Physical Therapy in Sport 16 (2015) 22–28

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original research

# Long-term deficits in quadriceps strength and activation following anterior cruciate ligament reconstruction

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ARTICLE INFO

*Article history:*
Received 7 August 2013
Received in revised form
31 January 2014
Accepted 11 February 2014

*Keywords:*
Anterior cruciate ligament
Quadriceps inhibition
Central activation ratio
Return to sport

ABSTRACT

*Objective:* Even some time after a ruptured ACL has been reconstructed thigh musculature atrophy, voluntary activation, and knee-extensor strength deficits may be encountered. The purpose of this study was to evaluate bilateral knee-extension strength, voluntary activation of the quadriceps, and thigh circumference in males and females with ACL reconstruction (ACLR).
*Design and participants:* Within-subject and between-subject designs were used to evaluate 24 unilateral ACLR individuals and 23 controls.
*Main outcome measures:* Isokinetic knee-extension strength was assessed in ACLR participants while central activation ratio (CAR) and thigh circumference measures were obtained from both groups.
*Results:* Knee-extensor strength deficits ($p < .039$) and lower CAR of the quadriceps were found in the ACLR limb compared to the uninvolved limb ($p = .047$). Extensor strength was greater in males ($p < .001$), however, CAR was not different between sexes ($p = .086$). No difference in voluntary activation was revealed among the ACLR limb, uninvolved limb, and control limb when compared as independent groups ($p = .460$). The strength deficits found in the ACLR limb are partly attributable to lower voluntary activation compared to the uninvolved leg, given that no difference was found in thigh circumference between legs.
*Conclusion:* Clinicians should consider the deficits in muscle function when returning patients to pre-injury activity levels.

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## 1. Introduction

Approximately 100,000 anterior cruciate ligament (ACL) reconstructions are performed annually in the United States and the cost of surgery is over 2 billion dollars (Lyman, Koulouvaris, Sherman, Do, Mandl, & Marx, 2009; Wilk, Macrina, Cain, Dugas, & Andrews, 2012). Restoring range of motion, strength, and neuromuscular control, as well as incorporating functional activity progressions are goals of rehabilitation so that a patient may return to pre-injury activity levels (Beynnon et al., 2005; Wilk et al., 2012). Even some time after the post-operative rehabilitation is completed, thigh musculature atrophy along with proprioception, voluntary activation, and knee-extensor strength deficits may be encountered (Anderson, Lamb, Barker, Davies, Dodd, & Beard, 2002; Coombs & Cochrane, 2001; Hiemstra, Webber, MacDonald, & Kriellaars, 2000; Hurley, 1997; Kobayashi, Higuchi, Terauchi, Kobayashi, Kimura, & Takagishi, 2004; Mattacola, Perrin, Gansneder, Gieck, Saliba, & McCue, 2002; Osteras, Augestad, & Tondel, 1998; Wilk et al., 2012; Wilk, Romaniello, Soscia, Arrigo, & Andrews, 1994). The quadriceps muscle serves as a dynamic knee stabilizer and aids in prevention of ACL rupture (Bodor, 2001; Eitzen, Fernandes, Nordsletten, Snyder-Mackler, & Risberg, 2013; Risberg, Holm, Myklebust, & Engebretsen, 2007). In some evaluations, as few as 12–16% of ACLR individuals regain up to 90% of knee-extensor strength of the uninvolved limb at six months post-operation (Osteras et al., 1998; Wilk et al., 1994). Others have found that recovery of strength to 80–90% can take upwards of 24 months (Kobayashi et al., 2004; Rosenberg, Franklin, Baldwin, & Nelson,

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http://dx.doi.org/10.1016/j.ptsp.2014.02.003
1466-853X/Published by Elsevier Ltd.

1992; Wojtys & Huston, 2000). Return-to-play criteria are commonly based on comparing the function of the ACL reconstructed limb to the uninvolved side (Anderson et al., 2002; Coombs & Cochrane, 2001; Hiemstra et al., 2000; Keays, Bullock-Saxton, Newcombe, & Keays, 2003; Kobayashi et al., 2004; Mattacola et al., 2002; Osteras et al., 1998; Wilk et al., 1994). A clinician may need to use such criteria with caution because bilateral strength deficits can persist post-injury (Urbach, Nebelung, Weiler, & Awiszus, 1999; Wojtys & Huston, 2000).

Evaluating the neural drive of the knee-extensors may provide insight to muscle function following ACLR. Twitch interpolation is a valid technique that involves the comparison of muscle activation during a maximal voluntary isometric contraction, which relies on central neural drive to the muscle, with a maximal superimposed electrically evoked contraction independent of the central nervous system (Hales & Gandevia, 1988; Milner-Brown, Stein, & Yemm, 1973). The ratio of peak force output during a voluntary maximal effort to an electrically evoked involuntary maximal contraction is known as the central activation ratio (CAR), and is used to assess the central inhibition in the muscle of an individual (Fig. 1). Incomplete motor unit activation of a muscle (i.e., CAR $<$ 100%) is an indicator of inhibition of the neural drive within the central nervous system during a maximal isometric contraction (Hunter, White, & Thompson, 1998). Urbach et al. (1999) found a deficit in voluntary maximal activation in the involved quadriceps and a crossover effect to the uninvolved quadriceps to the same extent in male patients with symptomatic, isolated ACL deficiency. When male ACLR patients were evaluated prior to surgery and two years after the reconstruction a similar bilateral deficit was found in voluntary quadriceps activation compared to the healthy controls (Urbach et al., 1999; Urbach, Nebelung, Becker, & Awiszus, 2001). Quadriceps voluntary activation improved significantly bilaterally 2 years after ACLR but remained less than the controls (Urbach et al., 1999). A bilateral quadriceps activation deficit was found by Hart, Turman, Diduch, Hart, and Miller (2011) in patients averaging 47 months following ACL repair. Snyder-Mackler, De Luca, Williams, Eastlack, and Bartolozzi (1994) failed to find a quadriceps activation deficit in male and female ACLR patients using the burst-superimposition technique. Based on mixed results concerning quadriceps activation deficits and lack of gender comparisons, further research is needed to determine the status of long-term muscle function after ACLR.

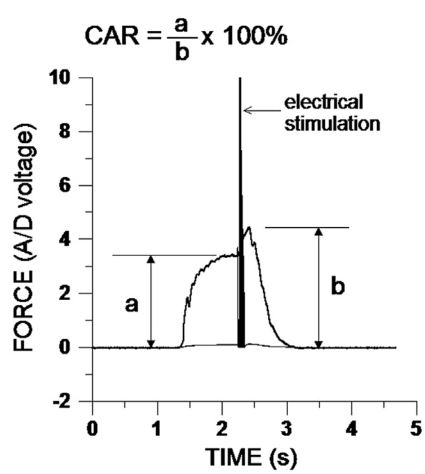


**Fig. 1.** Central activation ratio (CAR) is used to assess the central inhibition of the quadriceps muscle, where *a* is the pre-stimulation knee-extensor force and *b* is the post-stimulation knee-extensor force, during a single sustained maximum effort muscle contraction.

A comprehensive evaluation of long-term post-surgical outcomes including dynamic muscle strength, muscle activation, and thigh atrophy in ACLR patients who have completed a rehabilitation program is warranted. Although some of these factors have been examined independently in previous studies, a complete evaluation of muscle quality which includes gender comparisons in ACLR patients who are a few years post-surgery has yet to be performed. We focused specifically on muscle function via isokinetic strength testing and voluntary activation of the quadriceps femoris using a twitch interpolation technique along with comparing thigh circumference bilaterally. Based on findings reported in the literature (Arangio, Chen, Kalady, & Reed, 1997; Bizzini, Gorelick, Munzinger, & Drobny, 2006; Farquhar, Chmielewski, & Snyder-Mackler, 2005; Hart et al., 2011; Harter, Osternig, & Standifer, 1990; Hiemstra et al., 2000; Kobayashi et al., 2004; Natri, Jarvinen, Latvala, & Kannus, 1996; Urbach et al., 2001; Wilk et al., 1994, 2012), we hypothesized that a decreased peak isokinetic extension torque and a CAR deficit would be present in the ACLR limb compared to the uninvolved side. Furthermore, we hypothesized that there would be a CAR deficit in the ACLR group when compared to the healthy controls.

## 2. Method

### 2.1. Participants

Thirteen females (age: 20.2 $\pm$ 1.1 years, height: 163 $\pm$ 6 cm, weight: 592 $\pm$ 61 N, years post-surgery 2.5 $\pm$ 1.5 years) and 11 males (21.3 $\pm$ 2.5 years, 180 $\pm$ 7 cm, 772 $\pm$ 112 N, years post-surgery 3.3 $\pm$ 1.8 years) with unilateral ACL reconstructed knees were recruited from the university campus. Of the 24 ACLR participants, 18 had patellar tendon autografts, two had hamstring tendon autografts, and four had patellar tendon allografts. The time post-surgery was not different between males and females (unpaired *t*-test, $p = .247$). Eleven females (21.5 $\pm$ .8 years, 166 $\pm$ 5 cm, 606 $\pm$ 114 N) and 12 males (21.8 $\pm$ 1.1 years, 179 $\pm$ 5 cm, 855 $\pm$ 146 N) served as controls. Males in the control and ACLR groups were matched by age ($p = .555$), height ($p = .605$) and weight ($p = .141$) according to *t*-tests. Females in both groups were matched by height ($p = .184$) and weight ($p = .715$) but not by age ($p = .005$). All ACLR participants had completed physical rehabilitation programs, resumed pre-injury activity levels, and were cleared to return to full unrestricted activity prior to participation. All participants were recreationally active and free of any additional lower extremity injury that hindered their physical activity in the six months prior to testing. Participants signed an informed consent agreement that was approved by the Institutional Review Board before participation.

### 2.2. Procedures

All participants warmed-up on a treadmill for 5 min at their own preferred walking pace prior to testing. Thigh circumferences were measured in the ACLR and control groups bilaterally to estimate the size of thigh muscles before the warm-up. The same investigator made all measurements with a flexible measuring tape as the participant stood while the thigh muscles were relaxed. The tape was positioned mid-way over the quadriceps belly at the largest visible point. The distance above the superior border of the patella was measured and the same height was used for evaluating the circumference of the opposite thigh (Soderberg, Ballantyne, & Kestel, 1996).

A KinCom AP125 dynamometer (Chattanooga Group Inc., Hixson, TN) collecting torque data at 40 Hz was used for both isokinetic strength and motor unit activation evaluations. Tested in a seated