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Relationships between physical capacities and biomechanical variables during movement tasks in athletic populations following anterior cruciate ligament reconstruction

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Abstract

Background: Anterior cruciate ligament (ACL) reconstruction has a detrimental impact on athletic performance. Despite rehabilitation guidelines and criterion-based progressions to ensure safe restoration of fundamental physical capacities and maladaptive movement strategies, residual

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deficits in maximal strength, rate of force development (RFD), power and reactive strength are commonly reported. These combined with associated compensatory inter and intra-limb strategies increase the risk of re-injury.

Objective: The aim of this article is to examine the relationships between fundamental physical capacities and biomechanical variables during dynamic movement tasks.

Design: Narrative review.

Results: The available data suggests that quadriceps strength and rate of torque development, explain a moderate portion of the variance in aberrant kinetic and kinematic strategies commonly detected in ACL reconstructed cohorts in the later stages of rehabilitation and RTS.

Conclusion: The available data suggests that quadriceps strength and rate of torque development, explain a moderate portion of the variance in aberrant kinetic and kinematic strategies commonly detected in ACL reconstructed cohorts in the later stages of rehabilitation and RTS.

1. Introduction

Sports such as soccer, basketball or rugby, require skills including pivoting, cutting, landing, or jumping and expose athletes to a high risk (incidence rates from 0.03% to 3.67% per year) of sustaining an anterior cruciate ligament (ACL) injury during their career (Lindanger, Strand, Molster, Solheim, & Inderhaug, 2019; Moses, Orchard, & Orchard, 2012; Silvers-Granelli, Bizzini, Arundale, Mandelbaum, & Snyder-Mackler, 2017). Following ACL reconstruction, common return to sports (RTS) criteria are often achieved in cohorts with a relatively low rate of return to competitive sport (Ardern, Webster, Taylor, & Feller, 2011; Webster & Hewett, 2019). Thus, current approaches to determine physical capacity and examine movement competency are considered inadequate to identify those at a greater re-injury risk (Losciale, Zdeb, Ledbetter, Reiman, & Sell, 2019). This may be partly linked to biomechanical deficits which have been observed following ACL reconstruction, even in the presence of normalized between-limb comparisons in measures such as hop distance

(Davies, Myer, & Read, 2020; Losciale, Bullock, et al., 2019), and change of direction times (King, Richter, Franklyn-Miller, Daniels, Wadey, Jackson, et al., 2018).

Shallow knee flexion angle and pronounced knee valgus at the point of ground contact are commonly cited as a mechanism of injury, corresponding with positions of peak ACL strain (Della Villa et al., 2020; Walden et al., 2015). High magnitudes of knee joint loading, expressed as knee abduction moment, are thought to reflect increased knee injury risk (Fox, 2018). Knee abduction moment is influenced by whole body biomechanics during jumping and change of direction activities. In the ACL reconstructed limb, lower internal knee valgus moment, knee internal rotation angle and ankle external rotation moment, with the centre of mass less posterior to the knee are common findings across various single leg hop tests (King et al., 2018). In change of direction activities typical features include, lateral flexion/rotation of the trunk and position of the centre of mass away from the intended change of direction and from the stance leg, and greater hip flexion and internal rotation at initial contact during cutting manoeuvres. Furthermore, anticipatory adjustments in the step prior to penultimate foot contact during a change of direction, can also alter kinetic and kinematic variables associated with ACL strain magnitudes (Dos'Santos, Thomas, Comfort, & Jones, 2018).

Deficits in strength (Lisee, Lepley, Birchmeier, O'Hagan, & Kuenze, 2019; Petersen, Taheri, Forkel, & Zantop, 2014), rate of force development (RFD) (Angelozzi et al., 2012; Davis et al., 2017; Hsieh, Indelicato, Moser, Vandenborne, & Chmielewski, 2015; Turpeinen, Freitas, Rubio-Arias, Jordan, & Aagaard, 2020), power (Castanharo et al., 2011; O'Malley et al., 2018), and reactive strength (King et al., 2018; Lisee, Birchmeier, Yan, & Kuenze, 2019) have been identified in different populations following ACL reconstruction. Therefore, rehabilitation programmes have focused on regaining symmetrical range of motion and fundamental physical capacities (i.e. strength, RFD, power, and reactive strength) (Buckthorpe & Della Villa, 2020), in addition to normalisation of maladaptive biomechanical variables in a range of dynamic tasks associated with high peak ACL strains and re-injury risk, such as jumping, landing and change of direction (Gokeler, Neuhaus, Benjaminse, Grooms, & Baumeister, 2019). Nonetheless, the available data indicate that patients in the later stages of rehabilitation and RTS following ACL reconstruction, exhibit maladaptive movement strategies (i.e. altered neuromuscular control of the hip and knee during dynamic landing tasks) that may expose them to a greater risk of re-injury (Paterno et al., 2010). It is currently unclear if these aberrant mechanics are underpinned by sub-optimal physical capacities, graft type, time to RTS, psychological status or altered neuromuscular control.

Mounting body of evidence suggests that an adequate level of physical capacity is required to facilitate the execution of more complex athletic skills (Cormie, McGuigan, & Newton, 2011a, 2011b). However, a synthesis of the literature to determine the extent to which deficits in physical capacity affect biomechanical variables during movement execution in athletic cohorts following ACL reconstruction is unclear. Therefore, the aim of this narrative review was to examine relationships between strength, RFD, power, reactive strength, and kinetic and kinematic variables in dynamic tasks in ACL reconstructed athletes in the later stages of rehabilitation and RTS. The information included will assist clinicians, providing clear practical applications to optimise RTS.

2. Methodology

The lead author conducted a literature search of three electronic databases (MEDLINE, SPORTDiscus and CINHAL) on March 5, 2020. The studies were selected according to PICOS framework (Participants, Intervention, Comparison, Outcome, and Study design) (Liberati et al., 2009). Cohort studies investigating strength, power, RFD or reactive strength, and kinetic or kinematic variables in performance tests in participants in the later stages of rehabilitation and RTS following ACL reconstruction were considered. They had to be published in peer-reviewed journals and written using English language not before 2010. The keywords “strength” or “reactive strength” or “power” or “rate of force development” were combined with the Boolean operator “AND” to keywords pertinent to kinetics, kinematics and performance measures (e.g. “biomechanics”, “change of direction”, “landing”, etc.).

The additional inclusion criteria were: (1) participants with any graft type; (2) assessment of strength, power, RFD, or reactive strength using dynamometers or force platforms; (3) assessment of kinetic variables using force platforms; (4) assessment of kinematic variables using 3D motion capture analysis.

3. Physical capacity measurement

In this next section we will briefly summarise the assessment modes of physical capacities typically measured and described in ACL literature.

3.1. Strength

The majority of studies which have examined strength in athletic populations post ACL reconstruction included an isokinetic dynamometer at a variety of test speeds (60°/s, 120 °/s, 180 °/s, and 300 °/s) for both the quadriceps and hamstring muscles (Almeida, Santos Silva, Pedrinelli, & Hernandez, 2018; Baltaci, Yilmaz, & Atay, 2012; Królikowska, Reichert, Czamara, & Krzemińska, 2019; Miles & King, 2019; Mohammadi et al., 2013; O’Malley et al., 2018; Welling, Benjaminse, Lemmink, Dingenen, & Gokeler, 2019; Xergia, Pappas, Zampeli, Georgiou, & Georgoulis, 2013). Other testing modes included isometric MVIC on a dynamometer (Holsgaard-Larsen, Jensen, Mortensen, & Aagaard, 2014; Norouzi, Esfandiarpour, Mehdizadeh, Yousefzadeh, & Parnianpour, 2019; Schmitt, Paterno, Ford, Myer, & Hewett, 2015; Timmins et al., 2016; Ward et al., 2018), or uniaxial load cells (Timmins et al., 2016).

3.2. Power

The product of force (or strength) and velocity results in mechanical power; which, when divided by time, defines the rate at which work is performed (Turner et al., 2020). The ability to express high power outputs is an important factor related to increasing performance levels (Haff & Stone, 2015). Given the components of power (P), it appears intuitive that strength (indicating high levels of force production) and speed are the main physical determinants of athletic skills, such as jumping, landing (given the need for braking force), accelerating, and changing direction (Haff & Stone, 2015; Turner et al., 2020). In ACL literature power has been calculated primarily during bilateral (Castanharo et al., 2011; Read, Michael Auliffe, Wilson, & Graham-Smith, 2020) and single countermovement jumps (CMJ) (O'Malley et al., 2018). The synchronisation of kinetic and kinematic data has also been used to assess single joint power contribution, highlighting intra-limb compensation strategies commonly documented in ACL reconstructed cohorts (Baumgart, Schubert, Hoppe, Gokeler, & Freiwald, 2017; Gokeler et al., 2010; Paterno, Ford, Myer, Heyl, & Hewett, 2007).

3.3. Rate of force development (RFD)

RFD is defined as the ability of the neuromuscular system to produce a high rate in the rise of muscle force in the first 30-250 ms (Taber, Bellon, Abbott, & Bingham, 2016), and it is calculated as ΔForce/ΔTime, which is determined from the slope of the force time curve (generally between 0 and 250 ms) (Maffiuletti et al., 2016; Rodriguez-Rosell, Pareja-Blanco, Aagaard, & Gonzalez- Badillo, 2018). Impaired knee extension rate of torque development has been reported following ACL reconstruction (Angelozzi et al., 2012; Pua, Mentiplay, Clark, & Ho, 2017; Turpeinen et al., 2020). Assessment of RFD in a dynamic task (i.e. CMJ) has only been recently investigated (Read et al., 2020). Preliminary findings showed significant differences in eccentric deceleration RFD asymmetry between ACL reconstructed participants and healthy controls (Read et al., 2020), even greater than 9 months post-surgery which warrants further investigation to examine its validity to detect rehabilitation status and readiness to RTS (Read et al., 2020).

3.4. Reactive strength

Specific qualities of strength, such as maximal eccentric strength, underpin an athlete's reactive-strength ability, allowing efficient storage and reutilisation of elastic energy during stretch-shortening cycle activities (Beattie, Carson, Lyons, & Kenny, 2017; Suchomel et al., 2019). Quantification is typically via reactive strength index (RSI) ¼ jump height (m)/ground contact time (sec) during a drop vertical jump (DVJ) task (Flanagan & Comyns, 2008).

Reactive strength has been assessed in ACL reconstructed cohorts during a single leg drop jump (SLDJ) (King et al., 2018; Lisee, Birchmeier, et al., 2019). In their cohort of 156 male multidirectional sports athletes, King et al. (King et al., 2018), found significant interlimb asymmetries in RSI (21% deficits in the ACLR side, d = 0.73). This may have important clinical implications given that reactive strength significantly correlate with a reduced metabolic cost of running (running economy at 12-16 km h^{-1}) and change of direction performance (Li, Newton, Shi, Sutton, & Ding, 2019; Maloney, Richards, Nixon, Harvey, & Fletcher, 2017).

4. Movement tasks assessed

Bilateral jumping and landing tasks provide valuable insights on underlying kinematic and kinetic strategy. Single leg jumping, and landing tasks increase the load that the single limb needs to withstand, with speculation that single leg dynamic tasks better reflect a measure of limb capacity (Cohen et al., 2020). However, bilateral jumping assessments such as the CMJ or DVJ, offer more options to unload the ACL reconstructed limb than single leg tasks. This may occur via inter-limb compensatory strategies in which the uninjured limb is favoured, off-loading the previously injured side (Baumgart et al., 2017; Dai, Butler, Garrett, & Queen, 2014; Hart et al., 2019). This can be easily quantified by the vertical ground reaction force (vGRF) generated. Furthermore, force platform assessment of CMJ performance allows identification of phase specific vGRF (eccentric, concentric and landing phase variables) as well as the time to complete these phases (Hart et al., 2019).

Intra-limb compensation strategies may also be adopted in which lower peak power generation at the knee is compensated for by a higher proportion of power at proximal or distal joints (i.e. hip or ankle). These asymmetries appeared evident in sagittal plane variables such as hip extension moments ($d = 0.60$) during the eccentric phase, and hip flexion angles (d ¼ 0.57) and ankle plantarflexion moments ($d = 0.59$) at the end of the stance phase during DVJ push-off (King et al., 2019). More pronounced inter-limb asymmetries were also evident in the frontal and transverse planes for internal knee valgus moment ($d = 0.5$) and ankle external rotation moment ($d = 0.51$) through the middle of the stance phase in ACL reconstructed athletes vs. healthy controls (King et al., 2019).

5. Relationship between strength and kinetic variables

Schmitt et al. (Schmitt et al., 2015) assessed quadriceps MVIC with an isokinetic dynamometer at 60^{o} knee flexion in relatively young participants ($n = 77$, mean age = 17 years) who completed their rehabilitation programme and were cleared to return to high-level athletic activities (cutting and pivoting). They found significant correlations between quadriceps index (involved/un-involved x 100) and kinetic variables in the bilateral DVJ from a 31 cm box. No kinetic differences were reported between participants displaying high quadriceps index (>90%) and matched controls for any limb symmetry measures. Those with low quadriceps index (<85%) demonstrated greater limb asymmetry in sagittal plane knee joint mechanics (i.e. peak external knee flexion moment ($p < 0.001$), peak vGRF ($p < 0.001$) and peak loading rate (p ¼ 0.008) during the landing phase compared to the stronger individuals. Quadriceps index was the only significant predictor (beta value = 0.412; $p < 0.001$) for limb symmetry index (LSI) peak vGRF ($R^2 = 0.274$) and for LSI loading rate ($R^2 = 0.152$, beta value = 0.253; $p = 0.04$) after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms. For LSI peak external knee flexion moment ($R^2 = 0.501$), graft type (beta value = 0.295, $p = 0.002$) and quadriceps index (beta value = 0.510, $p < 0.001$) were the only statistically significant predictors. Ward et al. (Ward et al., 2018) also observed a low negative association between MVIC and peak vGRF ($r = -0.41$, $R^2 = 0.17$, $p = 0.03$) measured during a DVJ, indicating that greater knee extension strength may minimise vGRF, although only a small amount of the variance in kinetic strategies was explained. In female athletes, lower vGRF on the ACLR limb compared to the uninvolved limb may also be present 2 years post-surgery in both the landing and takeoff phase of a DVJ (Paterno et al., 2007). This strategy has been associated with increased risk of ACL injury in female athletes (Hewett et al., 2005), and has also been documented in mixed populations (Baumgart et al., 2017; King et al., 2018; Paterno et al., 2011).

Quadriceps strength also appears to effect slower movements as well as rebound tasks, as Miles et al. (Miles & King, 2019) observed a relationship between quadriceps strength and kinetics during a CMJ. Knee extensor strength asymmetry explained 39% ($R^2 = 0.39$; $p = 0.002$) and 18% ($R^2 = 0.18$; $p = 0.04$) of the variation in concentric impulse asymmetry during the CMJ in the bone patella tendon bone and the semitendinosus/gracilis groups respectively. No significant relationship was shown between knee extensor strength asymmetry and eccentric impulse asymmetry in any group. Thus, targeted strategies to increase quadriceps strength appear warranted to improve aberrant kinetics during bilateral tasks.

Strength also appears to be related to kinetic parameters during single leg jumping. In young athletes cleared to return to high-level athletic activities (cutting and pivoting) following ACL reconstruction (Ithurburn, Paterno, Ford, Hewett, & Schmitt, 2015; Palmieri-Smith & Lepley, 2015), greater kinetic asymmetries during a single leg horizontal (Palmieri-Smith & Lepley, 2015) and vertical (Ithurburn et al., 2015) landing task were more pronounced in participants with low quadriceps index compared to those with higher symmetry scores. Similarly, 78% of the variability in the lower external knee flexion moment detected in the ACL reconstructed limb during a single leg landing was explained by the knee extensor muscular capacities (R^2 = 0.78; $p < 0.002$) (Oberländer, Brüggemann, Höher, & Karamanidis, 2013). In the work of Palmieri-Smith et al. (Palmieri-Smith & Lepley, 2015), for knee flexion moment symmetry, only age (p = 0.042) and quadriceps index (p = 0.008) were significant predictors (R^2 change = 0.250 for quadriceps index) after controlling for age, mass, gender, time to RTS and meniscal status. Peak knee extension moment symmetry in the vertical drop land task was significantly predicted by quadriceps index (R^2 adjusted = 0.102; $p < 0.001$) (Ithurburn et al., 2015).

O'Malley et al. (O'Malley et al., 2018) found inter-limb differences in ACL reconstructed athletes in isokinetic knee-extension peak torque (d = -1.33), isokinetic knee-flexion peak torque (d = -0.19) single leg CMJ hip power contribution (d = 0.75), peak power (d =-0.47), and knee power contribution (d = - 0.37). Low to moderate correlations (r = 0.28-0.31) were also reported between isokinetic knee extension peak torque and power generation at each joint in the single leg CMJ. These data reinforce the notion that in unilateral tasks such, the ACL reconstructed limb may adopt intra-limb compensation strategies for lower peak power generation at the knee by generating a higher proportion of power at the hip. This is further evident as isokinetic knee extensor peak torque could only explain a small amount of variance in peak power generation during a single leg CMJ (O'Malley et al., 2018). To our knowledge, the relationship between single leg DVJ kinetic parameters and strength levels in ACL reconstructed cohorts has not been examined and further research is warranted. Indeed, evident compensatory strategies following ACL reconstruction include reduced ability to absorb and regenerate ground reaction forces upon landing (Lloyd, Oliver, Kember, Myer, & Read, 2020).

5.1. Relationship between strength and kinematic variables

Three dimensional kinematic data were collected using camera motion-systems and retro-reflective markers across different studies (Gokeler et al., 2010; Ithurburn et al., 2015; Lisee, Birchmeier, et al., 2019; Oberländer et al., 2013; Palmieri-Smith & Lepley, 2015; Schmitt et al., 2015; Ward et al., 2018). During a bilateral DVJ from a 31 cm box, Ward et al. (Ward et al., 2018) observed lower knee-flexion angles at initial contact ($p = 0.03$) in the ACL reconstructed limb, whereas Schmitt et al. (Schmitt et al., 2015) did not find any significant between-limb kinematic difference. A low positive association was reported between knee extensor MVIC and peak knee flexion angle ($r = 0.38$, $R^2 = 0.14$, $p = 0.045$) (Ward et al., 2018). Due to the paucity of studies which have examined the relationship between strength and kinematic variables in bilateral dynamic tasks, further research is warranted.

Equally, only a few studies have measured associations between physical capacities and kinematic variables in unilateral dynamic tasks. Compared to matched controls, greater limb asymmetry during a single leg drop landing task in knee flexion excursion and peak trunk flexion angle was found in ACL reconstructed participants cleared to return to high-level athletic activities (cutting and pivoting) (Ithurburn et al., 2015). Compared to the contralateral limb, decreased knee flexion excursion (Gokeler et al., 2010; Ithurburn et al., 2015; Palmieri-Smith & Lepley, 2015) and increased peak trunk flexion angle was reported (Ithurburn et al., 2015; Oberländer et al., 2013). These asymmetries during landing were more pronounced in participants with low quadriceps index compared to those displaying greater symmetry. Peak trunk flexion and knee flexion excursion symmetry were significantly predicted by quadriceps index (R^2 adjusted = 0.153, $p < 0.002$ and R^2 adjusted = 0.116, $p < 0.001$ respectively) (Ithurburn et al., 2015). This suggests that participants with low quadriceps index following ACLR adopt a strategy of greater trunk flexion when landing on the ACL reconstructed limb in a single leg drop landing task possibly to compensate for decreased knee extension strength. Similarly, in a predominantly female ACL reconstructed population, peak knee flexion angle during a single leg drop crossover hop task was predicted by peak knee extension torque ($R^2 = 0.467$, beta value = 8.517; $p < 0.001$) (Lisee, Birchmeier, et al., 2019), but this had no predictive value for any kinematic variable in the single leg step down task.

Collectively, the available evidence suggests that: 1) the level of correlation between knee extensor and flexor strength and kinematic variables needs to be further examined in relation to gender and task; 2) ACL reconstructed participants tend to adopt a “stiffer” landing strategy in the affected knee with less knee ROM during landing; 3) greater trunk flexion when landing in the single leg drop landing task on the injured limb may be adopted to compensate for decreased knee extension strength; 4) knee extensor deficits explain only a part of the variance in peak knee and trunk flexion angle in unilateral and bilateral tasks.

6. Correlation between RFD/power, kinetic and kinematic variables

Emerging research (Read et al., 2020) showed that the involved limb of male adults following ACL reconstruction (>6 months post-surgery) displays significantly lower eccentric deceleration RFD during a CMJ compared to the uninvolved limb. While in healthy individuals, positive correlations between knee extension RTD and jump performance have been indicated (Chang, Norcross, Johnson, Kitagawa, & Hoffman, 2015; de Ruiter, Van Leeuwen, Heijblom, Bobbert, & de Haan, 2006; de Ruiter, Vermeulen, Toussaint, & de Haan, 2007), the extent of this association with biomechanical variables in ACL reconstructed participants is currently lacking.

Castanharo et al. (Castanharo et al., 2011) compared CMJ performance and kinetic variables between a group of ACL reconstructed adult males with semitendinosus/gracilis graft ≥ 2 years post-surgery and a control group. No significant differences in jump height were present between groups, but peak knee joint power on the injured side was 13% lower than the contralateral limb. These results highlight an "offloading" strategy of the involved limb. These results are in line with a recent systematic review and metaanalysis (Kotsifaki, Korakakis, Whiteley, Van Rossom, & Jonkers, 2020), which showed moderate evidence of a strong effect for lower power absorption in the reconstructed knee (d = -0.98, 95% CI -1.37 to -0.60) during the SL hop.

Read et al. (Read et al., 2020) observed that despite obtaining similar jump height in the CMJ, the ACL reconstructed group at 6-9 months post-surgery displayed significantly greater asymmetry indexes in concentric impulse (9.6 ± 5.6; 95% CI: 8.2-10.9) and concentric peak vGRF (8.0 ± 4.3; 95% CI: 6.9e9.0) than the ACL reconstructed group at >9 months post-surgery (7.4 ± 5.1; 95%: CI 6.0-8.8, and 6.6 ± 4.2; 95%: CI 5.5-7.7). No significant differences between ACL reconstructed groups in asymmetry indexes were found in eccentric deceleration impulse and peak landing vGRF. However, asymmetry of all the aforementioned kinetic variables were greater in the involved limb of the ACL reconstructed participants than in the dominant limb of healthy controls with effect sizes ranging from moderate to very large (d = 0.54-1.35).

These results are in line with recent research (Jordan, Aagaard, & Herzog, 2018; Miles & King, 2019), which showed greater concentric impulse asymmetry in ACL reconstructed participants compared to healthy controls during bilateral jumping tasks. These residual deficits indicate inter-limb strategies that redistribute impulse production to favour the uninvolved side. Also, concentric impulse asymmetry index was strongly associated with rehabilitation status ($p < 0.001$). Furthermore, similar to Mohammadi et al. (Mohammadi et al., 2013) concentric peak vGRF were reduced on the ACL reconstructed side, thus indicating compensatory strategies which offload the involved limb in dynamic tasks.

During unilateral jumping, O'Malley et al. (O'Malley et al., 2018) found inter-limb differences in the ACL reconstructed group in single leg CMJ hip power contribution (d = 0.75), jump height (d = -0.71), peak power (d = -0.47), and knee power contribution (d = -0.37). Similar differences were also found between groups in jump height LSI (d = -1.12), jump height (d = -0.86), peak power $LSI_{modified}$ (d = -0.61), hip power contribution (d = 0.61), and knee power contribution (d = -0.40). This reinforces the notion that in unilateral tasks, the ACL reconstructed limb may adopt intra-limb compensation strategies for lower peak power generation at the knee by generating a higher proportion of power at the hip and ankle.

A recent study also analysed knee extensor early (<100 ms) and late RTD (>100 ms) and their association with performance tests in ACL reconstructed athletes. Birchmeier et al. (Birchmeier, Lisee, Geers, & Kuenze, 2019) showed that both RTD100 and RTD200 had no significant correlation with amortization time in the single leg DVJ, but were moderately correlated with jump height (r = 0.391 and 0.473 respectively). Lisee et al. (Lisee, Birchmeier, et al., 2019) revealed that only RTD200 had a weak relationship with peak knee extension moment (R^2 = 0.176, beta value = 0.066; $p <$ 0.025) in a single leg step down task. Together, the data suggests that the ability of the quadriceps to generate force rapidly may be important for lower extremity loading characteristics in hopping and jumping.

There is a paucity of studies to examine RFD/power and kinematic variables in this cohort. Lisee et al. (Lisee, Birchmeier, et al., 2019) showed that after ACL reconstruction, females with poorer quadriceps RFD100 landed with smaller knee flexion angles at initial contact during a single leg drop crossover hop task (R^2 = 0.198, beta value = 0.721; $p < 0.013$). Further studies are needed to investigate associations between RFD and kinematic variables in performance tests following ACL reconstruction.

7. Relationship between reactive strength and kinetic and kinematic variables

King et al. (King et al., 2018) examined RSI and kinetic variables in performance tests in an ACL reconstructed adult male population involved in multidirectional sports approximately at 9 months post-surgery (n = 156, mean age 24.8 ± 4.8). They showed reduced RSI (21% deficit) in the injured compared to the contralateral limb (d = -0.73). However, no analysis was completed to identify the predictive role of RSI on kinetic variables. To our knowledge, only Birchmeier et al. (Birchmeier et al., 2019) assessed the extent of the association between RSI and kinetic variables in a mixed cohort. No significant correlation was reported between RSI and amortization time in single leg DVJ. Significant correlations were found between RSI and triple hop distance (r = 0.689) and SLDJ height (r = 0.609) (Birchmeier et al., 2019). These findings may appear logical considering that RSI is a measure of stretch-shortening cycle performance, hence higher scores in RSI would positively enhance performance in repetitive jumps. Further research should explore if RSI values are predictive of relevant kinematic variables in participants following ACL reconstruction during rebound tasks.

A summary of the included studies investigating the relationship between physical capacities and biomechanical variables during dynamic tasks in ACL reconstructed individuals is included in Table 1. Fig. 1 depicts kinetic and kinematic variables commonly found in ACL reconstructed cohorts during the DVJ and SLDVJ.

TABLE 1 SUMMARY OF THE INCLUDED STUDIES INVESTIGATING THE RELATIONSHIP BETWEEN PHYSICAL CAPACITIES AND BIOMECHANICAL VARIABLES DURING DYNAMIC TASKS IN ACL RECONSTRUCTED INDIVIDUALS.

AUTHOR AND YEAR	PARTICIPANTS AND AGE (years)	PHYSICAL CAPACITIES TESTED	DYNAMIC TASK	MAIN FINDINGS
Schmitt et al. (2015	77 (males and females) Between 14 and 25	Knee extension isometric strength (MVIC) with an isokinetic dynamometer	DL DVJ Participants were positioned on the top of a 31-cm box and were instructed to drop off the box simultaneously with both feet, landing with each foot onto separate force platforms and then to perform a maximal effort vertical jump	**KINETIC** Quadriceps index was the only significant predictor (beta value = .412; p < 0.001) for limb symmetry index (LSI) peak vGRF (R^2 = .274) and for LSI loading rate (R^2 = .152, beta value = .253; p = 0.04) after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms. For LSI, peak external knee flexion moment (R^2 = .501), graft type (beta value = 0.295, p = 0.002) and quadriceps index (beta value = 0.510, p < 0.001) were the only statistically significant predictors **KINEMATIC** No significant between-limb kinematic difference
Ward et al. (2018)	28 (males and females) 22.4 ± 3.7	Knee extension isometric strength (MVIC) with a dynamometer	DL DVJ Participants performed a jump-landing task for a 30-cm box positioned at 50% of the participant's height from the front edge of the force plates. They jumped forward off the box to a double-legged landing with 1 foo on each force plate and then immediately jumped vertically as high as possible	**KINETIC** Low negative association between MVIC and peak vGRF (r = -0.41, R^2 = 0.17, p = 0.03) **KINEMATIC** Low positive association was reported between knee extensor MVIC and peak knee flexion angle (r = 0.38, R^2 = 0.14, p = 0.045)
Miles and King (2019)	Males only 44 = 22BPTB + 22STG	Isokinetic concentric knee extension and flexion strength (60°/s)	DL CMJ Participants were instructed to maintain hands placed on iliac	**KINETIC** Knee extensor strength asymmetry explained 39% (R^2 = .39; p = 0.002) and

AUTHOR AND YEAR	PARTICIPANTS AND AGE (years)	PHYSICAL CAPACITIES TESTED	DYNAMIC TASK	MAIN FINDINGS
	BPTB 23.4 ± 4.4 STG 26.1 ± 4.4		crests and to jump as high as they could with knees extended during the flight phase	18% (R^2 = .18; p = 0.04) of the variation in concentric impulse asymmetry during the CMJ in the bone patella tendon bone (BPTB) and the semitendinosus/gracilis (STG) groups respectively. No significant relationship was shown between knee extensor strength asymmetry and eccentric impulse asymmetry in any group
Ithurburn et al. (2015)	103 (males and females) 17.4	Knee extension isometric strength (MVIC) with an isokinetic dynamometer	SL drop land Participants stood at the edge of a 31-cm box on the limb being tested and were instructed to drop off of the box and land on a force platform on the same limb. Participants were required to maintain a controlled landing for at least 3 s after landing	**KINETIC** Quadriceps index was a significant predictor of peak knee extension moment LSI (R^2 adjusted = .102; p < 0.001) **KINEMATIC** Quadriceps index was a significant predictor of knee flexion excursion LSI (R^2 adjusted = .116; p < 0.001) and peak trunk flexion angle LSI (R^2 adjusted = .153; p < 0.001)
Palmieri-Smith and Lepley (2015)	66 (males and females) 14-30	Isokinetic concentric knee extension strength (60°/s)	SL hop Participants stood on their test leg and hopped forward as far as possible landing only on the same leg	**KINETIC** For knee flexion moment symmetry, only age (p = 0.042) and quadriceps index (p = 0.008) were significant predictors (R^2 change = 0.250 for quadriceps index) after controlling for age, mass, gender, time to RTS and meniscal status. Peak knee extension moment symmetry in the vertical drop land task was significantly predicted by quadriceps index (R^2 adjusted = .102; p < 0.001) **KINEMATIC** Meniscal status, mass, and time to

AUTHOR AND YEAR	PARTICIPANTS AND AGE (years)	PHYSICAL CAPACITIES TESTED	DYNAMIC TASK	MAIN FINDINGS
				return to activity were not found to be significant predictors of biomechanical symmetry for peak knee flexion angle ($p > 0.05$), while age ($p = 0.013$) and gender ($p = 0.049$) did influence values. After controlling for all these variables in the model quadriceps index was also a significant predictor for knee flexion angle symmetry (R^2 change = .285)
Oberländer et al. (2013)	10 (gender not specified) 28 ± 7	Isometric strength (MVIC) with a custom-built dynamometer with a strain gauge load cell	SL hop test Participants performed a modified single leg hop test for distance, keeping their hands on their hips. This hop was performed with one leg over a given distance of 0.75 _ body height. Landing had to be on the force plate within a target area corresponding to the given distance ±5 cm	**KINETIC** 78% of the variability in the lower external knee flexion moment detected in the ACLR limb was explained by the knee extensor muscular strength ($R^2 = .78$; $p < 0.002$)
O'Malley et al. (2018)	Males only 118 Patellar tendon 23.6 ± 5.8	Isokinetic concentric knee extension and flexion strength (60°/s)	SL CMJ Participants were instructed to stand with 1 foot on the force plate and the free leg behind at approximately 90°. With their hands on their iliac crests, they were asked to complete an SL CMJ, jumping as high as possible.	**KINETIC** Low to moderate correlations ($r = 0.28$ -0.31) were reported between isokinetic knee extension peak torque and power generation at each joint
Lisee, Birchmeier, et al. (2019)	52 (males and females) 22.6 ± 4.4	Knee extension isometric strength (MVIC) and RTD with an isokinetic dynamometer	SL step down Participants were instructed to step down off a 30-cm box onto the force plate and continue walking forward as if stepping off the final step of a set of stairs.	**KINETIC** Peak knee extension torque is the only predictor of peak knee extension moment ($R^2 = .404$) during SL drop crossover hop landing. RTD200 had a weak relationship with

AUTHOR AND YEAR	PARTICIPANTS AND AGE (years)	PHYSICAL CAPACITIES TESTED	DYNAMIC TASK	MAIN FINDINGS
			SL drop crossover hop Participants were instructed to jump off the involved limb from a 30 cm box landing onto the force plate with the same limb. Immediately after landing on the force plate, participants hopped as far as possible diagonally along a line projecting 45° from the centre of the force plate	peak knee extension moment (R^2 = .176, beta value = 0.066; $p < 0.025$) during the SL step down **KINEMATIC** Peak knee flexion angle was predicted by peak knee extension torque (R^2 = .467, beta value = 8.517; $p < 0.001$)) Individuals with poorer quadriceps RFD100 landed with smaller knee flexion angles at initial contact (R^2 = .198, beta value = 0.721; $p < 0.013$) during SL drop crossover hop landing
Birchmeier et al. (2019)	52 (males and females) 22.9 ± 5.0	Knee extension isometric strength (MVIC) and RTD with an isokinetic dynamometer RSI measured during a SLDVJ	SL hop Participants hopped as far as possible from the designated starting line on one leg SL triple hop for distance Participant hopped 3 consecutive times on the same leg as far as possible	**KINETIC** Peak knee extension torque, RTD100 and RTD200 had no significant correlation with amortization time in the SLDJ

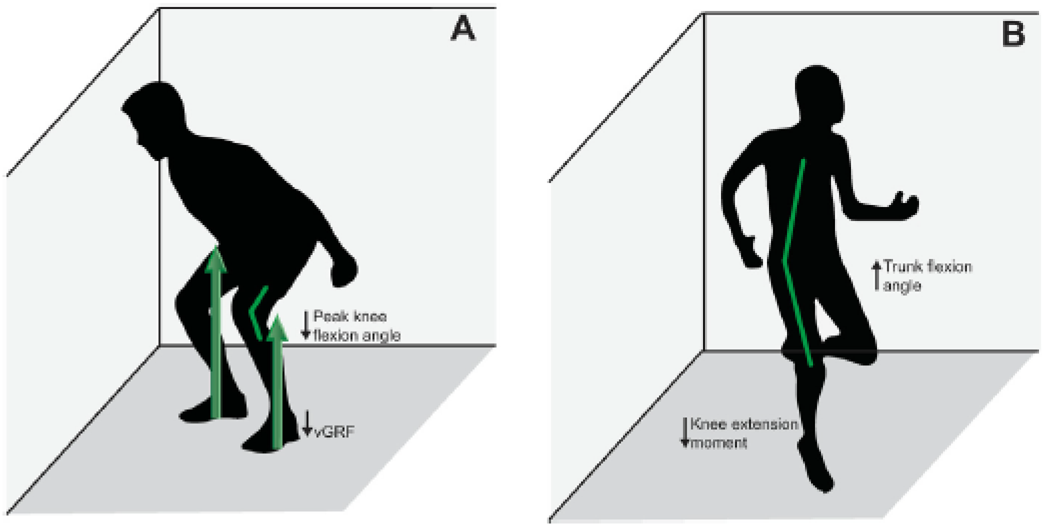

FIGURE 1 EXAMPLE OF KINETIC AND KINEMATIC VARIABLES COMMONLY FOUND IN ACL RECONSTRUCTED COHORTS DURING THE (A) DROP VERTICAL JUMP (DVJ) AND (B) SINGLE LEG DROP VERTICAL JUMP (SLDVJ).

8. Practical applications and recommendations for future research

Deficits in knee extensor torque are commonly reported in ACL reconstructed cohorts and are associated with inter-limb and intralimb compensation strategies indicative of greater re-injury risk (Ithurburn et al., 2015; Lisee, Birchmeier, et al., 2019; Miles & King, 2019; O'Malley et al., 2018; Oberländer et al., 2013; Paterno et al., 2007; Paterno et al., 2010; Schmitt et al., 2015). Specifically, in bilateral tasks inter-limb compensation strategies are adopted to reduce GRF on the ACL reconstructed limb, whereas in unilateral tasks intra-limb "offloading" strategies reduce the peak vGRF and power contribution at the knee by generating more power at the hip and ankle joint. Knee extensor strength deficits explain part of the variance in kinematic variables such as peak knee (R^2 = 14%-46.7%) and trunk flexion angles, and in kinetic variables such as, peak knee extension moment (R^2 = 40.4%-78%), peak vGRF (R^2 = 17%-27.4%) and concentric impulse asymmetry (R^2 = 18%-39%) in jumping tasks. Concentric impulse asymmetry index during a CMJ is strongly associated with rehabilitation status, with lower values indicating better function (Miles & King, 2019) and is related to quadriceps strength [8]. Therefore, it appears of the utmost importance that strategies to increase maximal quadriceps strength are an integral component of rehabilitation. Large deficits in peak knee extension strength are commonly reported in ACL reconstructed participants in the later stages of rehabilitation and RTS (Johnston, McClelland, Feller, & Webster, 2020; Maestroni, Read, Turner, Korakakis, & Papadopoulos, 2021). Thus, sports and healthcare professionals are encouraged to adopt specific exercise selection, dosage and progressions in line with current best practice ("American College of Sports Medicine position stand. Progression models in resistance training for healthy adults," 2009; Morton, Colenso-Semple, & Phillips, 2019). Future research is warranted to examine global strength capacity following ACL reconstruction to determine if stronger associations with biomechanical variables during movement tasks are present. For detailed information regarding practical applications to return athletes to high performance we recommend recently published articles (Buckthorpe, 2019; Buckthorpe & Della Villa, 2020; Maestroni, Read, Bishop, & Turner, 2020; Welling et al., 2019).

Our understanding of how residual deficits in power and RFD during single and multi-joint movements and their relationships with kinetic and kinematic variables is limited and should be the focus of future studies. Similarly, due to its association with stretch-shortening cycle performance, relationships between reactive strength and biomechanical variables should also be examined in athletic populations following ACL reconstruction. In addition, the importance of monitoring contralateral limb capacity during rehabilitation (i.e. concentric/eccentric strength, RFD and RSI) should not be underestimated due to the potential for deconditioning which may increase injury risk and reduce an athlete's readiness to re-perform.

When interpreting the conclusions of this review, it should be considered that we did not perform a systematic review. Thus, a specific inclusion criteria was not applied and the level of evidence, methodological quality and risk of bias in individual studies were not assessed in this manuscript. The current narrative review provides a synthesis and critique of the literature in this broad research area, and thus further opportunities for critical analysis.

9. Conclusions

This article examined the degree of association between fundamental physical qualities, such as strength, rate of force development/power and reactive strength and biomechanical variables during movement tasks in participants following ACL reconstruction. The available data suggests that quadriceps strength and RTD, explain a moderate portion of the variance in aberrant kinetic and kinematic strategies commonly detected in ACL reconstructed cohorts in the later stages of rehabilitation and RTS. The concepts expressed in this article may help clinicians to optimise rehabilitation outcomes following ACL reconstruction and reduce re-injury risk.

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