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Commonly used clinical criteria following ACL reconstruction including time from surgery and isokinetic limb symmetry thresholds are not associated with between-limb loading deficits during running

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ABSTRACT

Objectives: We included objective measures of gait and functional assessments to examine their associations in athletes who had recently commenced running after ACL reconstruction.
Design: Cross-sectional.
Setting: Sports medicine.
Participants: 65 male athletes with a history of ACL reconstruction.
Main outcome measures: Time from surgery, isokinetic knee extension/flexion strength (60°/s), and peak vertical ground reaction force (pVGRF) measured during running using an instrumented treadmill. We also investigated if a range of recommended isokinetic thresholds (e.g. > 70% quadriceps limb symmetry index) affected the magnitude of pVGRF asymmetry during running.
Results: There were significant relationships between quadriceps ($r = 0.50$) and hamstrings ($r = 0.46$) peak torque and pVGRF. Quadriceps peak torque explained a quarter of the variance in pVGRF ($R^2 = 0.24$; $p < 0.001$). There was no association was between running pVGRF and time from surgery. Between-group differences in running pVGRF LSI% were trivial ($d < 0.20$) for all quadriceps and hamstring peak torque LSI thresholds.
Conclusions: Current clinical criteria including time from surgery and isokinetic strength limb symmetry thresholds were not associated with lower pVGRF asymmetry measured during running. Quadriceps strength is important, but ‘minimum symmetry thresholds’ should be used with caution.

1. Introduction

Anterior cruciate ligament (ACL) injury and subsequent reconstruction (ACLR) results in substantial time-loss from sport. Return to competition at the same level is not guaranteed (Ardern et al., 2014), and there is a high risk of re-injury (Walden et al., 2006). This in part may be attributed to functional limitations (Lohmander et al., 2004) and residual between-limb deficits (Pandy & Andriacchi, 2010). These often include reductions in strength (Ochi et al., 1999), proprioception (Ochi et al., 1999), jump performance (Paterno et al., 2010), and muscle function (specifically of the quadriceps and hamstrings) (Lewek et al., 2002). However, analysis of the loading characteristics and between-limb deficits during running in athletic populations in the early stages following ACLR is limited, with most studies included in a recent literature synthesis including participants in the later stages of rehabilitation or several years after (Pairot-de-Fontenay et al., 2019).

Commencement of running after ACLR is an important clinical milestone, forming part of the return to sport continuum (Rambaud et al., 2018). A recent scoping review showed that time post-surgery is the most common criteria to determine when an

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individual can begin running (Rambaud et al., 2018). While a minimum time-period post operatively is required to allow for sufficient biological recovery (Myer et al., 2012), wide variation in strength and functional recovery is expected during this time (Bizzini et al., 2006; Joreitz et al., 2016). Time points used within the literature are variable and arbitrary (Rambaud et al., 2018), and no studies have examined relationships between this criterion and running mechanics. Previous research shows no association of time from surgery with functional deficits after ACLR, albeit during a single leg vertical hop (Myer et al., 2012). Thus, research is needed to explore these relationships using a running task, and it appears prudent to also consider a criteria-based approach.

Previous research has also frequently reported a normal gait pattern as an important pre-requisite for returning to run but often there was no objective gait assessment conducted (Rambaud et al., 2018). This limits our interpretation of how an athlete is distributing loading between-limbs during rehabilitation. Objective assessments of gait after ACLR report alterations in kinematic, spatiotemporal, and kinetic characteristics (DeVita et al., 1998; Di Stasi et al., 2013; Gokeler et al., 2013; Minning et al., 2009). However, these variables were mainly examined during walking (Gokeler et al., 2013; Minning et al., 2009). A recent study reported large peak vertical ground reaction force (pVGRF) between-limb differences in a cohort of elite male soccer players running at a range of speeds who were <9 months post ACLR compared to non-injured controls and those who were >9 months from surgery (Thomson et al., 2018). Ground reaction forces are associated with knee joint moments, and therefore may be used as a surrogate for evaluating compensation strategies in knee kinetics (Dai et al., 2014).

While functional assessments are recommended prior to returning to sport following ACLR, with specified ‘pass’ thresholds (Burgi et al., 2019; Grindem et al., 2016), there is limited research to objectively quantify running mechanics in the earlier stages of rehabilitation. Clinical tests, questionnaires, strength, and performance assessments are used to guide this process (Rambaud et al., 2018); yet no consensus exists for a ‘standard test battery’. Strength measurements of the hamstrings and quadriceps are the most common objective assessment mode likely due to their role in active knee joint stabilization (Tourville et al., 2014). Rambaud et al. (Rambaud et al., 2018) reported that specified thresholds (e.g., >65%,70% and 75% quadriceps and hamstrings limb symmetry index) have been used most frequently in the available literature (8/13) as the criteria to clear patients to begin running, but there is a paucity of data to examine the relationships between isokinetic strength using these pre-defined cut-off scores and objective measures of running in athletes during early phase rehabilitation following ACLR.

Thus, our primary aim was to examine the relationships between time from surgery, isokinetic measures of knee extension/flexion strength, and running gait related variables in the early phases of rehabilitation after ACLR. Our secondary aim is to investigate if a range of previously utilised thresholds (e.g. > 70% quadriceps limb symmetry index) affect the magnitude of ground reaction force limb asymmetry during running. These data have important indications for clinical decision making providing an evidence-based analysis of the suitability of current practice guidelines. We hypothesized that quadriceps strength would demonstrate significant relationships with peak ground reaction force measured during running, but those breaching previously suggested limb symmetry thresholds for quadriceps and hamstrings peak torque would not display heightened between-limb differences in ground reaction force when running.

2. Materials and methods

2.1. Experimental design

Participants with a history of ACL reconstruction attended Aspetar Orthopaedic and Sports Medicine Hospital as part of routine follow up during which they performed a running gait assessment and isokinetic dynamometry. A mixed cross-sectional design was used to examine relationships between isokinetic measures of knee extension/flexion strength, time from surgery, and pVGRF during running. The order of testing was standardized with running performed prior to undergoing isokinetic testing. All participants were familiarized with the relevant test procedures and equipment and completed a standardized warm up consisting of 5 min of pulse raising activity (stationary cycling performed at 60% of maximum perceived effort) followed by dynamic body weight movements including squatting (bilateral and unilateral), lunging and step ups.

2.2. Participants

65 male team sport athletes (24.7 years; stature 176.2 ± 9.4 cm; 75.1 ± 13.2 kg; 19.1 ± 3.2 weeks post ACL reconstruction) volunteered to take part in this study. Inclusion criteria required athletes to be male, > 18 years of age, having undergone primary surgical unilateral reconstruction using either a bone patellar bone (BTB) (64%) or hamstring tendon (semitendinosus and gracilis) (34%) autograft respectively, and competing as a registered athlete in one of the various clubs and federations in Qatar as part of the National Sports Medicine Program prior to their injury. Participants were excluded if they reported a previous ACL or other knee ligament or cartilage injury to either the operated or non-operated leg. Informed written consent and ethical approval was obtained prior to commencement of testing. This study was approved by the Anti-Doping Laboratory (ADLQ), Doha, Qatar (IRB: F2017000227).

2.3. Procedures

Following ACLR at Aspetar, athletes are required to attend the clinical assessment unit every six-weeks during their rehabilitation. Once an athlete had been cleared to run by their treating physiotherapist in the rehabilitation department, their next scheduled appointment at the assessment unit was used to collect objective running data and we characterised this as their ‘first run’ to be included in the study. This assessment typically occurred within 2–4 weeks from clearance. The criteria used by the physiotherapists included minimal/trace (stable) swelling, normal gait (walking) pattern, and full range of motion.

Isokinetic assessment: Maximal knee extension and flexion strength was measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, New York, USA). Procedures replicated those outlined in previous research (Van Dyk et al., 2016). Five repetitions of concentric knee flexion and extension at 60°/s (QCon60 and HCon60) were performed with the highest peak torque value (absolute (N/m) recorded and these were also normalized to body weight (Nm/kg). Before each test, participants were instructed as to the relevant completed and 3 to 5 practice repetitions. The test was performed on both the un-involved and involved limb in that order. Vigorous verbal encouragement was provided throughout by the same assessor who conducted all tests.

Running gait assessment: Tests were conducted barefoot on an instrumented treadmill (Zebris FDM-THQ, Zebris Medical GmbH, Germany), with a pressure plate embedded beneath the running belt. The system measures the dynamic pressure distribution under the feet at a sampling rate of 300 Hz. This treadmill has shown acceptable reliability (ICC ≥ 0.7) and a standard error of 5.4% (Donath et al., 2016; Van Alsenoy et al., 2019). The treadmill was level (0% grade) for all testing. The sensing area of the pressure plate is 1.36×0.64 M consisting of 10,240 sensors. The sensor threshold is set at 1 N/cm^2.

All participants had previously used a treadmill during their rehabilitation and a walking assessment at their previous 6-week routine appointment. During the data collection session, participants first walked for 60 s at 4 km/h to warm-up and familiarize themselves with the treadmill. The speed was then gradually increased to 10 km/h and participants were instructed to run until their gait felt consistent and comfortable (Thomson et al., 2018) (~20 s). Data were then captured for an additional 30 s and recorded values were averaged across the test period. Maximum plantar vertical force (pVGRF) was estimated by multiplying the pressure values measured by each of the individual sensors by the cross-sectional constant area for each sensor. The resulting matrix of force data were then summed to then provide a final maximum pVGRF value.

2.4. Statistical analysis

We initially explored our data to check the distribution using the Shapiro-Wilk normality test and descriptive statistics (mean ± SD) for all variables were calculated. Between-limb differences were also examined using a paired samples *t*-test and limb symmetry index scores were recorded (involved limb/un-involved limb x 100). Following these steps, we included a series of statistical analyses outlined below to test our stated hypothesis.

1) Pearson's product correlation coefficients were used to examine the strength of the relationships between isokinetic variables and pVGRF measured during running on both the involved and un-involved limb. Time from surgery (days) and isokinetic test variables that were significantly correlated with running pVGRF were then entered into a multivariate stepwise linear regression model to determine predictive factors and constructs of performance on the involved limb. Multicollinearity was determined by assessing the variation inflation factor, to ensure values were less than 2.0 in order to eliminate the suggestion of strong multicollinearity with predictor variables included in the model.
2) Independent samples t-tests were used to examine between-group differences in gait pVGRF and step length limb symmetry using previously recommended thresholds (34): quadriceps LSI < 65%; <70%; <75%; <80%; and hamstring LSI < 80% and <85%. Lower thresholds were not used for hamstring LSI as there were insufficient participants who fell below these values to ensure appropriate statistical power. Cohen's *d* effect sizes (ES) were calculated to interpret the magnitude of between group differences using the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for small, medium, and large effect sizes, respectively (Cohen, 1992).

All data were computed through Microsoft Excel® 2010. t-tests, quartiles, Pearson and spearman correlations, and multivariate linear regressions were processed using SPSS® (V.22. Chicago Illinois). The level of statistical significance was set at alpha level $p \leq 0.05$.

3. Results

Descriptive statistics (mean ± SD) for all reported isokinetic and running gait variables are displayed in Table 1. Isokinetic quadriceps ($p < 0.001$; $d = 1.08$) and hamstring strength ($p < 0.05$; $d = 0.37$), and pVGRF ($p < 0.001$; $d = 0.39$) were significantly lower on the involved limb. Limb symmetry index (LSI) values ranged from 75.2 to 97.6% with the largest deficits shown for quadriceps peak torque.

Table 1
Descriptive statistics.

Test variable	Mean ± SD	Relative scores (Nm/kg; N/BW)
Quadriceps PT INV (N/m)	175.9 ± 51.2**	2.31 ± 0.52
Quadriceps PT unINV (N/m)	234 ± 56.2	3.11 ± 0.52
Quadriceps PT LSI%	75.2 ± 13.4	–
Hamstring PT INV (N/m)	120.9 ± 31.5*	1.61 ± 0.33
Hamstring PT unINV (N/m)	132.6 ± 31.7	1.76 ± 0.32
Hamstring PT LSI%	91.7 ± 14.7	–
10 km/h pVGRF INV (N)	1677 ± 344**	2.29 ± 0.33
10 km/h pVGRF unINV (N)	1809 ± 357	2.47 ± 0.36
10 km/h pVGRF LSI%	92.9 ± 6.4	–

Significantly lower than involved limb *($p < 0.05$); ** ($p < 0.001$).
PT = peak torque; pVGRF = peak vertical ground reaction force INV = involved limb. unINV = un-involved limb; LSI = limb symmetry index.

Significant relationships were indicated between absolute quadriceps ($r = 0.50$) and hamstrings ($r = 0.46$) peak torque at 60 deg/sec and 10 km/h pVGRF, relative values were not significantly associated. No relationships were observed for any LSI variables and 10 km/h pVGRF. The stepwise linear regression indicated that quadriceps peak torque was the only variable significantly associated with 10 km/h pVGRF ($R^2 = 0.24$; $p < 0.001$). No association was observed between running pVGRF and any other isokinetic variable or time from surgery.

10 km/h pVGRF LSI scores displaying comparisons formulated by grouping athletes who scored above or below each previously suggested isokinetic LSI threshold (Paulos et al., 1981) are shown in Table 2. No between-group differences were seen in 10 km/h pVGRF LSI% for any quadriceps or hamstring peak torque LSI thresholds, and effect sizes were small. Furthermore, no evident trends were observed when examining the distribution of running pVGRF scores with respect to time from surgery and those who attained peak torque LSI scores <70% (Fig. 1).

Size of dots = Quadriceps peak torque limb symmetry index [%].
Orange dots = Quads PT LSI <70%.
Blue dots = Quads PT LSI >70%.
Dashed grey line = 100% limb symmetry index for pVGRF.
Dashed light blue line = mean of weeks post ACLR.

4. Discussion

The aim of this study was to investigate the relationships between time from surgery, isokinetic measures of knee extension/flexion strength, and running gait related variables in the early phases of rehabilitation after ACLR. In addition, a range of previously suggested isokinetic limb symmetry index thresholds used as criteria to determine when an individual can recommence running were applied to examine their ability to differentiate between those who display greater loading symmetry during running. Our results showed no association between pVGRF during gait and time from surgery. Involved limb quadriceps peak torque displayed the strongest relationship, explaining ~ a quarter of the variance in running pVGRF. No significant between-group differences in pVGRF symmetry were observed for any of the recommended quadriceps or hamstring peak torque LSI thresholds.

Isokinetic strength limb symmetry thresholds of the quadriceps and hamstrings are often recommended in scientific literature describing rehabilitation protocols (Pairot-de-Fontenay et al., 2019; Sasaki & Neptune, 2006; Schache et al., 2014) and their effects on patient outcomes following ACLR (Karasel et al., 2010; Lemiesz

Table 2
Between-group LSI scores based on specified isokinetic LSI thresholds.

Gait variable	Isokinetic variables		p-value	Cohens *d*
	<65% Quad PT LSI (n = 15)	>65% Quad PT LSI (n = 50)		
pVGRF LSI%	91.7 ± 9.4	93.6 ± 5.7	0.34	0.24
	< 70% Quad PT LSI (n = 24)	**> 70% Quad PT LSI (n = 41)**		
pVGRF LSI%	91.9 ± 7.7	93.9 ± 6.1	0.25	0.29
	< 75% Quad PT LSI (n = 35)	**> 75% Quad PT LSI (n = 30)**		
pVGRF LSI%	93.2 ± 7.1	93.2 ± 6.4	0.97	0.01
	< 80% Quad PT LSI (n = 43)	**> 80% Quad PT LSI (n = 22)**		
pVGRF LSI%	93.1 ± 7.0	93.4 ± 6.2	0.86	0.04
	< 80% Ham PT LSI (n = 52)	**> 80% Quad PT LSI (n = 13)**		
pVGRF LSI%	93.2 ± 5.9	93.1 ± 6.9	0.97	0.01
	< 85% Ham PT LSI (n = 21)	**> 85% Quad PT LSI (n = 44)**		
pVGRF LSI%	93.7 ± 6.0	92.9 ± 7.1	0.66	0.12

PT = peak torque; pVGRF = peak vertical ground reaction force; LSI = limb symmetry index.

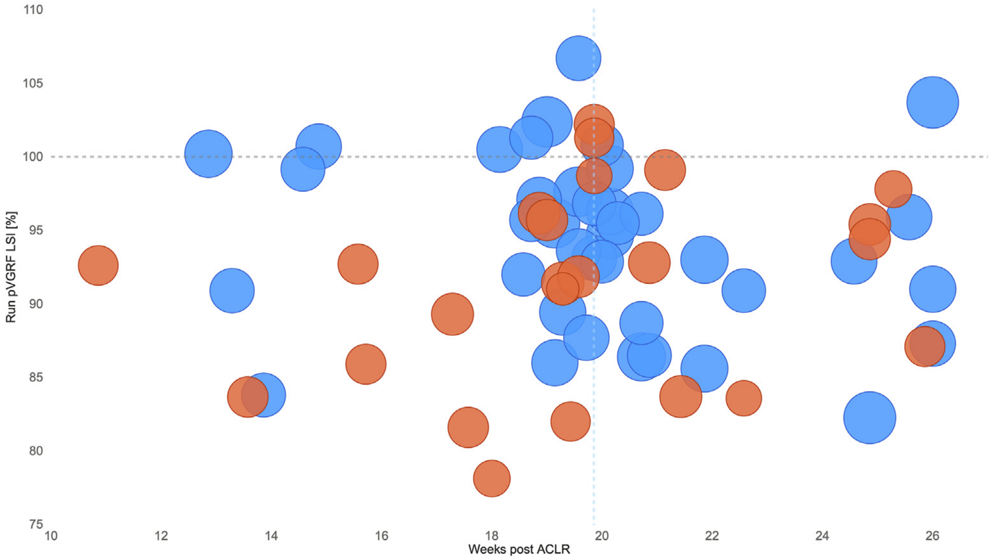

Fig. 1. Legend: Peak vertical ground reaction force limb symmetry index [%] when running at 10 km/h at the week post ACLR.

et al., 2011) as a pre-requisite for ‘safe’ return to running (Rambaud et al., 2018). Specifically, values > 65, 70 and 75% have been most commonly identified and are recommended for use as a cut-off criterion (Rambaud et al., 2018). Our study did not identify meaningful differences in pVGRF LSI measured during running in athletes who breached the thresholds examined (<65, 70, 75 or 80% LSI), and no clear trend was evident in the distribution of participant scores (<70% quadriceps peak torque LSI) (Fig. 1). In addition, only 5 participants recorded <70% LSI in hamstring peak torque. Thus, current recommendations which suggest achievement of isokinetic LSI thresholds may warrant further investigation as these do not appear to relate to PVGRF measured during running. These data indicate that asymmetries are task and variable dependent (Read et al., 2020a) and the current study provides further support to the notion that arbitrary thresholds should not be applied for the purposes of clinical decision making (Read et al., 2020b).

While our study showed quadriceps peak torque limb symmetry thresholds do not appear to differentiate between those with higher vs. lower pVGRF asymmetry during running, the role of quadriceps strength should not be discounted as an important component of rehabilitation following ACLR. Chronic knee extensor strength deficits are expected with prior ACL injury (Hiemstra et al., 2000) and have been associated with increased risk of second injury following ACLR (Grindem et al., 2016). A previous literature synthesis has shown that quadriceps strength is more likely to be associated with knee kinetics during running after ACLR than surgical technique (Pairot-de-Fontenay et al., 2019), albeit in the later stages of rehabilitation or several years after surgery. The current study showed a significant positive relationship between quadriceps peak torque and pVGRF during running, indicating that increased strength is correlated with a concomitant increase in pVGRF. Our participants displayed lower ground reaction forces during running on the involved limb which is in accordance with previous research (Thomson et al., 2018). Decreased ground reaction forces are a mechanical representation of reduced knee moments (Dai et al., 2014), attributed at least in part to strength deficits (Ingersoll et al., 2008). The quadriceps play an important role in running for both energy dissipation during flexion, acting as a force absorber to stabilize the knee joint upon loading during early stance (Montgomery et al., 1994), and during the mid to late stage of the gait cycle, aiding propulsion (Sasaki & Neptune, 2006; Yeow, 2013). Thus, restoring quadriceps strength should be a key focus of rehabilitation following ACLR. Nonetheless, insufficient evidence is available to prescribe a specific ‘minimum threshold’ of quadriceps strength to determine if an athlete will display improved mechanics during running following ACL reconstruction. This has been shown previously in walking, whereby quadriceps strength symmetry is not correlated with persistent gait biomechanical asymmetries in athletes who had returned to sport (Arhos et al., 2021). Cumulatively, it appears that after reaching a minimum threshold of quadriceps strength, this alone may not be sufficient to minimise gait asymmetries.

Time from surgery is the most common criteria used for returning to running following ACLR (Rambaud et al., 2018). However, previous research has not examined relationships between time from surgery and running gait variables. The inclusion of a time-based criterion has been reported in all studies that specify guidelines for return to running following ACLR, with a median of 12 weeks, although as early as 8 weeks has been suggested with others recommending 16 weeks (Rambaud et al., 2018). The mean time post-surgery of the recorded gait assessment for our participants was ~19 weeks and we observed no association with running pVGRF which provides an indication of global lower limb function. These results are in accordance with previous research, albeit in a single leg hopping task (Myer et al., 2012). Recovery of functional performance is highly variable following ACLR (Wells et al., 2009), and residual deficits lasting > 9 months (Rambaud et al., 2018) to 2 years are common (Paterno et al., 2010). Thus, while a minimum time period (Nagelli & Hewett, 2017), and undertaking of sufficient rehabilitation to eliminate effusion, minimise pain, and restore knee joint range of motion is required prior to commencement of dynamic loading activities such as running (Rambaud et al., 2018), criteria-based protocols including assessment of strength and functional performance are recommended and the specific timeframe is likely to vary on an individual or case by case basis.

When aiming to determine functional performance and readiness to return to sport following ACLR, it is common to use a battery of tests (Burgi et al., 2019). This approach has also been proposed to inform decision making when deciding if an athlete should commence running (Rambaud et al., 2018). The results of our study indicate that quadriceps strength is important, but isokinetic knee extension strength only accounted for a quarter of the variance in running pVGRF. Research has shown that a range of muscles contribute to propulsion (forward acceleration of the center of mass) and support (upward acceleration of the center of mass) during running (Hamner et al., 2010), including the gluteus maximus, gluteus medius, vasti, soleus, and gastrocnemius (Pairot-de-Fontenay et al., 2019). The quadriceps and plantarflexor muscles (soleus and gastrocnemius) are the main contributors to the breaking phase of stance and during propulsion respectively (Hamner et al., 2010). These observations have been confirmed elsewhere (Dorn et al., 2012; Schache et al., 2014), with the soleus and gastrocnemius identified as the lower-limb muscles most responsible for increasing vertical force production (Dorn et al., 2012; Hamner et al., 2010). Specifically, their contributions to vertical ground reaction force have been estimated through computer simulation to be ~50–60% in jogging and slow-paced running (Dorn et al., 2012; Schache et al., 2014). Thus, including exercises that target these muscles early in rehabilitation and utilising assessments to determine their functional capacity may be considered an important aspect of the return to run process.

Steady state running also requires the lower-limb musculature to function in a spring like fashion, storing and releasing energy with each ground contact (Schache et al., 2014). Elastic storage of energy has been identified as an important component of increasing running efficiency (Dickinson et al., 2000; Hamner et al., 2010), and in particular, the ankle plantarflexors undergo significant stretch-shortening activity during the stance phase of running (Karasel et al., 2010; Komi, 2000; Kubo et al., 2000; Lichtwark & Wilson, 2007). Through their attachments to the more compliant Achilles tendon, elastic energy can be stored and subsequently released during the early and late part of the stance phase (Schache et al., 2014). Cumulatively, the available research and our data indicates the relative importance of developing and assessing the foot-ankle complex as part of a ‘battery’ of tests during the return to running process, along with lower limb and quadriceps strength. Also, characterisation of stretch-shortening cycle function is recommended through appropriate assessment modes based on the individual’s stage of rehabilitation (i.e. sub-maximal hopping, ankling hops, pogo jumps etc.). Few studies have used multiple criteria to clear patients for running (Rambaud et al., 2018), and it is unclear whether these assessments relate to ‘safe’ and more informed return to run decisions and this warrants further investigation.

When interpreting the results of the current study, some limitations should be acknowledged. Firstly, our analysis of running mechanics included pVGRF, which provides only an instantaneous time-point on a force-time curve and a global measurement of lower limb loading. Vertical ground reaction force has been implicated in some running related injuries [46.52]. However, some research has indicated that no differences are present in pVGRF between those with a history of lower limb stress fractures and matched controls, whereas loading rate displayed a higher level of sensitivity (van der Worp et al., 2016; Zadpoor & Nikooyan, 2011). Nonetheless, decreased ground reaction forces are a mechanical representation of reduced knee moments (Dai et al., 2014), and significant between-limb (involved vs. un-involved) and between-group (vs. healthy controls) differences have been shown during running in athletes who were <9 months post ACLR (Shelbourne & Nitz, 1990). Conversely, no differences in ground contact time were observed (Thomson et al., 2018) providing support for our methodology. Another limitation was that each patient had begun running prior to their participation in the study, and variation was evident in the length of time this occurred prior to their assessment. Our protocol captured the patients first objective running observation and was therefore not used as part of the decision-making process to determine ‘is the individual ready to run’. Finally, the running task was performed on an instrumented treadmill at a standardized speed, providing the advantage of controlled, experimental conditions. Biomechanical differences have been observed between treadmill and overground running (Riley et al., 2008), indicating more research is required to measure athletic populations during running tasks that more accurately represent their playing environment, possibly using wearable technology. We could have also allowed participants to self-select their running speed; however, our aim was to increase standardization and previous research has shown that humans choose to progress from walking to running at speeds just over 2 m/s (Hreljac, 1995). The running speed we used (10 km/h) is equivalent to ~ 2.7 m/s which we believe provides an indication of slow ‘jogging’ and is characteristic of the speed’s athletes would commence running protocols during rehabilitation. Cumulatively, due to the paucity of empirical data available to characterise an athlete’s ‘first run’ and our limited understanding of what criteria are important to inform the clinician of ‘when an athlete can run’ (Rambaud et al., 2018), we believe this study provides novel data in-spite of these observed limitations. Future research should include a broad ranging battery of strength and functional tests at the exact time when an athlete is ‘cleared to run’ to determine relationships with gait kinetics and kinematics as a means to identify if they have any clinical value.

5. Conclusions

The results of our study provide preliminary evidence to indicate that time from surgery, which is the most commonly used criteria to decide when to commence running after ACLR, is not associated with between-limb differences in pVGRF measured during gait in the early phases of rehabilitation, re-enforcing the notion that decisions regarding when to commence running should be individualised for each patient using a criteria-based approach. Furthermore, previously suggested quadriceps and hamstring LSI peak torque thresholds (e.g. > 70%) could not differentiate between those with higher vs. lower pVGRF asymmetry during running. These results have important implications for clinicians indicating that arbitrary thresholds should be used with caution for the purposes of clinical decision making and asymmetries are task and variable dependent.

Quadriceps strength was identified as an important component due to its relationship with pVGRF measured during running; however, only a small amount of the variance was explained by this factor. Thus, satisfaction of common clinical criteria (swelling, ROM etc.), time, and knee strength alone are not sufficient to determine if an athlete will display improved between-limb loading during running in the early phases of rehabilitation following ACLR. Existing research suggests other factors should be considered, including the relative importance of the foot-ankle complex during different phases of ground contract and the requirement of the lower-limb musculature to function in a spring like fashion, storing and releasing energy. However, it is unclear whether assessing these physical capacities will correspond with ‘safer’ running mechanics and this warrants further investigation. Therefore, we propose that future research should examine a broad ranging battery of strength (including the lower limb, quadriceps and foot-ankle complex) and functional tests (characterising stretch shortening cycle function) at the time an athlete is ‘cleared to run’ to determine relationships with gait kinetics and kinematics. Prospective investigations using established criteria to commence running and examination of patient reported outcomes are also warranted. This will enhance our understanding of factors associated with improved running mechanics, and subsequently, clinical decision making.

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Ethical statement

Participants provided and signed informed consent prior to the commencement of testing. Ethical approval was granted by the institutional ethics committee and the Anti-Doping Laboratory (ADLQ), Doha, Qatar (IRB: F2017000227).

Declaration of competing interest

Paul J. Read, Sean McAuliffe and Athol Thomson confirm there are no conflicts of interest associated with any aspects or content of this manuscript.

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