2). Post hoc analysis revealed that, although the injured leg was not statistically lower than the un-involved limb during the first test, Hedge's *g* was about 0.5 and decreased nearly to 0 by the third test (Figure 2).

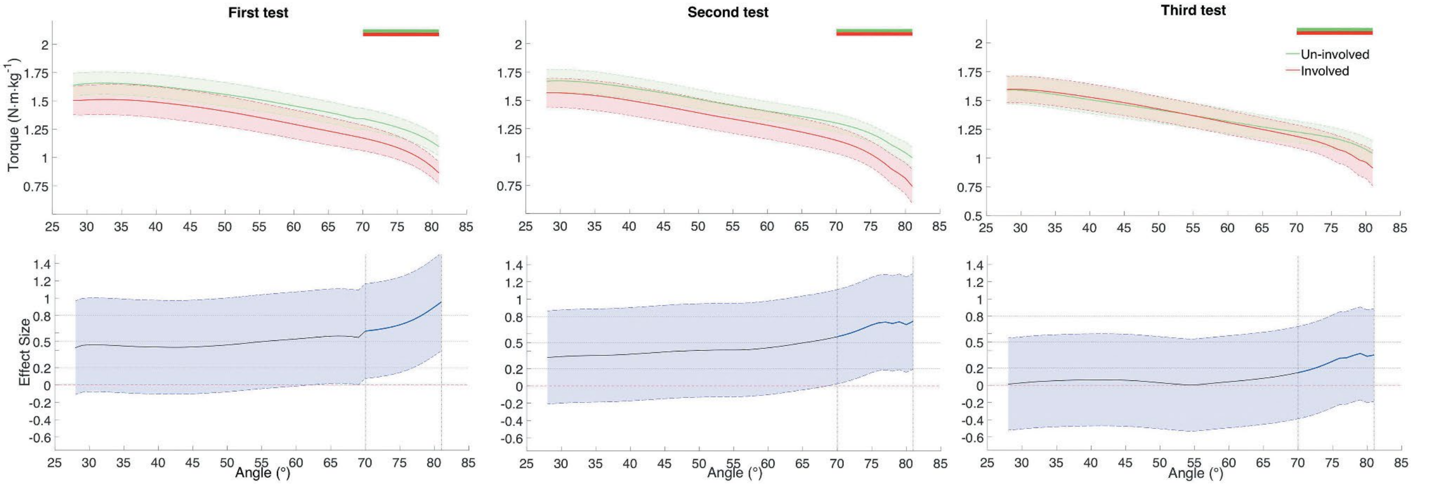

Figure 2 Mean ± 95% confidence interval flexion torque angle-series at each time point separated for the involved and un-involved leg (upper panel) and their corresponding effect sizes.

There was a main effect of time over [33–81°] and injury over [33–75°] in torque-angle H/Q ratio ($p < 0.001$, Figure 3). There was a significant interaction effect over [46–79°] ($p < 0.001$). Post hoc analyses showed that the ratio on the injured leg increased from the first to the second and third assessments (on [33–81°]), but the ratio on the un-involved limb increased also from the first to the second (on [33–45°]) and third (on [33–72°]) assessment; without changes from the second to the third assessment in both legs. Thus, the ratio was higher on the injured compared to un-involved leg over [33–77°] during the first assessment, and over [33–45°] only during both the second and third assessments (Figure 3).

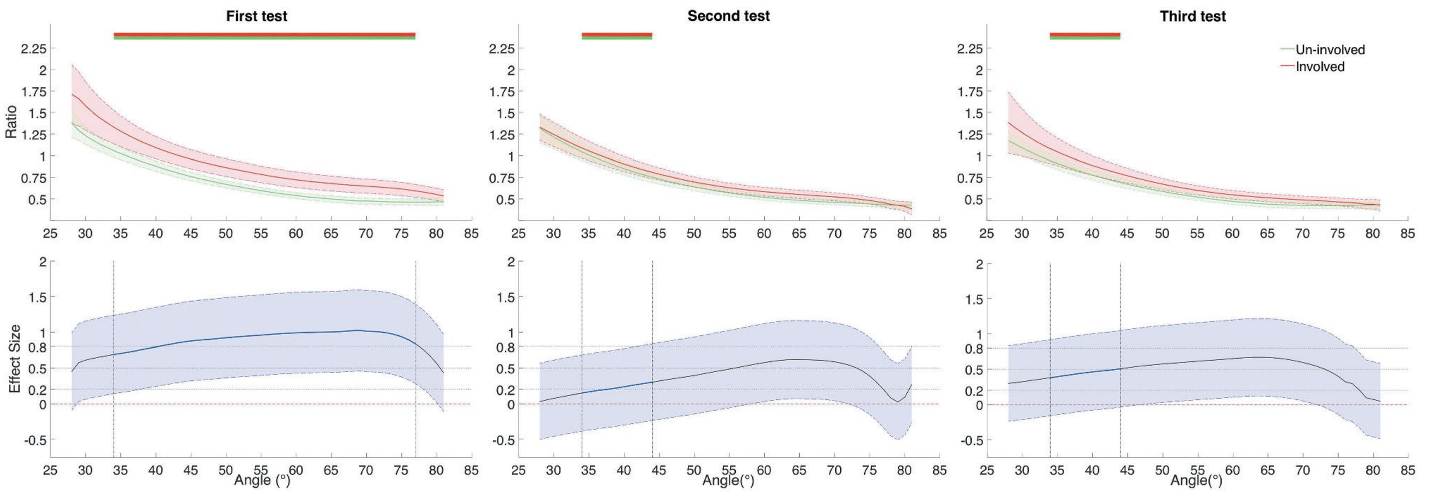

Figure 3 Mean ± 95% confidence interval HQ ratio angle-series at each time point separated for the involved and un-involved leg (upper panel) and their corresponding effect sizes.

DISCUSSION

This study examined the longitudinal strength characteristics of soccer players who had undergone ACL reconstruction. Significant involved limb increases in knee extension peak torque and reductions in asymmetry were shown across the three assessments; however, between limb differences were observed at each time-point. Knee flexion peak torque was greater on the un-involved limb at assessments 1 and 2 only. No differences were observed in the between-limb angle of peak torque at individual time-points or within-limbs across the three test sessions. SPM analysis revealed involved limb angle-specific reductions in extension torque across the full ROM at assessments 1 and 2 but the location of these deficits was confined to deeper knee flexion angles [51–80°] at time-point 3. Similarly, while longitudinal reductions in H/Q ratio were shown using peak torque data, angle-specific differences were identified using SPM, which more accurately reflect muscle balance with the ratio changing across different joint angles.

Flexion and extension torque improved linearly during rehabilitation in our cohort. Nonetheless, longitudinal between-limb differences in extension torque were reported in accordance with previous research. (Welling et al., 2018) This is likely due to altered neural and morphological characteristics. (Lepley et al., 2019) However, the angle of peak torque was not different in either limb at any time-point consistent with previous research (Ikeda et al., 2002; Yosmaoglu et al., 2017) or within-limbs across the three assessments. Conversely, SPM showed lower torques on the involved limb over the entire ROM [28–81°] during the first test, but the differences were reduced to 32–81° and 51–80° during the second and third assessments, respectively. These data indicate the need for angle-specific analysis to more accurately determine knee function and identify residual deficits that are not readily apparent when using traditional modes of analysis. Future research may wish to investigate if angle-specific deficits are present in those who meet current recommended (Grindem et al., 2016) return-to-sport "pass" criteria (>90% peak torque limb symmetry), and potential associations with alterations in function and re-rupture.

The angle-specific deficits in knee extension torque production we identified at the third assessment in positions of deeper knee flexion (51–80°) correspond to previous research. Cross-sectional data from male and female team sport athletes ~ 6 months post hamstring tendon graft ACL reconstruction revealed more pronounced between-limb differences in extension torque at knee flexion angles >50º. (Baumgart et al., 2018) Our data indicate that this angle-moment profile is present even in the later stages of rehabilitation in male soccer players if targeted exercise prescription is not provided. Conversely, ACL-deficient cohorts have shown increased between-limb differences in quadriceps torque production in knee angles <40º of flexion. (Eitzen et al., 2010; Huang et al., 2017) Strain on the ACL is highest in positions nearer full extension. (Escamilla et al., 1998) We did not identify significant knee extension torque differences <50º at the third assessment; thus, it appears that reductions in torque are not related to mechanical stability of the graft in the later stage of rehabilitation following reconstruction.

To explain the lower knee extensor torque production shown in deeper knee flexion positions, we must consider the force–length relationship. Active muscle torque peaks at an optimal sarcomere length, with decreases observed at shorter and longer lengths. (Sale et al., 1982) Knee extensor torque is greatest within the mid-range of seated knee movement. (Hahnn et al., 2011) At angles approaching full knee extension, the quadriceps muscles are at a mechanical disadvantage therefore torque will reach its lowest relative values. (Hahnn et al., 2011; Kellis, 1998) Reductions in torque production >50º may be indicative of lower maximal strength capacity as a means of reducing joint torque due to reduced quadriceps voluntary activation, spinal-reflexive and corticospinal excitability, and smaller muscle volumes. (Lepley et al., 2014) These data further emphasise the need for targeted quadriceps strength development for the duration of the athletes reconditioning period.

The H/Q ratio reduced at each assessment on the involved limb but remained significantly higher compared to the contralateral side throughout the duration of the study. A ratio >0.6 has been recommended. (Coombs & Garbutt, 2002) Values above this have been suggested as evidence of improved muscle strength balance. The higher ratio on the involved limb in our study was due to a reduction in quadriceps torque output as opposed to increased hamstring strength. This leads to an inflated ratio that may limit the value of using traditional modes of analysis. Moreover, the ratio of two peak torques obtained at different angle does not reflect dynamic knee joint stabilization. We observed angle-specific H/Q ratios ranging from 1.60– to 0.74 during the full ROM across the three assessments. Thus, the load a joint will experience is dependent not only on the maximal capacity of involved muscles to produce torque but also the magnitude of torque production when the muscles are at the same respective angle. The peak moments generated by the flexors and extensors in our study occurred at ~ 25º and 65º, respectively. Other research has shown similar results in individuals 1 year following ACL reconstruction. (Hiemstra et al., 2000) SPM analysis revealed that H/Q ratios far exceeding 1.0 are present in athletes following ACL reconstruction when the knee is closer to extension. In this position, the hamstrings are at an optimal length for torque production and the quadriceps are shortened, reducing their force generating capacity. (Aagaard et al., 1995) Thus, more detailed analysis is required to determine knee function and overcome the limitations of conventional ratios using peak torque.

The results of our study provide evidence that targeted exercise prescription is needed to restore quadriceps muscle strength following ACL reconstruction. SPM analysis also more clearly elucidated angle-specific reductions in torque on the involved limb, and these data could be used to identify thresholds where reciprocal muscle balance is insufficient. Angle-specific isokinetic torques have shown stronger relationships with hop performance and provided clinically meaningful information not apparent with the use of peak torque alone. (Eitzen et al., 2010) Therefore, in addition to traditional resistance training that encourages force production through the entire ROM at a range of velocities, it may also be prudent to train in partial ranges of motion when the quadriceps are lengthened and isometric training with the knee in different positions. Angle-specific neuromuscular adaptations (Noorkõiv et al., 2014) and changes in peak torque (Alegre et al., 2014) have been shown at both short and long lever lengths. Thus, research is needed to examine the effects of isometric training in athletic populations following ACL injury and reconstruction at specific-joint angles in which known deficits in quadriceps strength are present.

When interpreting the findings from our study, it should be considered we did not include a healthy control group. Research has indicated that isokinetic strength on the contralateral limb is reduced compared to healthy controls following ACL reconstruction. (Chung et al., 2015) However, the aim of our study was to examine longitudinal changes and temporal recovery at different time points during rehabilitation and also to determine if angle-specific analysis revealed between-limb deficits in knee function not readily apparent when using peak torque alone. We also did not include eccentric hamstring torque to examine functional H/Q ratios. Eccentric data were not available in the earlier stages following ACL reconstruction in our cohort due to protocol restrictions, and our aim was to conduct longitudinal analysis. Concentric/concentric ratios have also most commonly been used in isokinetic assessment following ACL reconstruction. (Undheim et al., 2015) Finally, we were unable to include analysis of different graft types due to sample size limitations. It is currently unclear if this would have affected the findings as similar results have been shown by others. (Baumgart et al., 2018) Our participants mostly (70%) underwent bone-patellar tendon-bone graft reconstruction. (Baumgart et al., 2018) recruited team sport athletes following ACL reconstruction using a hamstring tendon graft with comparable deficits identified but athletes were only tested at a single time point (5.7–9.0 months post-surgery). Future research may wish to use SPM and longitudinal study designs to more clearly elucidate if angle-specific profiles are present in different graft types at key clinical milestones following ACL reconstruction and examine functional H/Q ratios.

CONCLUSION

Our study confirms that angle-specific deficits in knee extension torque are present following ACL reconstruction and SPM provides a more comprehensive H/Q profile to accurately represent muscle strength balance compared to assessment of peak torque. Therefore, examination of angle-specific moment curves may be useful to monitor patterns of strength development during rehabilitation. Residual deficits in extension torque identified in positions of deeper knee flexion suggest that targeted exercise prescription is needed to restore knee function throughout the entire ROM. Our findings also have potential implications for re-injury and performance, which could be considered in the context of return-to-sport decisions.

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