The effect of anterior cruciate ligament reconstruction on hamstring and quadriceps muscle function outcome ratios in male athletes

Marko Kadija[1], Olivera M. Knežević[2], Darko Milovanović[1], Aleksandar Nedeljković[3], Dragan M. Mirkov[3]

[1]Institute of Orthopedic Surgery and Traumatology, Clinical Centre of Serbia, Belgrade, Serbia;
[2]University of Belgrade, Institute for Medical Research, Neurophysiology Lab, Belgrade, Serbia;
[3]University of Belgrade, Faculty of Sport and Physical Education, The Research Centre, Belgrade, Serbia

SUMMARY

Introduction Maximal strength ratios such as the limb symmetry index (LSI) and hamstring-to-quadriceps ratio (HQ) may be considered the main outcome measures in the monitoring of recovery after anterior cruciate ligament (ACL) reconstruction. Although explosive strength is much more important than maximal strength, it is generally disregarded in the follow-up of muscle function recovery.

Objective The purpose of this study was to compare ratios between maximal (F_{max}) and explosive strength (rate of force development – RFD) in individuals with ACL reconstruction.

Methods Fifteen male athletes were enrolled and had maximum voluntary isometric quadriceps and hamstring contractions tested (4.0 ± 0.1 months post reconstruction). In addition to F_{max}, RFD was estimated ($RFD_{max,}$ as well as RFD at 50, 100, and 200 ms from onset of contraction) and LSI and HQ ratios were calculated.

Results The involved leg demonstrated significant hamstring and quadriceps deficits compared to uninvolved leg ($p < 0.01$). Deficits were particularly significant in the involved quadriceps, causing higher HQ ratios (average 0.63), compared to the uninvolved leg (0.44). LSI was significantly lower for RFD variables (average 55%) than for F_{max} (66%).

Conclusion The assessment of RFD may be considered an objective recovery parameter for one's readiness to return to sports and should be an integral part of standard follow-up protocol for athletes after ACL reconstruction. Moreover, the combination of indices derived from maximal and explosive strength may provide better insight in muscle strength balance, as well as a clear picture of functional implications.

Keywords: anterior cruciate ligament (ACL); knee extensors; knee flexors; isometric

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among most frequent disabling injuries associated with athletic activity. Most ACL injuries occur during sports that involve dynamic movements such as jumping, pivoting, and cutting [1], so returning to preinjury levels of activity requires high-level neuromuscular control to dynamically stabilize the femur on the tibia [2, 3]. An increased quadriceps and hamstring strength has been shown, amongst a number of factors, to contribute to recovery, and correlate with a positive outcome following ACL reconstruction [4–7]. Maximal strength (F_{max}) typically achieved after 3–5 seconds of a sustained maximum voluntary isometric contraction (MVC) has often been applied to assess and monitor quadriceps and hamstring strength recovery following the ACL reconstruction. However, one of the problems associated with maximum strength relates to the fact that F_{max} is achieved 400 to 600 ms after the onset of the contraction, while most rapid sport-related movements (such as sprinting, kicking, and jumping) typically involve contraction times of 50–250 ms [1, 8, 9]; thus, the short contraction times during fast limb movements may not allow maximal muscle force to be reached. In addition to F_{max}, the rate of force development (RFD) of quadriceps and hamstring can also be obtained from MVC. This is calculated from the slope of the recorded force–time curve and has generally been used to assess the explosive strength qualities of the neuromuscular system [8, 10].

Several studies have shown that the ability to quickly produce high levels of force is more important for executing high performance movement tasks of limited duration than just being able to produce high levels of force, and therefore could be a better predictor for functional difficulties in sporting activities than just maximal strength itself [1, 8, 11, 12]. This has been supported by findings from Zebis et al. [1] who have compared hamstring-to-quadriceps ratios (HQ ratios) calculated from RFD, obtained from the slope of the force–time curve, with the traditional F_{max} HQ strength ratio in elite soccer players. They found that a lower RFD HQ ratio could be associated with a reduced potential for knee joint stabilization during the initial phase of muscle contraction and could be therefore used

Correspondence to:
Marko KADIJA
Institute for Orthopaedic Surgery and Traumatology
Clinical Centre of Serbia
Koste Todorovića 26, Belgrade
Serbia
kadija.marko@kcs.ac.rs

as possible risk indicator for ACL injury. However, RFD strength ratios could also be used as potentially valuable outcome measures in monitoring recovery of muscle function following surgical procedures. For example total knee arthroplasty leads to significant limb asymmetries in quadriceps' RFD compared to maximal strength [13, 14], while subjective knee function is more strongly related to RFD measures than to maximal strength. More importantly, it has been shown that ACL reconstruction can lead to large deficiencies in rapid force generation [15]. This has been supported by the findings from Angelozzi et al. [12], who followed 45 male soccer players recovering from ACL injuries. They found that there was a deficit in RFD despite a nearly full recovery of maximal strength and standard clinical outcome measures [International Knee Documentation Committee (IKDC), Tegner, KT1000 (MEDmetric Corporation, San Diego, CA, USA), and MVC], which are often used in deciding when an athlete can return to sport. Furthermore, it has been suggested that the ratio of hamstring to quadriceps strength should be assessed over a long-term period following surgery in order to identify chronic strength deficits in athletes [5]. Based on these findings it has been concluded that RFD may be a useful outcome when deciding to return athletes to sports.

Although these studies have confirmed importance of taking into account RFD measures in the recovery of athletes after ACL reconstruction and their return to sports, they were mainly focused on quadriceps explosive strength qualities, with a relative lack of information regarding hamstring RFD, in particular to the capacity of RFD to assess the potential strength asymmetries within and between the hamstring and quadriceps. The paucity of hamstring data is significant limitation to these cited studies as the ability to rapidly activate hamstring relative to quadriceps is important, particularly in situations of rapid anterior tibial translation, where hamstring has an important role in initial knee stabilization.

OBJECTIVE

To address the aforementioned shortcomings, we designed a study aiming to compare the strength ratios (LSI and HQ ratio) in maximal strength with corresponding ratios in explosive strength qualities, in athletes following ACL reconstructions. We hypothesize that ACL reconstructed athletes will have greater deficiencies in explosive strength compared with maximal strength.

METHODS

Participants

Fifteen male athletes (age 22 ± 4 years; body mass 84.0 ± 11.1 kg; height 180.3 ± 4.0 cm, mean ± SD) with recent ACL reconstruction (4.0 ± 0.1 months following the surgery) were included in the study. The inclusion criteria were as follows: first ACL injury, no other knee ligaments injured, and no history of concurrent fractures, osteoarthritis, or hereditary and neuromuscular diseases. The ACL reconstruction procedure was identical in all patients performed by the same surgeon.

The reconstruction included direct arthroscopy whereby ACL lesion was verified. The involved leg was placed on an arthroscopic leg holder, which enabled lower leg flexion from 110° to 115°. After graft material was taken (bone-patellar tendon-bone – BPTB – graft), the femoral graft insertion site was selected in all patients [16]. After the medial aspect of the lateral condyle was cleared of the ruptured ACL remains, the surgeon, with the aid of the bifurcation ridge and the resident ridge, determined the center of insertion, located at the point of meeting between the superior and the middle third of the height of the bifurcation ridge. After that, maximal flexion was performed and a canal was drilled through the anteromedial portal with a guide (2.5 mm). At the same time, the optics was located in the accessory medial portal positioned above and laterally to the medial portal while the angle between the guide and the medial aspect of the lateral condyle was maximal (leaning on the medial femoral condyle). The canal was dilated with a rigid reamer of appropriate thickness (the thickness was graft-dependent). Both femoral and tibial side of the reconstructed ligament were fixed with titanium interference screws.

Following the surgery, the patients were allocated to a standard postoperative rehabilitation program for athletes. They were included in the study after being discharged from physical therapy. Ethical clearance for the study was obtained from the University IRB committee and the subjects signed the institutionally approved informed consents in line with Helsinki declaration.

Procedures

Standard clinical assessments included questionnaires (IKDC subjective score, and Tegner score) and knee laxity test performed with KT1000 instrumented arthrometer at 13.61 kg of force. All clinical assessments were performed by an experienced orthopedic surgeon at the Clinic of Orthopaedic Surgery and Traumatology.

The assessment of muscle function was performed at Research Centre of Faculty of Sport and Physical Education, using a Kin-Com isokinetic dynamometer (Chatex Corp., Chattanooga, TN, USA), set to isometric conditions. Prior to muscle strength testing, each subject was given a five-minute warm-up period on a stationary bicycle, followed by passive stretching exercises. The subjects were seated in an upright position and fixed to the testing apparatus, with the straps around the pelvis, the thigh, and malleoli (Figure 1). The axis of rotation of the dynamometer was aligned with the lateral femoral epicondyle. The knee angle was fixed at 45 degrees in flexion [17, 18]. Afterwards, a set of two submaximal contraction pre-tests were performed for each muscle group in the dynamometer. The uninvolved leg was tested first. Two MVCs were performed both for quadriceps and hamstring at 60-second intervals,

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Figure 1. Subject's positioning during muscle strength testing

while the patients were carefully instructed to contract as fast and hard as possible, sustaining the contraction for 5 s [19]. Trials with visible initial countermovement were excluded and an extra trial was performed [8, 9]. A better result was taken into further analysis.

The force–time curves were recorded at a rate of 500 s^{-1} and low-pass filtered (10 Hz) using a fourth-order (zero-phase lag) Butterworth filter. The F_{max} was defined as the highest force value, and RFD_{max} as the highest positive value from the first derivative of the force signal (i.e. the greatest slope of the force–time curve). RFD was also derived from the average slope of the force–time curve during intervals 0 to 50, 0 to 100, and 0 to 200 ms ($RFD_{0–50ms}$; $RFD_{0–100ms}$; $RFD_{0–200ms}$) relative to the onset of contraction (Graph 1) [8]. The onset of MVC was defined as the point where the first derivative of force–time curve exceeded the baseline by 3% of its maximum value. To eliminate inter-individual differences and possible effect of body mass, all variables were normalized with $m^{2/3}$ [20].

LSI and HQ ratio were calculated for all dependent variables (F_{max}, RFD_{max} and $RFD_{0–50ms}$, $RFD_{0–100ms}$, $RFD_{0–200ms}$). LSI was calculated as $[(DV_{UNINVOLVED} - DV_{INVOLVED}) / DV_{UNINVOLVED} \times 100$; DV – corresponding dependent variable], while HQ ratio was calculated as ($DV_{HAMSTRING} / DV_{QUADRICEPS}$).

Statistical Analysis

Descriptive statistics (mean and standard deviation) deviation calculated for all variables. To compare potential differences between legs and muscles for each of the recorded variables (F_{max}, RFD_{max}, $RFD_{0–50ms}$, $RFD_{0–100ms}$, $RFD_{0–200ms}$), two-factor ANOVA [factors: leg (uninvolved and involved), and muscle group (quadriceps, hamstring)] was performed and followed by Bonferonni post hoc test. Between-within ANOVA was used to examine differences within corresponding muscle groups (quadriceps and hamstring) in LSI derived from F_{max} and RFD variables (RFD_{max}, $RFD_{0–50ms}$, $RFD_{0–100ms}$, $RFD_{0–200ms}$). Between-within ANOVA was performed to examine differences in HQ ratios derived from F_{max} and RFD (RFD_{max}, $RFD_{0–50ms}$, $RFD_{0–100ms}$, $RFD_{0–200ms}$) between the uninvolved and the involved leg. When significant effects were found, contrast analysis [21] was performed. The effect size ("$_p\eta^2$") was used to estimate the magnitude of differences of main effects, their interactions, and the contrast differences [22]. Finally, a one-group Student's t-test was used to quadriceps and hamstring LSI with the criterion for a safe return to sports (i.e. LSI over 85%). The level of statistical significance was set to p = 0.05. Data were analysed using SPSS 20.0 software (IBM Corp., Armonk, NY, USA).

RESULTS

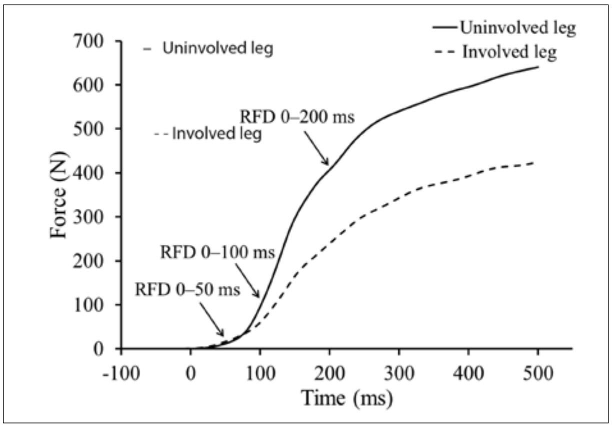
Group scores for IKDC and Lysholm knee scoring system were 75.1 ± 14.1 (out of 100) and 85.7 ± 15.8 (out of 100), respectively. The mean Tegner scores (out of a maximum score of 10) were 5.2 ± 1.8. Finally, the average amount of tibial anterior displacement during testing with the KT1000 was 1.7 ± 1.3 mm.

Typical force–time curve profiles obtained from one of the participants are presented in Graph 1a (quadriceps) and 1b (hamstring).

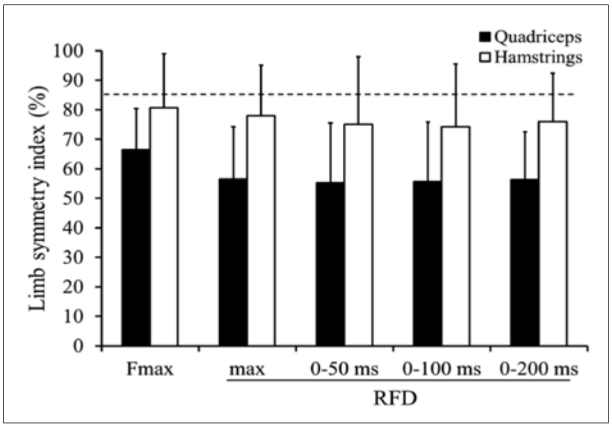
Descriptive statistics for F_{max} and RFD variables are presented in Table 1. Univariate statistics revealed significant main effect of leg (all F from 50.1 to 79.9, $p < 0.01$, $_p\eta^2 = 0.41–0.53$) and muscle (all F from 130.1 to 173.3, $p < 0.01$, $_p\eta^2 = 0.65–0.71$) on all dependent variables, with effect sizes generally greater for RFD variables ($_p\eta^2$ ranged 0.43–0.69) than for F_{max} ($_p\eta^2 = 0.41$). Regarding the muscle group, quadriceps exerted higher values of F_{max} and all RFD variables than hamstring. The interaction between factors was also significant for all variables (all F from 14.5 to 31.2, $p < 0.01$, $_p\eta^2 = 0.17–0.3$). Pairwise comparisons revealed that F_{max} and RFD variables of the involved leg were lower than of the uninvolved leg, both in quadriceps (all $p < 0.01$) and hamstring (all $p < 0.05$).

Limb symmetry index (LSI)

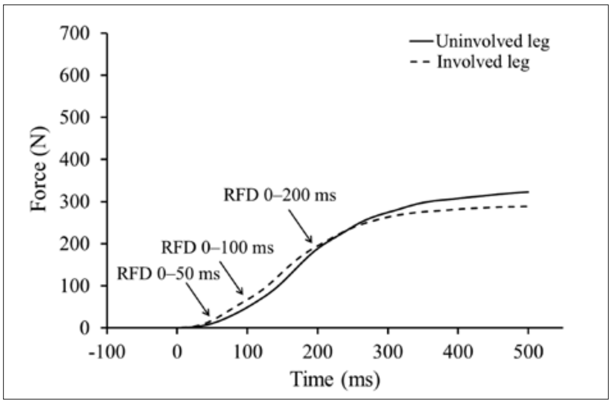
Limb symmetry index of quadriceps and hamstring, calculated from F_{max} and RFD variables are depicted in Graph 2. The obtained results indicated significant main effect of muscle group ($F_{1, 36} = 11.87$; $p < 0.01$; $_p\eta^2 = 0.25$), since symmetry index of quadriceps was lower when compared to hamstring. The main effect of variable was also significant ($F_{2, 70} = 5.23$; $p < 0.01$; $_p\eta^2 = 0.14$), showing that LSI in RFD were overall significantly lower than LSI calculated from F_{max}, regardless of the muscle group. It should



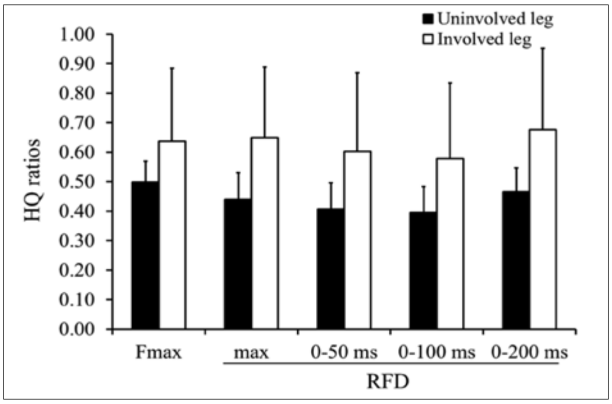
Graph 1a. Typical maximum voluntary isometric contraction (MVC) force–time curves of quadriceps obtained from one of the participants. Arrows depict the time points on the force– time curve used to calculate rate of force development (RFD) during selected intervals (0–50 ms, 0–100 ms, and 0–200 ms from the onset of contraction).



Graph 2. Limb symmetry index in Fmax and RFD variables of quadriceps and hamstrings (individual bars correspond to mean ± SD). Top dashed line represents the most often used criterion for safe return to sports (i.e. LSI = 85%).



Graph 1b. Typical MVC force–time curves of hamstrings obtained from one of the participants. Arrows depict the time points on the force–time curve used to calculate RFD during selected intervals (0–50 ms, 0–100 ms, and 0–200 ms from the onset of contraction).



Graph 3. Hamstring-to-quadriceps ratios from Fmax and RFD variables (individual bars correspond to mean ± SD)

Table 1. Descriptive statistics (mean ± SD) of absolute strength measures

Variable	Quadriceps		Hamstrings	
	Uninvolved	Involved	Uninvolved	Involved
F_{max} (N/kg$^{2/3}$)	36 ± 5	24 ± 7**	18 ± 3	14 ± 3**
RFD_{max} (N/s×kg$^{2/3}$)	207 ± 34	116 ± 38**	89 ± 15	68 ± 13**
$RFD_{0–50 ms}$ (N/s×kg$^{2/3}$)	39 ± 9	22 ± 8**	16 ± 3	11 ± 3**
$RFD_{0–100 ms}$ (N/s×kg$^{2/3}$)	91 ± 19	51 ± 20**	36 ± 8	26 ± 8**
$RFD_{0–200 ms}$ (N/s×kg$^{2/3}$)	126 ± 21	71 ± 23**	58 ± 9	43 ± 10**

F_{max} – maximal force; RFD_{max} – maximal rate of force development; $RFD_{0–50ms}$, $RFD_{0–100ms}$, $RFD_{0–200ms}$ – rate of force development derived from the average slope of the force–time curve during intervals 0 to 50, 0 to 100, and 0 to 200 ms; ** significant difference between the involved and uninvolved leg ($p < 0.01$)

be noted that both quadriceps and hamstring LSI were significantly lower than the generally accepted criterion (i.e. >85%) for a safe return to unrestricted activity (one sample T-test range 3.44–8.86; $p < 0.01$), particularly in explosive strength sports.

HQ ratios

The comparison of HQ ratios between the involved and the uninvolved leg revealed significant main effects of leg ($F_{1, 36} = 10.69$; $p < 0.01$; $_p\eta^2 = 0.23$), and variable ($F_{5, 180} = 8.05$; $p < 0.01$; $_p\eta^2 = 0.18$), but no interaction ($F_{5, 180} = 1.19$; $p > 0.3$; $_p\eta^2 = 0.03$). Contrast analysis revealed significantly higher HQ ratios in the involved leg than in the uninvolved one, both for F_{max} and all RFD variables (Graph 3). The largest difference between involved and uninvolved leg was observed in HQ ratio calculated from RFD at 0–200 ms interval. It should be noted that the effect size (differences among HQ ratios between the legs) for HQ ratios calculated from RFD ($_p\eta^2$ ranged 0.04–0.23), were higher than the effect size for HQ ratios calculated from F_{max} ($_p\eta^2 = 0.03$).

DISCUSSION

The aim of this study was to investigate differences in strength ratios calculated from RFD and F_{max} from male athletes recovering from ACL reconstruction. According to the obtained results, the involved leg demonstrated significant hamstring and quadriceps deficits compared to the uninvolved leg. Deficits were particularly prominent in the explosive strength qualities of the involved quadriceps, resulting in significantly lower LSI (55% on average for all RFD measures) than in F_{max} (66%). In addition, significantly weaker quadriceps caused significantly higher HQ ratios in the involved than in the uninvolved one. Finally, it should be noted that both quadriceps and hamstring LSI were significantly lower from the criterion value for safe return to sports (i.e. >85%).

Findings from previous studies suggest that lower between-limb symmetry in quadriceps F_{max} and higher HQ ratio are inherent to ACL injury and reconstruction, particularly in the early phase of rehabilitation. However, reported isometric strength measures of individuals with ACL reconstruction were obtained from various phases of recovery, ranging from two weeks to up to several years postoperatively [3, 5, 6, 23, 24]. In addition, some reports lack the assessment of hamstring strength. Due to different testing conditions (e.g. time, knee angle, apparatus used etc.), it was difficult to compare previously reported absolute quadriceps and hamstring strength measures with the ones obtained from the current study. Nevertheless, between-limb asymmetry and higher within leg muscle imbalance were explained to have mainly originated from relatively impaired strength of quadriceps.

A large deficit observed in RFD of the involved quadriceps suggests that these asymmetries are likely associated with reduction in muscle size as well as with reduction in the input from neural drive. Namely, the impaired neuromuscular activation, particularly of fast twitch motor units could be the underlying mechanism of persistent quadriceps weakness often observed in the first six months of recovery following the ACL reconstruction [25, 26]. The results of the present study also indicated that the applied surgical technique (BPTB) resulted in significant loss of both the maximum and the explosive strength of the involved hamstring as compared with the uninvolved side. However, the precise mechanism of hamstring's strength loss are yet to be determined since previous studies indicated that the mechanism of muscle weakness of the hamstring after reconstruction (regardless of the applied surgical technique) was different from that of the quadriceps [27]. Nevertheless, a profound muscle weakness typically associated with the ACL injury and reconstruction could be particularly prominent regarding the explosive strength. As a result, one could generally conclude that in addition to maximum strength, the indices of explosive strength should be routinely obtained for the assessment of the quadriceps and hamstring muscle function following an ACLR. This could be of particular importance for both clinicians and conditioning specialists since the inclusion of both measures in the follow up of the patients' recovery could provide additional information regarding the underlying impairments in the neural and/or contractile mechanisms.

Having this in mind, it seems that evaluation of the capacities for fast muscle activation in the initial phase of contraction could be equally important to strength evaluation. Surprisingly, RFD has been rarely used as measure of predisposing risk factor for ACL injury, or more importantly, as a functional outcome measure in patients rehabilitating after knee injuries [1, 12, 13]. Although the results of some recent studies have suggested that RFD obtained from the slope of the isometric force–time curve at different intervals could better predict functional difficulties in sport activities than maximal strength itself [1, 5, 13], RFD has been rarely used as a functional outcome measure in patients rehabilitating after ACL injury [12].

Only recently ratios based on RFD have been introduced as potentially important measures that could be related to increased risk for ACL injuries, or to functional recovery following ACL reconstruction, respectively [1, 12, 15]. In particular, Zebis et al. [1] introduced and investigated an RFD HQ strength ratio and compared it with the traditional F_{max} HQ strength ratio in elite soccer players. Their results revealed high test–retest reliability of the introduced RFD HQ strength ratios and suggested that the proposed method could be a relevant tool in standardized clinical evaluation of the knee joint agonist–antagonist relationship. On the other hand, Angelozzi et al. [12] used LSI from RFD to monitor recovery following ACL reconstruction. Their results demonstrated that it took 12 months, including 20 weeks of training emphasizing RFD improvement, before the RFD values returned to their preinjury levels. However, their testing protocol was based on the leg-press test that 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.

The limitations of the present study could originate from several factors. The sample size was relatively small and limited only to male participant. The surgical technique included the ACL reconstruction utilizing autograft BPTB tendons. It should be noted that an ideal study group would be reconstructed using allograft tendon or bone-tendon-bone allograft, such that there is no additional donor site morbidity, which might slightly skew the results. Considering a higher incidence of ACL injuries in female athletes, the lack of female subject could also be a limiting factor. Due to cross-sectional design, the present study did not allow for controlling the rehabilitation progress that could have had some confounding effects on the observed outcomes. Moreover, some studies reported that there is a substantial amount of evidence indicating that changes in muscle function occur in the uninvolved leg as well [7, 15, 28, 29], thus lowering the external validity of derived limb symmetry index ratios. Therefore, further evaluation regarding the time related changes of RFD measures across the rehabilitation is necessary in order to investigate bilateral changes in muscle function and estimate the optimal duration of rehabilitation process needed to regain the preinjury RFD levels. Namely, since the strength recovery criteria are based only on maximal strength measures, it could occur that after a given rehabilitation time, an athlete reaches the preinjury levels of maximal strength, and therefore fulfils (among a number of other) the "return-to-play criteria," but still having deficits in ability to rapidly generate force.

CONCLUSION

The observed findings suggest that athletes rehabilitating after ACL reconstruction are deficient not only in muscle strength but also in the explosive strength qualities, while those deficits mainly originated from the week quadriceps of the involved leg. The results suggest that in addition to F_{max}, the assessment of the RFD may provide another objective parameter regarding recovery and return to sports. Therefore, the evaluation of the ability to rapidly develop force gives us an insight into the changes in the force–time curve and along with maximal strength could be an important functional outcome measure of hamstring and quadriceps neuromuscular function following the ACL reconstruction. Moreover, the combination of measures (LSI and HQ ratios) based on F_{max} and RFD variables could serve to provide a more complete picture of the strength balances for maximal and explosive muscle actions, thus giving a clear picture of functional implications.

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Јачине и односи јачина мишића екстензора и флексора колена код спортиста након реконструкције предњег укрштеног лигамента

Марко Кадија[1], Оливера М. Кнежевић[2], Дарко Миловановић[1], Александар Недељковић[3], Драган М. Мирков[3]

[1]Клиника за ортопедску хирургију и трауматологију, Клинички центар Србије, Београд, Србија;
[2]Универзитет у Београду, Институт за медицинска истраживања, Лабораторија за неурофизиологију, Београд, Србија;
[3]Универзитет у Београду, Факултет спорта и физичког васпитања, Методичко-истраживачка лабораторија, Београд, Србија

Увод Максималне јачине екстензора и флексора колена, њихов међусобни однос (eng. *hamstrings-to-quadriceps ratio*; *HQ*), као и индекс симетрије оперисане и неоперисане ноге (*eng*. *limb symmetry index*; *LSI*) важни су показатељи помоћу којих се прати опоравак након реконструкције *LCA*. Иако је за извођење бројних функционалних задатака експлозивна јачина важнија од максималне, ова способност генерално је занемарена у праћењу опоравка мишићне функције.

Циљ рада Циљ рада био је да се упореде односи максималне јачине (F_{max}) и односи експлозивне јачине (*eng*. *Rate of Force Development – RFD*) код спортиста са реконструкцијом *LCA*.

Методе рада У студију је укључено 15 спортиста, којима је тестирана максимална вољна изометријска контракција (МВК) екстензора и флексора колена (4,0 ± 0,1 месеца постоперативно). Поред F_{max}, процењиван је и *RFD* (RFD_{max}, као и *RFD* на 50, 100 и 200 *ms* од почетка контракције) и рачунати односи јачине (*LSI* и *HQ* однос).

Резултати Максимална јачина и екстензора и флексора оперисане ноге била је значајно нижа него код неоперисане ноге ($p < 0,01$). Дефицити су били посебно изражени код екстензора оперисане ноге, услед чега су и *HQ* односи на тој страни (просечно 0,63) били већи него код неоперисане ноге (0,44). Индекс симетрије је био значајно нижи за варијабле *RFD* (prosečno 55%) него за F_{max} (66%).

Закључак Процена експлозивне јачине може бити још један објективни показатељ опоравка и спремности за излагање специфичним оптерећењима и кретњама, због чега би требало да буде део стандардног протокола за праћење спортиста након реконструкције *LCA*. Штавише, комбинација индекса изведених из максималне и експлозивне јачине могла би дати комплетнији увид у баланс јачине мишића за кретње које захтевају максималне и експлозивне акције, као и јасну слику о функционалним импликацијама.

Кључне речи: *lig. cruciatum anterius* (*LCA*); квадрицепс; хамстрингс; изометрија

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