STRENGTH ASSESSMENT IN ATHLETES FOLLOWING AN ANTERIOR CRUCIATE LIGAMENT INJURY

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Review
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Abstract:

The anterior cruciate ligament injury is one of the most common injuries in athletes. A limited range of motion, abnormal gait mechanics, quadriceps and hamstring muscles strength loss, and very often a decreased return to pre-injury levels of activity are concomitant to ligament reconstruction. Tremendous efforts have been made over the past two decades toward an accelerated rehabilitation in order to minimize the functional and mechanical knee instability as well as quadriceps and hamstring muscles strength loss. Various strength test protocols have been employed to determine the magnitude of reduction in muscle strength, and to provide criteria for an athlete's progression through the phases of recovery. However, since it is only the open kinetic chain feature that enables specific quantification of strength deficits in isolated muscles, this manuscript will focus on the methods for strength assessment which utilize unilateral OKC movements. By summarizing the principles and methods for strength assessment (isokinetic, isometric and isoinertial), we aimed at providing a comprehensive understanding of the current state of research that could guide the clinicians in conducting reasoned interventions.

Key words: *quadriceps, hamstrings, dynamometry, rehabilitation*

Strength assessment in athletes following an anterior cruciate ligament injury

The rupture of the anterior cruciate ligament (ACL) constitutes one of the most serious injuries in sports. Sport-related activities involving complex movements (e.g. cutting and pivoting) account for approximately 70% of acute ACL injuries (Lautamies, Harilainen, Kettunen, Sandelin, & Kujala, 2008; Lund-Hanssen, Gannon, Engebretsen, Holen, & Hammer, 1996; Micheo, Hernandez, & Seda, 2010). A complete ACL rupture is a complex trauma to the knee joint with concomitant mechanical and functional instability, commonly followed by a limited range of motion, muscle weakness and abnormal gait mechanics and very often leads to a decreased return to pre-injury levels of activity (Bryant, Kelly, & Hohmann, 2008; Kobayashi, et al., 2004; Mattacola, et al., 2002; Pezzullo & Fadale, 2010).

Commonly, injured athletes are able to continue playing high-performance sports without the need for ACL reconstruction (classified as copers; Fitzgerald, Axe, & Snyder-Mackler, 2000), while others who want to retain the same level of sports involvement but have strength deficits and episodes of giving way are advised to undergo surgery (classified as non-copers). Evidence-based rehabilitation after ACL reconstruction takes about 22–24 weeks and, several algorithm/criteria-based rehabilitation programs have been proposed over the years (Eitzen, Eitzen, Holm, Snyder-Mackler, & Risberg, 2010; Fitzgerald, et al., 2000; Myer, Paterno, Ford, & Hewett, 2008; van Grinsven, van Cingel, Holla, & van Loon, 2010).

Evaluation of strength has been an integral part of a testing battery consisting of multiple outcome measures, e.g. questionnaires, knee stability tests, postural control, and sport-specific measures, aimed at monitoring rehabilitation progress after ACL injury or reconstruction. The aim of this review is to summarize the principles and methods for strength assessment and to provide a comprehensive understanding of the current state of research that could guide the clinicians in conducting reasoned interventions.

The importance of muscle strength for recovery after ACL injury

Knee joint stability depends on the strength of the surrounding active and passive stabilizers (i.e. muscles and ligaments). Quadriceps and hamstrings are the most important muscle groups, while ACL is the most important ligament in stabilizing the knee joint. Mechanically speaking, the ACL and the quadriceps muscle are antagonists (Alkjaer, Simonsen, Magnusson, Dyhre-Poulsen, & Aagaard, 2012; Jarvela, Kannus, Latvala, & Jarvinen, 2002), while the role of hamstring muscles is to act as ACL agonists and to protect the ligament by reducing anterior and/or rotary instability induced by quadriceps contraction (Bryant, et al., 2008; Holcomb, Rubley, Lee, & Guadagnoli, 2007; Lund-Hanssen, et al., 1996).

Following the ACL injury and reconstruction, quadriceps and hamstrings strength has been shown to correlate with a good outcome after ACL reconstruction (Li, Maffulli, Hsu, & Chan, 1996; Moisala, Jarvela, Kannus, & Jarvinen, 2007), indicating that the goal of ACL reconstruction cannot be achieved if muscle strength has not been recovered to a pre-injury or even a higher level (Angelozzi, et al., 2012; Kobayashi, et al., 2004). The presence of any strength deficit may result in a decreased dynamic stability of the knee and a greater strain on ACL (Jarvela, et al., 2002). Traditionally, quadriceps and hamstrings strength measures derived from maximum force or moment of force have been used as one of the important criteria for releasing athletes to full training and competition. However, rather than maximum force itself, it is possible that the capacity of both hamstring and quadriceps muscles to rapidly generate force with respect to each other could be of greater importance for knee joint stabilization (Angelozzi, et al., 2012; Zebis, Andersen, Ellingsgaard, & Aagaard, 2011).

Principles of strength assessment

The main goal of the strength assessment is to follow up the strength recovery of quadriceps and hamstrings of the involved leg, with respect to the uninvolved leg. Strength is usually assessed by force or torque achieved during maximal voluntary contraction against external resistance, under isometric, isokinetic or isoinertial conditions (Knezevic & Mirkov, 2011). The external resistance could be defined using isokinetic dynamometers, resistance-training machines or other custom-built devices. Strength assessment could be performed either bilaterally or unilaterally, in closed or open kinetic chain movements.

Closed kinetic chain (CKC) movements are those in which the distal segment of the limb is in contact with a support surface (i.e. weight bearing). In recent years, the importance of using CKC in muscle strength assessment and particularly in rehabilitation has been emphasized, due to the belief that closed as opposed to open kinetic chain movements have a more functional nature (Augustsson & Thomee, 2000; Beynnon, Johnson, Abate, Fleming, & Nichols, 2005; Dubljanin-Raspopovic, Kadija, Mirkov, & Bumbasirevic, 2011). Also, it is thought that anterior tibial translation is reduced during these movements, due to knee compression forces which promote quadriceps/hamstrings co-contraction, for which CKCs are considered safe to use, particularly in the early phases of rehabilitation (Dubljanin-Raspopovic, et al., 2011; Micheo, et al., 2010; Risberg, Lewek, & Mackler, 2004). CKC exercises can be safely incorporated into the rehabilitation process as early as two weeks postoperatively, as long as undue strain on the healing graft is avoided (i.e. limiting knee range of motion from 0–60°) (Adams, Logerstedt, Hunter-Giordano, Axe, & Snyder-Mackler, 2012). However, despite the named advantages, testing protocols based on CKC movements could not sufficiently trace the recovery progress of the knee function after ACL reconstruction. According to Pua et al. (2008, p. 334), "considerable evidence exists to suggest that quadriceps strength deficits can be masked during testing in a CKC fashion (e.g. squats and vertical jumps)". Namely, CKC is not specific to the function of the quadriceps, as it requires the activation of other muscles, such as the hip extensors, which may have the ability to compensate for residual deficits of the quadriceps (Angelozzi, et al., 2012).

Open kinetic chain (OKC) movements are single-joint movements (e.g. seated knee extension or flexion) in which the distal segment is free to move (non-weight bearing) and they pose the ability to isolate the muscle of interest and allows a clinician to localize and quantify specific muscle deficits (Pua, et al., 2008). Nevertheless, it is the non-weight bearing nature of the OKC movements that they have been criticized for as undesirable or contraindicated in the early stages of recovery following the ACL reconstruction. While allowing for isolation of a single muscle, OKC have been found to produce increased anterior tibial translation, which results in a greater ACL graft strain than in CKC movements, particularly at low flexion angles and low levels of quadriceps activity (Callaghan, McCarthy, Al-Omar, & Oldham, 2000; Dubljanin-Raspopovic, et al., 2011). OKC exercises should not be incorporated into rehabilitation until six weeks postsurgery, with a large restriction in the range of motion (90° to 45°) to keep the reconstructed ligament from overstrain, progressing to a range of motion from 90° to 10° by week 12 (Adams, et al., 2012).

Methods for strength assessment

Based on the contraction type involved, strength assessment methods are classified to isokinetic, isometric or isoinertial. The decision which method should be employed depends on a variety of factors: available equipment, time lapsed from the ACL reconstruction, similarity of testing outcomes and athletic performance, test measures' sensitivity to the effect of rehabilitation, etc. Since it is only the

OKC feature that enables specific quantification of strength deficits in isolated muscles (Eitzen, et al., 2010; Micheo, et al., 2010; Pua, et al., 2008), this manuscript will provide an emphasis on the methods for strength assessment which utilize unilateral OKC movements.

Isokinetic strength assessment

Over the decades isokinetic dynamometry has become the preferred method for quadriceps and hamstring muscle strength evaluation both in healthy individuals and in ACL deficient subjects (Dvir, 2004; Eitzen, et al., 2010; Pua, et al., 2008; Zemach, Almoznino, Barak, & Dvir, 2009). Isokinetic assessment involves measurement of muscular torque while the limb is moving at a constant angular velocity. Most commonly, multiple velocity testing protocols (Zemach, et al., 2009) are used to collect as much information as possible about the patient's recovery. Significant variability exists in the strength testing protocols applied in the studies reviewed, particularly regarding the angular velocities and number of repetitions (see Table 1 for more details).

Isokinetic dynamometry measures could be obtained from three types of muscular contractions—isometric, isokinetic concentric and eccentric, and isoinertial. While the angular velocity of 0º/s corresponds to isometric contraction, isokinetic contractions could be assessed throughout the range of angular velocities that could be up to 500º/s, depending on the type of dynamometer. When applied on ACL deficient subjects, among the various protocols, testing has been most commonly conducted using at least two angular velocities, usually one lower (30–90º/s) and one higher (120–240º/s) (Kannus, 1988a; Knezevic, Mirkov, Kadija, Milovanovic, & Jaric, 2012; Lautamies, et al., 2008; Lee, Seong, Jo, Park, & Lee, 2004; Moisala, et al., 2007). However, tests based on velocities >180º/s may be inappropriate and invalid due to the fact that the test is not isokinetic. Specifically, in speeds >150º/s the isokinetic sector could be very limited or even negligible, resulting in, basically, a ballistic movement (Reichard, Croisier, Malnati, Katz-Leurer, & Dvir, 2005; Zemach, et al., 2009). Not only that recorded data would be less reliable than testing at a lower speed, but, according to Jarvela et al. (2002), the use of very high velocities (>240º/s) may cause problems to some patients since they may not be able to reach sufficient acceleration of the lever arm at the beginning of the movement and keep up the speed.

The range of motion during isokinetic knee extension and flexion movements is usually set from 0–90º (±5º) of flexion, while the number of repetitions varied across the applied protocols (Table 1). However, as mentioned earlier a certain caution is necessary when setting the range of motion, particularly during the earlier stages following ACL reconstruction, because maximal testing near full extension may put the reconstructed ligament at risk (Dubljanin-Raspopovic, et al., 2011). Furthermore, as shown by Reichard et al. (2005), testing quadriceps and hamstring strength using the middle sector of knee motion (30–60º) provides muscle torque and EMG data that are close and well correlated with those derived from testing the knee along the commonly used (0–90º) range of motion.

Although isokinetic dynamometry is widely applied on ALC deficient subjects, their shortcomings have been well recognized in literature. The main arguments are related to the absence of a stretch-shortening cycle (SSC) and that single-joint, that is, an isolated assessment bears little resemblance to functional performance (Pigozzi, Giombini, & Macaluso, 2012; Pua, et al., 2008). In addition, the similarity of isokinetic movements with everyday activities is questionable, since individuals have to work against a "constant" velocity, which is too low with respect to maximum speeds achieved during "unloaded" movements of human limbs.

Assessing strength under isometric conditions

While isokinetic tests have been routinely conducted using isokinetic dynamometers (Pua, et al., 2008), the isometric strength test has been conducted using either an isokinetic dynamometer or strain gauge force transducer attached to custom-built equipment (Suzovic, Nedeljkovic, Pazin, Planic, & Jaric, 2008; Wilson & Murphy, 1996). The use of isometric strength tests in subjects with ACL reconstruction (ACLR) has been valuable, particularly in the cases when isokinetic dynamometers were not available. The isometric test is based on the maximum voluntary contraction of a selected muscle group, performed under isometric conditions (Jaric, 2002; Wilson & Murphy, 1996).

It has been well known that the outcome of isometric tests is dependent on the level of familiarization, the type of instruction given, muscular pretension and the joint angle selected for the strength assessment (Abernethy, Wilson, & Logan, 1995; Wilson & Murphy, 1996). Regarding the last one, as the muscles lengths vary with changes in the knee joint angle, the magnitude of hamstrings and quadriceps force varies too. The coupling of their forces will probably change with the change in muscle length, and consequently affect their capacity to stabilize the knee joint (Osternig, Ferber, Mercer, & Davis, 2001). According to the length-tension relationship, the hamstring and quadriceps muscles exert a maximum force at particular muscle lengths, which correspond to particular joint positions, ~30° of knee flexion for hamstring and ~60° of knee flexion for quadriceps (Dvir, 2004).

Table 1. A review of studies using strength tests based on unilateral, open kinetic chain movements to assess strength imbalances in ACL patients

Author	Subjects	Testing Time	Strength Test	Protocol	Bilateral deficit %
Kobayashi et al., 2004	ACLR N=36	1, 6, 12 and 24 months postoperatively	Isokinetic concentric extension and flexion	5 rep. at 60º/s 5 rep. 180º/s	Q: 30% at 6 months, and 10% at 24 months, H: 10% at 6 months.
Mattacola et al., 2002	ACLR N=20	18±10 months postoperatively	Isokinetic concentric and eccentric extension and flexion	3 rep. at 120º/s 3 rep. at 240º/s	Quadriceps strength was not within the normal limits when compared with contralateral limb eg. BLD was high.
Risberg et al., 1999	ACLR N=56	6, 12 and 24 months postoperatively	Isokinetic concentric extension and flexion	5 rep. at 60º/s 30 rep. at 240º/s	Q: 34% at 6 months; 18% at 12 months and 7% at 24 months H: 16 % at 6 months, 7% at 12 months and 5% at 24 months
Eitzen et al., 2010	ACLD N=76	Within 3 months from the injury	Isokinetic concentric extension	5 rep. at 60º/s	Q: Copers 10% Non-copers 15.1%
Goradia et al., 2006	ACLR N=85	44 months postoperatively	Isokinetic concentric extension and flexion	60º/s 300º/s	Q: 3.4% at 60º/s; -2.4% at 300º/s H: 2.9% at 60º/s; 1.6% at 300º/s
Lund-Hansen et al., 1996	ACLR N=22	15 months postoperatively	Isokinetic concentric extension and flexion	5 rep. at 60º/s 15 rep. at 240º/s	No comparison between the involved and uninvolved leg
Morrisey et al., 2004	ACLR N=24	2 weeks postoperatively	Isometric extension and flexion Isokinetic concentric and eccentric extension and flexion	3 x 5s. MVC at 60º at 60º/s at 210º/s	Q: 70% at 0º/s; 69% at 60º/s; 64% at 210º/s H: 49% at 0º/s; 46% at 60º/s; 42% at 210º/s
Thomee et al., 2011	ACLR N=82	Preoperatively and 3, 6, 12, 24 months postoperatively	Isoinertial extension and flexion power assessment Leg press	5 trials on 5 weight levels 5 trials on 5 weight levels	Q: 10% preoperatively; 24% at 6 months; 10.0% at 12 months; 1% at 24 months H: -1% preoperatively; 6% at 6 months; 4% at 12 months; 2% at 24 months
Zemach et al., 2009	ACLI N=26	9 months to 6 years following the injury	Isometric extension Isokinetic concentric and eccentric extension	MVC at 45º 2 submax and 3 max rep. at 30, 60, 90, 120º/s	Q: 14% at 0º/s; 16% at 30º/s; 14% at 60º/s; 14% at 90º/s; 15% at 120º/s
Pigozzi et al., 2004	ACLR N=48	6 months postoperatively	Isokinetic leg press Isokinetic extension and flexion	3 rep. at 20 cm/s; 12 rep. at 50 cm/s 3 rep. at 80º/s; 12 rep. at 160º/s	Q: 15% at 20 cm/s; no data for 50 cm/s Q: 30% at 80º/s; 14% at 160º/s
Keays et al., 2001	ACLR N=31	preoperatively and 6 months postoperatively	Isokinetic extension and flexion	60º/s 120º/s	Q: 7.3% preoperatively; 12% at 6 months (at 60º/s); 7.8% preoperatively, 10.3% at 6 months (at 180º/s) H: 10% at 6 months (at 60º/s); 9.9% at 6 months (at 180º/s)
Neeter et al., 2006	ACLD N=23	6 months following the injury	Isoinertial extension and flexion Leg press	5 trials on 5 weight levels 5 trials on 5 weight levels	9 out of 10 patients after reconstruction and 6 out of 10 of the patients after ACL injury had LSI less than 90%
Ageberg et al., 2008	ACLD and ACLR N=total of 54	2 to 5 years following the injury	Isoinertial extension and flexion Leg press	5 trials on 5 weight levels 5 trials on 5 weight levels	Q: 6% in ACLR; 6% in ALCD H: 3% in ACLR; 2% in ALCD
St Clair Gibson et al., 2000	ACLD N=18	At least one year following the injury	Isokinetic concentric and eccentric extension and flexion	3 rep. at 60º/s 3 rep. at 120º/s	Qecc: 38% Qcon: 16% Hecc: 15% Hcon: 8% Involved: HeccQecc 0.80, HeccQcon 0.75; HconQecc 0.79 Uninvolved: HeccQecc 0.55; HeccQcon 0.77; HconQecc 0.50
Hiemstra et al., 2007	ACLR N=12	3.5 years postoperatively	Isokinetic concentric and eccentric extension and flexion	at 50, 100, 150, 200 and 250º/s	No significant strength differences between legs for any of the contractions and speeds tested (BLD range 0 to 8.5%). Significant strength deficit between legs for knee flexor of 13.3% averaged across all angular velocities.
Jarvela et al., 2002	ACLR N=86	7 years postoperatively	Isokinetic extension and flexion	5 rep. at 60º/s 5 rep. at 180º/s 25 rep. at 240º/s	Q: 10% at 60 º/s H: less than 5%

Author	Subjects	Testing Time	Strength Test	Protocol	Bilateral deficit %
Kadija et al., 2010	ACLR N=19	5 months postoperatively	Isometric extension and flexion Isokinetic extension and flexion	3 MVC at 60º 5 rep. at 60º/s 5 rep. at 120º/s 5 rep. at 180º/s	Q: 36% at 0º/s; 36% at 60º/s, 28% at 120º/s, 23% at 180º/s H: 15% at 0º/s; 6% at 60º/s; 2% at 120º/s; 4% at 180º/s HQ involved: 0.49 at 0º/s; 0.92 at 60º/s, 0.97 at 120º/s, 1.05 at 180º/s HQ uninvolved: 0.47 at 0º/s; 0.67 at 60º/s, 0.77 at 120º/s, 0.88 at 180º/s
Ageberg et al., 2009	ACLR N=36	Up to 3 years postoperatively	Isoinertial extension and flexion power strength assessment	5 trials on 5 weight levels	Q: 6% in HT graft; 6% in PT graft H: 12% in HT graft; -6% in PT graft Involved: HQ 0.63 in HT graft; 0.77 in PT graft
Kannus 1987	ACLR N=40	Up to 8 years postoperatively	Isometric extension and flexion Isokinetic extension and flexion	MVC at 60º 5 rep. at 60º/s 5 rep. at 180º/s	Q: 16% at 60º/s; 22% at 180º/s H: 12% at 60º/s: 20% at 180º/s BLD of the isometric tests was similar to isokinetic values
Lautamies et al., 2008	ACLR N=288	5 years postoperatively	Isokinetic extension and flexion	5 rep. at 60º/s 5 rep. at 180º/s	Q: 10% in PT graft; 6% in HT graft (at 60º/s); 9% in PT graft; 5% in HT graft (at 180º/s) H: 2% in PT graft; 4% in HT graft (at 60º/s); 3% in PT graft; 5% in HT graft (at 180º/s)
Lee et al., 2004	ACLR N=67	3.5 years postoperatively	Isokinetic extension	at 60°/s at 180°/s	Q: 28% preoperatively; 36% at 6 months; 18% after 1 year; 18% after 2 years (at 60°/s); 22% preoperatively; 26% at 6 months; 18% after 1 year; 11% after 2 years (180°/s)
Mittlmeier et al., 1999	ACLR N=10	preoperatively and 12 and 24 weeks postoperatively	Isokinetic extension and flexion	5 rep. at 60º/s 15 rep. at 180º/s	Q: 51% preoperatively; 48% after 12 weeks; 43% after 24 weeks (at 60º/s); 38% preoperatively; 31% after 12 weeks; 30% after 24 weeks (at 180º/s) H: 22% preoperatively; 15% after 12 weeks; 18% after 24 weeks (at 60º/s); 15% preoperatively; 11% after 12 weeks; 12% after 24 weeks (at 180º/s)
Moisala et al., 2007	ACLR N=48	4 to 7 years postoperatively	Isokinetic extension and flexion	5 rep. at 60º/s 5 rep. at 180º/s	Q: 10% in PT graft; 7% in HT graft (at 60º/s); 5% in PT graft; 2% in HT graft (at 180º/s) H: less than 3% in both grafts and velocities HQ ratios: 0.59 in PT graft, 0.58 in HT graft (at 60º/s); 0.64 in PT graft; 0.64 in HT graft (at 180º/s)
Reinking et al., 1996	ACLD N=23	No data	Isometric Hand-held dynamometry Isokinetic concentric and eccentric extension	3 x 3 sec MVC at 60º 4 max rep. at 60º 4 rep. at 60º/s	Q: 11% isometric, 11% in hand-held; 12% in concentric isokinetic; 18% in eccentric
Li et al., 1996	ACLD N=46	2 weeks after arthroscopy	Isokinetic extension and flexion	at 60º/s and 180º/s	Average BLD and HQ ratios were not provided

Note: ALCR – ACL reconstructed; ACLD – ACL deficiency, ACLI – ACL injured; rep. – repetition; Q – quadriceps muscle; H – hamstrings muscles; HQ ratio – hamstrings-to-quadriceps ratio; PT – patellar tendon graft; HT – hamstring's tendon graft

However, measuring force at a single joint position that is not specific to performance of most human activities has been the major argument against isometric testing (Abernethy, et al., 1995). Additionally, the underlying neural activation pattern of isometric tests could be different from the same pattern in rapid and cyclic movements, or a relatively long and fatigue-prone procedure based on a sustained contraction, which could be inappropriate for some populations, such as the injured or elderly (Abernethy, et al., 1995; Enoka & Fuglevand, 2001; Jaric, Radosavljevic-Jaric, & Johansson, 2002; Pua, et al., 2008).

Unlike the standard isometric test, recently proposed tests based on *consecutive maximum contractions* (CMC; Suzovic, et al., 2008) and *alternating consecutive maximum contractions* (ACMC; Bozic, Pazin, Berjan, & Jaric, 2012; Bozic, Suzovic, Nedeljkovic, & Jaric, 2011) could have partial similarity with a muscle action regime typical for various rapid and cyclic movements. Specifically, ACMC is based on consecutive isometric contractions of quadriceps and hamstrings, performed in an alternating fashion at a knee angle of 60º, at a frequency that could be considered as self-selected (instruction as hard and as quickly as possible). A typical outcome was a quasi-sinusoidal force profile that allows for the assessment of the maximum force and rate of force development in both the knee flexion and knee extension, with relatively stable and reliable variables.

CMC and ACMC tests have been evaluated on healthy and physically active subjects and they appeared to have both a moderate external validity regarding the prediction of various functional performances and the ability to detect the differences among individuals with different levels of physical fitness (Bozic, et al., 2012; Bozic, et al., 2011). ACMC test has been also evaluated on ACLR subjects, and the findings revealed that the variables had relatively stable values which proved to be reliable (Knezevic, et al., 2012). The test revealed sufficient sensitivity, and concurrent validity (with respect to the isokinetic tests) which is comparable with the validity of a standard isometric strength test. Nevertheless, ACMC retains important methodological advantages over the standard isometric test, such as a brief and simple procedure for testing two antagonistic muscles, as well as exposing the muscle and joint tissues to relatively low and transient forces. Based on the evaluation of both healthy and ACLR subjects, the results suggest that ACMC could be developed into a test of neuromuscular function that could be either alternative or complementary to the standard isometric test.

Isoinertial strength assessment

Isoinertial tests (previously known as isotonic) are based on limb movement against a constant external load (Abernethy, et al., 1995). These tests are used to assess muscle strength and power. In healthy subjects maximum isoinertial strength is most commonly assessed through one repetition maximum (1 RM) for a particular task (Abernethy, et al., 1995; Wilson, Lyttle, & Murphy, 1995). Another way to assess both strength and power under isoinertial conditions is using linear encoders to measure the load displacement of any machine using gravitational loads as external resistance (e.g. seated leg extension and flexion in OKC, or leg press, dips, pull-down, etc. in CKC), which allows for the calculation of muscle power during dynamic movements. Recently, the isoinertial assessment has been the favourite among some researchers because it allowed "the most natural pattern of movement of the human limbs, which apply force to an external load that is accelerated, and allows the achievement of all ranges of velocities" (Pigozzi, et al., 2012, p. 2). However, those against isoinertial assessment tend to emphasize poor reliability and objectivity due to inter-subject, inter-trial and inter-laboratory variations (Abernethy, et al., 1995).

There is a lack of literature regarding the use of isoinertial tests for strength assessment in ACLR subjects. Only a few studies have explored isoinertial strength assessment following the ACLR (Ageberg, Roos, Silbernagel, Thomee, & Roos, 2009; Ageberg, Thomee, Neeter, Silbernagel, & Roos, 2008; Neeter, et al., 2006; Thomee, et al., 2012). This group of authors applied the same isoinertial testing battery (seated leg extension and flexion, and leg press) in order to investigate the differences in quadriceps and hamstrings power between the contralateral limbs (see Table 1 for more details). Based on the findings, the proposed power test battery revealed a high ability to determine the deficits in leg power at different time points after ACL reconstruction and may contribute to the decision-making process whether and when the subjects can safely return to strenuous physical activities.

Strength test outcome measures

Among a number of variables extracted from strength test, maximum torque achieved under a given contraction mode is regularly used as a measure of quadriceps and hamstrings strength after ACL injury (Bryant, et al., 2008; Eitzen, et al., 2010; Pua, et al., 2008). Torque-time profiles from isokinetic and isoinertial measurements could be also used to calculate average measures, such as average torque, average work or average power, or to investigate torque-angle relationship (Pua, et al., 2008) that enables identifying the specific angle at which the peak moment occurs (Dvir, 2004). However, some evidence exists that these measurements are less reliable than peak measurements, because they are known to vary as a function of the test velocity, i.e. a higher velocity results in a delay in reaching the peak moment. Over the years, the priority in monitoring rehabilitation has been given to measuring strength, but more recently, the particular relevance of muscle power (product of force and velocity) and rate of force development (RFD) has been emphasized. RFD is usually assessed through isometric (or isoinertial) tests and represents a measure of the explosive strength qualities of the neuromuscular system and the abilities to execute high-performance movement tasks with limited duration (Mirkov, Nedeljkovic, Milanovic, & Jaric, 2004; Wilson & Murphy, 1996). Along with these measures, various lower limb strength imbalance ratios have been used to monitor recovery progress and to identify possible risk factors for developing knee or hamstring injury and re-injury (Dauty, Tortellier, & Rochcongar, 2005; Impellizzeri, Bizzini, Rampinini, Cereda, & Maffiuletti, 2008).

Bilateral difference (BLD) is used as a measure of strength imbalance of the corresponding muscles of the involved and uninvolved leg. BLD is usually calculated either from strength or power measures, and is used as a criterion when evaluating whether the athlete is ready to return to high-performance sport participation (Eitzen, et al., 2010; Keays, Bullock-Saxton, Keays, & Newcombe, 2001; Lee, et al., 2004; Zebis, Andersen, Bencke, Kjaer, & Aagaard, 2009). However, it has been suggested recently that BLD calculated from rate of force development should be used as an adjunctive measure in the decision-making process (Angelozzi, et al., 2012). The main rationale when using BLD is to ensure that the involved side reaches a sufficient level of symmetry with the uninvolved leg to minimize the risk of re-injury when returning to training and competition (Thomee, et al., 2012). Bilateral difference is usually expressed as:

$$BLD = \frac{Noninvolved - Involved}{Noninvolved} x100 \qquad \text{(Eq.1)}$$

representing the percent difference between the strength test outcomes of the uninvolved and involved limb relative to the uninvolved. However, some authors prefer to express this difference as an index of symmetry between the legs (LSI), which is calculated as the ratio of the involved leg score and the uninvolved leg score expressed in per cent:

$$LSI = \frac{Involved}{Noninvolved} x100 \qquad \text{(Eq.2)}$$

A small bilateral difference (i.e. high limb symmetry index) of strength indicates a good muscle function, in contrast to the low LSI which is associated with an increased risk of injury or re-injury (Ageberg, et al., 2008; Hiemstra, Webber, MacDonald, & Kriellaars, 2007). Nevertheless, a certain caution is needed when using BLD or LSI. Namely, in some subjects, strength of the uninvolved side decreases over time due to cross-over inhibition of motor activation, de-conditioning or insufficient reconditioning (Hiemstra, et al., 2007; Thomee, et al., 2012). Such strength loss could affect the ratio between the involved and uninvolved leg, i.e. the obtained ratio would be an underestimate of the real strength loss in the involved leg.

In addition to BLD, hamstrings-to-quadriceps ratio (HQ) is used as an indicator of normal balance between hamstrings and quadriceps, describing the hamstrings' ability to protect the ligament from excessive anterior shear forces produced by a quadriceps contraction, and to stabilize the knee joint. Li et al. (1996) found a clear association between a high HQ ratio and good function of the knee, i.e. HQ strength ratio has been shown to predict the functional ability of the ACL deficient knees, while the imbalance in this ratio has been identified as a potential risk factor for ACL injury (Kannus, 1988b; Li, et al., 1996; Moisala, et al., 2007; Zebis, et al., 2011). Conventionally, the HQ ratio is determined from peak isometric or concentric torques of both hamstrings and quadriceps ($Hamstring_{con}/Quadriceps_{con}$), and thus is called the conventional HQ ratio (Dvir, 2004; Holcomb, et al., 2007; Hole, et al., 2000).

The typical isokinetic HQ ratio of a healthy knee ranges from 0.5 to 0.8, depending on the angular velocity. An HQ ratio of 0.66 or higher has usually been accepted as "normal" during low angular velocities (e.g. 60º/s), with it approaching 1.0 at high angular velocities (e.g. 240º/s or 300º/s) (Coombs & Garbutt, 2002; Hewett, Myer, & Zazulak, 2008; Kannus, 1988b; Kong & Burns, 2010). Although isometric dynamometry allows for comparison of hamstrings to quadriceps balance, the isometric outcome measures (Fmax and RFD) are dependent on selected knee angle, which makes a comparison of the results among studies difficult (Kong & Burns, 2010). Nevertheless, isometric HQ ratios are generally lower than the concentric HQ ratios, with reported values up to 0.50 (Kadija, Knezevic, Milovanovic, Bumbasirevic, & Mirkov, 2010; Yoo, et al., 2010).

Since concentric actions do not occur simultaneously in antagonistic muscles, the HQ ratio calculated from either eccentric hamstrings torque over concentric quadriceps torque, or concentric hamstrings torque over eccentric quadriceps torque, has been used (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998; Dvir, 2004; St Clair Gibson, Lambert, Durandt, Scales, & Noakes, 2000). Dvir et al. (1989) refer to this ratio as "dynamic control ratio (DCR)":

$Hamstring_{con} : Quadriceps_{ecc} = DCR\ of\ knee\ flexion$ (Eq.3)

$Hamstring_{ecc} : Quadriceps_{con}$ = DCR of knee extension (Eq.4)

The DCR ranges from 0.3 to 1.2 depending on the selection of contraction modes and angular velocities (Aagaard, et al., 1998; Hole, et al., 2000). Unfortunately, the predictive value of DCR with respect to ACL injury has not been investigated thoroughly. Daneshjoo et al. (2012) reported these ratios for professional soccer players, concluding that these athletes have higher predisposition of getting knee injuries because both HQ ratio and DCR were found to be lower than the average values.

More recently RFD based HQ ratio has been introduced (Zebis, et al., 2011), due to the belief that a peak torque based HQ ratio may not reflect the real potential for dynamic knee joint stabilization during rapid movements. Namely, the ability to rapidly activate the hamstrings relatively to the quadriceps is important. The rationale is that the time required to develop force in many types of daily and sports activities is significantly shorter than the time needed to exert maximal strength (Zebis, et al., 2011). As shown by Greco et al. (2013), this ratio obtained during the early contraction phase is affected by fatigue to a lesser extent than conventional HQ ratios, indicating that soccer-specific intermittent protocols do not reduce the potential for knee joint stabilization during the initial phase of contraction.

When to apply strength tests?

As one of the ultimate goals of the rehabilitation process after ACL injury is the strength recovery, strength should be closely monitored through the whole rehabilitation process. Strength measures obtained following the injury or few days prior to ACL reconstruction are very useful since they could serve as a baseline for later comparisons. The reason for such an approach is that a substantial loss in strength could occur even in the uninvolved leg, thus postoperative strength outcome measures such as BLD can be underestimations of the real patient's side-to-side differences (Neeter, et al., 2006).

Since more functional tests, such as jumping and cutting, are inappropriate during the early stages of recovery (within the first eight weeks), it is obvious that the assessment of knee function and performance has to rely on muscle strength testing. During that period, strength could be assessed with an isometric test applied at the knee angle that is within the safe range of motion (Dvir, 2004; Pua, et al., 2008). Some clinicians prefer to use high speed isokinetic protocols (300 and 180º/s) (Myer, Paterno, Ford, Quatman, & Hewett, 2006), although the results recorded at these speeds should be taken with caution for the earlier stated reasons (i.e. torques may be invalid because the tests are virtually ballistic). Specific recommendations and algorithms which could be a guide through recovery, have been proposed to help determine the right timing for the maximum muscle strength testing (Adams, et al., 2012; Myer, et al., 2006), with respect to the graft healing process, anterior pain and swelling limitations. Maximum strength tests are usually applied for the first time 12 to 24 weeks postoperatively (Angelozzi, et al., 2012; Meyers, Sterling, & Marley, 2002; Mittlmeier, et al., 1999; Risberg, Holm, Tjomsland, Ljunggren, & Ekeland, 1999; Thomee, et al., 2012) (see Table 1 for more details). Several studies have reported quadriceps and hamstring muscle performance periodically after ACLR, e.g. three, six and 12 months following surgery (Angelozzi, et al., 2012; Kobayashi, et al., 2004; Mittlmeier, et al., 1999; Risberg, et al., 1999; Thomee, et al., 2012). The number and timing of follow-up testing sessions depended on the athlete's progress through the stages of recovery and the final testing has been generally defined by a rehabilitation time frame (e.g. six months postoperatively, or sometimes even 12 months).

Muscle strength as the criteria for a return to full training and competition

Numerous ACL reconstruction protocols provide various specific criteria-based guidelines or algorithms for different phases of rehabilitation (Myer, et al., 2006; Pezzullo & Fadale, 2010). Among a number of multiple outcome measures used to determine the timing for a return to full training and competition (e.g. questionnaires, knee stability tests, postural control, sport-specific measures), lower limb strength has been proved to be an important one (Eitzen, et al., 2010; Myer, et al., 2006).

Following the reconstruction, loss in quadriceps strength is profound particularly when a patellar tendon graft is used for ruptured ligament replacement (Bryant, et al., 2008; Hiemstra, et al., 2007; Shelbourne & Gray, 1997). Athletes could attempt to pass the criteria for return-to-sport training as early as three months following the ACLR if at least 80% of the symmetry in quadriceps strength has been achieved (Hartigan, Zeni, Di Stasi, Axe, & Snyder-Mackler, 2012). However, more often a six-month period is recognized as a landmark for return to sports activity after an accelerated rehabilitation programme, although only 35–50% of athletes pass the criteria to return to sports at that time (Hartigan, et al., 2012; Hiemstra, et al., 2007; Pigozzi, et al., 2012). Even when using the aggressive approach in rehabilitation, the differences between the involved and uninvolved leg six months postoperatively are on average 25% for quadriceps and 10% for hamstring muscles, depending on the type of graft used for reconstruction (Angelozzi, et al., 2012; Hartigan, et al., 2012; Kadija, et al., 2010). One year after the ACLR muscle strength is usually almost fully recovered, but the athletes could still have significant deficits in explosive force capacities (RFD) (Angelozzi, et al., 2012).

Making a decision regarding an athlete's readiness for progressing through rehabilitation should not be based on certain time frames, but whether certain levels of symmetry are reached or not. Myer et al. (2008) have suggested that athletes who want to initiate the return-to-sport training should demonstrate a minimal baseline level of isokinetic knee extension torque/body mass of at least 40% (male) and 30% (female) at 300º/s and 60% (male) and 50% (female) at 180º/s. At the final stage of recovery the criteria are more stringent, and an athlete must demonstrate at least a 90% symmetry (less than 10% of BLD) between the involved and uninvolved leg for quadriceps strength in order to return to high load and complex activities (Angelozzi, et al., 2012; Hartigan, et al., 2012; Hiemstra, et al., 2007; Thomee, et al., 2012).

Regarding the strength ratio between the antagonistic muscle groups, it is commonly accepted that conventional isokinetic HQ ratio of 0.6 or greater and DCR more than 1.0 when measured at higher velocities (120º/s) are desirable in rehabilitation (Holcomb, et al., 2007; Kong & Burns, 2010). Although some could question the validity of HQ ratio as a criterion, it should be included as an outcome measure. Namely, it could happen that after a given rehabilitation time, an athlete eliminates strength deficits between contralateral muscles, fulfilling (among a number of other) the "return-to-play criteria", but still having deficits regarding the antagonist/agonist (HQ ratio) strength ratio.

Conclusions and recommendations

In subjects with ACL injury or following reconstruction the assessment of muscle strength is important for determining the location and extent of muscle weakness. Strength should be monitored through all phases of rehabilitation (post-injury and periodically following the surgery).

When assessing strength with isokinetic dynamometry, clinicians should choose among different angular velocity (reasonable would be between 60 and 180º/s) and contraction mode options, while taking into consideration the phase of recovery, range of motion, applied loads/speeds, etc. Regarding the isoinertial dynamometry, it deserves additional attention in rehabilitation monitoring, since it enables power assessment under light loads. Last but not least, the isometric tests are also valuable, particularly the novel test based on alternating consecutive contractions which gives us the possibility to assess the strength and rapid force capacities of antagonistic muscles within the same trial, thus decreasing the overall loading on the muscle and joint connective tissues.

Regardless of the selected method, a strength test should provide outcome measures that are most closely related to the functional ability of the involved limb or area and may detect any strength imbalances. Since outcome measures are strongly affected by the selected method, as well as velocities and joint positions, we suggest that both absolute and strength imbalance ratios should be used in the decision-making process. Additional investigation is needed regarding the use of adjunctive outcome measures that could be more functional (such as those based on RFD) than those derived from torque.

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PROCJENJIVANJE JAKOSTI NAKON OZLJEDE PREDNJE UKRIŽENE SVEZE U SPORTAŠA

Ruptura prednjega križnog ligamenta (*Anterior Cruciate Ligament* – ACL) svrstava se u najčešće i najozbiljnije ozljede u sportu. Ozljedu prate ograničen opseg pokreta, narušen obrazac hoda, slabost opružača i pregibača zgloba koljena i vrlo često nemogućnost povratka na razinu sportske aktivnosti prije ozljede. Tijekom posljednja dva desetljeća rehabilitacijski protokoli znatno su unaprijeđeni kako bi se ograničila funkcionalna i mehanička nestabilnost koljena i spriječio veći gubitak jakosti opružača i pregibača. Nakon ozljede, primjenjuju se različiti protokoli za procjenu jakosti radi utvrđivanja veličine redukcije mišićne jakosti, ali i za određivanje standarda za napredovanje sportaša kroz faze oporavka. Kako samo testovi koji se izvode u otvorenom kinetičkom lancu dopuštaju kvantifikaciju deficita u mišićnoj jakosti izoliranog mišića, ovaj pregledni članak bavit će se ponajviše metodama procjene jakosti koje su zasnovane na unilateralnim pokretima koji se izvode u otvorenom lancu. Cilj je ovog rada bio da se pregledom principa i metoda za procjenu jakosti (izokinetičke, izometrijske i izoinercijske) omogući razumijevanje rezultata novijih istraživanja, koji bi liječnicima mogli pomoći u realizaciji odgovarajućih intervencija.

Ključne riječi: *quadriceps (četveroglavi mišić natkoljenice), mišići stražnje strane natkoljenice, dinamometrija, rehabilitacija*