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Rate of Force Development as an Adjunctive Outcome Measure for Return-to-Sport Decisions After Anterior Cruciate Ligament Reconstruction

STUDY DESIGN: Descriptive, prospective, longitudinal single-cohort study.

OBJECTIVE: To investigate the rate of force development to 30% (RFD_{30}), 50% (RFD_{50}), and 90% (RFD_{90}) of maximal voluntary isometric contraction (MVIC) as an adjunct outcome measure for determining readiness for return to sport following an anterior cruciate ligament (ACL) reconstruction.

BACKGROUND: One criterion of full recovery following an ACL reconstruction is the ability to achieve 85% or 90% of the maximal strength of the contralateral limb. However, the time required to develop muscular strength in many types of daily and sports activities is considerably shorter than that required to achieve maximal strength. Therefore, in addition to maximal strength, neuromuscular functions such as RFD should also be considered in the definition of recovery.

METHODS: Forty-five male professional soccer players who underwent an ACL reconstruction were recruited. Assessment with the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Tegner score, and KT1000 instrumented arthrometer was performed postinjury/prereconstruction and at 6 and 12 months after ACL reconstruction. MVIC, RFD_{30}, RFD_{50}, and RFD_{90} testing was performed preinjury, as part of standard preseason assessment, and at 6 and 12 months post–ACL reconstruction.

RESULTS: The average MVIC value 6 months postreconstruction was 97% of the preinjury average value. In contrast, at 6 months, the RFD_{30}, RFD_{50}, and RFD_{90} values were 80% (*P* = .04), 77% (*P* = .03), and 63% (*P* = .007), respectively, of the preinjury values. The mean RFD values for the reconstructed knee attained or exceeded 90% of the preinjury mean values only at the 12-month post–ACL reconstruction assessment (RFD_{30}, *P* = .86; RFD_{50}, *P* = .51; RFD_{90}, *P* = .56).

CONCLUSION: Despite the near recovery of MVIC strength to preinjury levels, there were still significant deficits in RFD at 6 months post–ACL reconstruction. An RFD similar to the preinjury RFD was achieved at 12 months post–ACL reconstruction, following a rehabilitation program focusing on muscle power. These results suggest that, following an ACL reconstruction, RFD criteria may be a useful adjunct outcome measure for the decision to return athletes to sports. *J Orthop Sports Phys Ther 2012;42(9):772-780, Epub 19 July 2012. doi:10.2519/jospt.2012.3780*

KEY WORDS: *ACL, knee, soccer*

The anterior cruciate ligament (ACL) is the most frequently injured ligament in the knee and is typically managed, especially in the athletic population, with arthroscopic reconstruction followed by rehabilitation treatment.[18] Generally, rehabilitation programs after arthroscopic ACL reconstruction include progression through the acute, subacute, functional, and return-to-activity phases of rehabilitation.[28] The ultimate goal of ACL reconstruction and subsequent rehabilitation procedures is the restoring of the patient's functional knee stability to prevent reinjury and allow safe return to previous activity levels.[27,28]

Despite the obvious progress in ACL reconstruction techniques and rehabilitation procedures after ACL injury, two-thirds of athletes who undergo ACL reconstruction do not return to preinjury sport levels.[4,18] Moreover, among the athletes who return to their preinjury sport levels, ACL reinjury occurs in 3% to 19% of ACL-reconstructed knees, and 5% to 24% of athletes sustain a contralateral ACL injury.[21,31]

The authors of a recent review reported that, although the great majority (nearly 90%) of athletes obtained what was considered normal or near-normal strength values (greater than or equal to 85% to 90% of muscle strength capacity in their injured leg compared to their noninjured leg), the rate of return to sport was low.[5] This suggests that muscle strength tests commonly used as criteria

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to return athletes to unrestricted sports activities postsurgery are not demanding enough or that variables more important for safe return to unrestricted sports activities are not being evaluated postsurgery. A recent editorial[10] highlighted the potential for residual neuromuscular deficits to be present in both limbs following ACL injury and reconstruction.

Currently, based on objective criteria, there is no consensus as to when athletes should safely return to their preinjury sport level after ACL reconstruction and postreconstruction rehabilitation, especially in sport activities that require high dynamic neuromuscular control with power generation and absorption.[27,28] This indicates that there is a continuous need to develop better criteria for a safe return to sports, and recently there have been many efforts toward that goal.[27,28]

The outcomes investigated in previous studies of ACL injury and reconstruction have focused on muscle qualities (eg, maximal strength, muscle cross-sectional area), sensory information deficits (eg, proprioception, kinesthesia), and neuromuscular parameters (eg, neural drive). However, researchers have not yet considered the rate of force development (RFD) as an adjunctive outcome measure for the return-to-sport decision-making process.

One criterion that has been used to determine recovery and readiness to return to sport following an ACL reconstruction is achieving 85% or 90% of the maximal strength of the contralateral limb.[28,35] However, it has been shown that the time required to develop muscular strength in many types of daily[2] and sports activities[38] is considerably shorter (0-200 milliseconds) than that required to achieve maximal contraction strength (300 milliseconds or greater).[2] Therefore, under the time-restricted conditions (approximately 200 milliseconds) of these explosive muscle actions, RFD may be a more important descriptor of muscle function than maximal muscle strength.[2,11] The RFD quantifies the ability to produce muscle force quickly.[2] In isolated muscle preparations, contractile RFD is obtained from the slope of the force-time curve (change in force divided by change in time), whereas, for intact joint actions, RFD is calculated as the slope of the joint moment-time curve (change in moment divided by change in time).[2]

The RFD measured under isometric conditions has been identified as a key parameter characterizing the extent of neural drive to the muscle during explosive muscle actions.[2,3] Explosive muscle actions involve a short starting time and maximum speed, with no possibility of correcting or adjusting the movement during execution.[42] Based on this definition, explosive muscle actions are therefore preprogrammed.[12] In young adults, improvements in the RFD have been attributed to increases in neural drive in the first 100 milliseconds of muscle activation.[44] Training studies demonstrating concurrent increases in RFD and the efferent neuromuscular drive of skeletal muscle support this hypothesis.[1]

The RFD is one of the most important variables affecting performance in sports activities that require great acceleration.[25] Hoff and Helgerud[20] showed that in a group of 8 soccer players training for neural adaptations 3 times a week for 8 weeks (4 sets of 5 repetitions using 85% of the 1-repetition maximum, with emphasis on maximal speed during the concentric action), their half-squat 1-repetition maximum increased by 75% and their RFD by 52%. Also, their sprint times over 10 m and 40 m improved by 0.09 seconds and 0.13 seconds, respectively.[20]

In sport, the ability to generate strength quickly is of utmost relevance to both performance and protection against injury.[22] However, few studies have focused on the relationship between strength measurements and performance indices in either sport[38] or rehabilitation.[32] Moreover, the relationship between functional performance and explosive activation of the quadriceps may add information that is important to determine when athletes can safely return to sport activity. Therefore, the present study was designed to investigate the recovery of RFD post–ACL reconstruction to determine its potential usefulness as an adjunct parameter of functional recovery for a safe return to sports.

METHODS

Patients

Data were collected over a span of 6 seasons from a sample of 45 male professional soccer players (mean ± SD age, 23.4 ± 4.7 years; mass, 79.3 ± 8.2 kg; height, 178.4 ± 6.7 cm; body mass index, 24.9 ± 3.3 kg/m^2) who had sustained a unilateral ACL rupture. All players underwent arthroscopic ACL reconstruction using the doubled semitendinosus and gracilis tendon technique performed by the same orthopaedic surgeon.

All players had been tested prior to starting the season, as part of a standard evaluation process. The mean ± SD amount of time between preseason testing and each player's ACL injury was 2.4 ± 1.8 (range, 1-5) months. The amount of time between the injury and ACL reconstruction surgery was 4.3 ± 2.8 (range, 2-9) months. The amount of time between preseason testing and the 6-month postsurgery assessment was 11.3 ± 2.2 (range, 8-14) months. Finally, the amount of time between preseason testing and the 12-month postsurgery assessment was 18.5 ± 2.8 (range, 15-22) months.

To be included in this study, patients had to meet the following criteria: a diagnosis of complete ACL rupture confirmed by arthroscopy, arthroscopic ACL reconstruction, no previous knee surgery or other serious injuries of the lower limbs, and no neurological deficits. All patients included in the study received the same standard postoperative accelerated rehabilitation protocol, which aimed for return to sport within 6 months,[27,45] performed under the supervision of experienced physiotherapists in the same rehabilitation center.

The rehabilitation protocol started within a week of surgery and was performed 3 times a week, focusing on early restoration of full knee extension and weight bearing as tolerated from the first postoperative day. Both weight-bearing and non–weight-bearing exercises for neuromuscular, strength, plyometric, and agility training of the lower limb and sport-specific tasks were used, with gradually increased loads and complexity.

Because the analysis of our data at 6 months indicated a significant deficit of RFD, we recommended that the athletes not return to their sport activities and, instead, perform an additional 20-week training program, with an emphasis on RFD improvement. Training strategies that emphasize RFD typically incorporate a combination of high-force low-velocity, low-force high-velocity, and high-force high-velocity exercises, with the intention to maximize power.[2,17] Attempting to activate the musculature as rapidly as possible appears to be an important training strategy to enhance RFD, as it is necessary to invoke rapid motor-unit activation.[33]

All clinical assessments were performed by a physician, the functional assessments by an athletic trainer, and the statistical analyses by a statistician not involved with the surgical procedure and rehabilitation process. Informed written consent was obtained from all participants, the protocol for the study was approved by the Institutional Review Board of Arcamedica Institution, and the study was conducted in conformity with the Helsinki Declaration.

Outcome Measurements

All patients were assessed bilaterally postinjury/pre–reconstruction surgery and at 6 and 12 months postsurgery, using the International Knee Documentation Committee (IKDC)[19] evaluation system, the Tegner score,[41] and the KT1000 instrumented arthrometer (MEDmetric Corporation, San Diego, CA) at 13.61 kg of force.

As part of their standard preseason testing, all patients underwent bilateral isometric leg-press strength tests to assess the maximal voluntary isometric contraction (MVIC) and RFD of the quadriceps muscle. Testing of the MVIC and RFD was also performed 6 and 12 months after the ACL reconstruction, using the same procedure.

FIGURE 1. Position for the isometric leg-press strength test.

Procedures

The isometric leg-press strength test (**FIGURE 1**) was performed using a horizontal leg-press training machine (RHA680; Panatta Sport srl, Apiro, Italy). Several previous studies have reported high levels of reliability of isometric testing procedures.[8,47] In our laboratory, test-retest reliability for MVIC and RFD using the isometric leg-press test is very high, with intraclass correlation coefficients of 0.89 (95% confidence interval: 0.83, 0.95) and 0.85 (95% confidence interval: 0.80, 0.89), respectively.

The MVIC and the RFD were calculated using a system for muscle performance measurement (MuscleLab 4000; BoscosystemLab SpA, Rieti, Italy). The apparatus was used to set the knee angle during the horizontal leg-press test with an electronic goniometer (BoscosystemLab SpA) and to record the force-time curve with a strain gauge load cell set (ET-STG-02; BoscosystemLab SpA) that collected data at a sampling rate of 100 Hz. All patients were refamiliarized with the leg-press strength test procedures 7 days before each test session and asked not to do any physical activity in the 2 days prior to the test. The patients were also asked to continue their activities of daily living as usual during the study period. In each data-collection session, the patient sat on the horizontal leg-press machine (**FIGURE 1**), with the seatback at a 130° angle and the foot of the leg being tested positioned in a standard location on the leg-press plate. Foot position and abduction angle were standardized using a grid on the plate. The back was kept in contact with the seatback. Although the RFD could be influenced by knee angle, de Ruiter and colleagues[11] reported that during voluntary isometric knee extension at 30°, 60°, and 90° of flexion, there

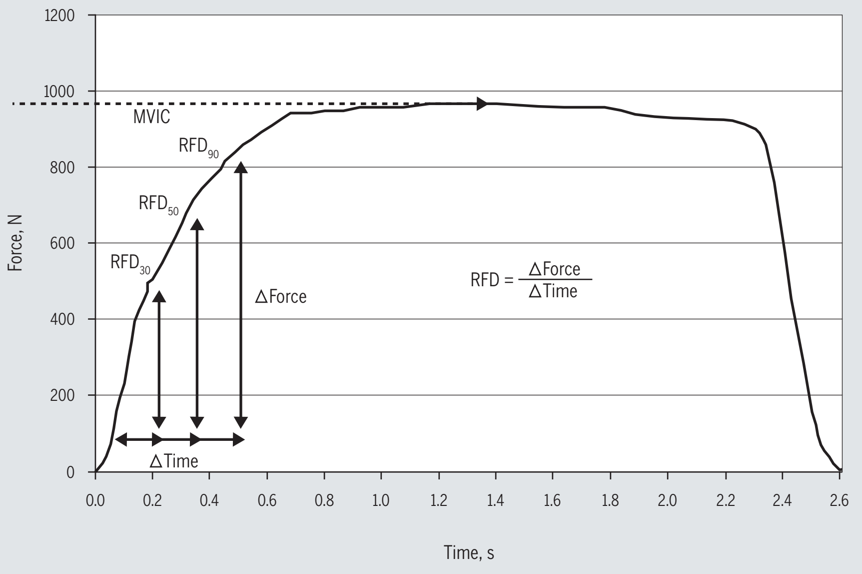

FIGURE 2. Force-time relationship from 1 athlete. Maximal voluntary isometric contraction (MVIC) is the peak value. The rate of force development at 30% (RFD_{30}), 50% (RFD_{50}), and 90% (RFD_{90}) of MVIC is the slope of the force-time curve from initiation of the force application to the respective threshold.

was no statistically significant difference in the maximal rate of torque development between angles. Because quadriceps activity is significantly greater for weight-bearing exercises performed at knee angles greater than 80°,[13] an electronic goniometer (BoscosystemLab SpA) was used to set the knee angle at 80° for testing.

This position was then fixed with a pretensioning system to help the patient hold the position, without any active intervention or negative effects due to muscular pretensioning.[46] Visual feedback was provided for the patients in the form of a real-time display of the dynamometer force output on a monitor. The patients were instructed to complete each trial "as hard and fast as possible," a method reported to produce optimal results for MVIC and RFD.[33] At each session, the patient performed 3 isometric trials with as high an intentional RFD as possible for the involved leg, holding the MVIC for 3 seconds. Two minutes were allowed between each trial. The trial with the highest peak force value was selected for further analysis.[2] Trials with an initial countermovement were discarded, and extra trials were performed.[15] The variables analyzed were the MVIC and the RFD at 30% (RFD_{30}), 50% (RFD_{50}), and 90% (RFD_{90}) of the MVIC (**FIGURE 2**), which correspond to the mean slope of the force-time curve. The force onset was defined as the instant at which the force rose above 1% of the MVIC and did not drop for the following 3 data samples.

Statistical Analysis

The Kolmogorov-Smirnov test was used to determine that the data were normally distributed, allowing the use of parametric tests. Data were reported as group mean ± SD.

Four separate, 2-way, repeated-measures analyses of variance (ANOVAs) with factors of limb (involved versus uninvolved) and time (before ACL reconstruction and 6 and 12 months post–ACL reconstruction) were used to assess the presence of significant differences for RFD_{30}, RFD_{50}, RFD_{90}, and MVIC. A Tukey post hoc comparison was used to determine significant differences between mean values when significant interactions or main effects were found. A 1-way ANOVA was used to compare mean values of IKDC, Tegner, and KT1000 scores between postinjury and 6 and 12 months postreconstruction.

The relationships between RFD_{30}, RFD_{50}, RFD_{90}, and MVIC and clinical outcome measures (IKDC, Tegner, KT1000) were calculated 6 months post–ACL reconstruction using the Pearson correlation coefficient, and interpreted as follows: 0.00 to 0.19, very weak correlation; 0.20 to 0.39, weak correlation; 0.40 to 0.69, moderate correlation; 0.70 to 0.89, strong correlation; and 0.90 to 1.0, very strong correlation.[14] All analyses were conducted using MedCalc Version 10.2.0 (MedCalc Software bvba, Mariakerke, Belgium) and Stata Version 8.2 (StataCorp LP, College Station, TX). An alpha level of .05 was considered to be statistically significant.

RESULTS

At the postinjury/prereconstruction IKDC assessment, 2 patients (4%) rated their knee as normal (grade A), 7 patients (16%) as nearly normal (grade B), 15 patients (33%) as abnormal (grade C), and 21 patients (47%) as severely abnormal (grade D). At the 6-month postreconstruction assessment, 31 patients (69%) rated their reconstructed knee as normal, 13 patients (29%) as nearly normal, and 1 patient (2%) as abnormal. At the 12-month postreconstruction assessment, 38 patients (84%) rated their reconstructed knee as normal and 7 patients (15%) as nearly normal. Group IKDC scores were 44 ± 3 out of a possible 100 points at postinjury/prereconstruction, and 86 ± 7 and 93 ± 9 points at 6 and 12 months postreconstruction, respectively. The differences in scores at the 3 time points were statistically significant (*P*<.05).

The mean Tegner scores (out of a maximum score of 10) were 3.5 (range, 0-6) at postinjury/prereconstruction, 6.5 (range, 4-8) at 6 months, and 8.6 (range, 6-10) at 12 months. The differences between these values were statistically significant (*P*<.05).

TABLE 1 Comparison Between Baseline and 6- and 12-Month Postreconstruction Scores of MVIC and RFD_{30}, RFD_{50}, and RFD_{90}*

		6-mo Postreconstruction (n = 44)			12-mo Postreconstruction (n = 44)		
Outcomes	Baseline (n = 44)	Outcomes	Mean Difference Compared to Baseline Assessment (95% CI)	*P* Value	Outcomes	Mean Difference Compared to Baseline Assessment (95% CI)	*P* Value
MVIC, N							
Involved	1241 ± 510	1208 ± 516	–33 (–245, 179)	.75	1290 ± 630	49 (–188, 286)	.68
Uninvolved	1278 ± 519	1260 ± 497	–18 (–228, 192)	.86	1310 ± 530	32 (–185, 249)	.77
Mean difference (95% CI)	37 (–176, 250)	52 (–157, 261)			20 (–221, 261)		
P value	.73	.62			.87		
RFD_{30}, N/s							
Involved	3959 ± 2087	3168 ± 1669	–791 (–1573, –8)	.04	3886 ± 2029	–73 (–925, 779)	.86
Uninvolved	3980 ± 2123	3985 ± 1897	5 (–829, 839)	.99	3995 ± 2187	15 (–887, 907)	.97
Mean difference (95% CI)	21 (–851, 893)	817 (77, 1557)			109 (–704, 922)		
P value	.96	.03			.79		
RFD_{50}, N/s							
Involved	4904 ± 2751	3791 ± 2106	–1113 (–2127, –98)	.03	4560 ± 2245	–344 (–1384, 696)	.51
Uninvolved	4918 ± 2123	4819 ± 2497	–99 (–1059, 861)	.83	4980 ± 2455	62 (–888, 1012)	.89
Mean difference (95% CI)	14 (–1003, 1031)	1028 (71, 1984)			420 (–554, 1394)		
P value	.97	.03			.39		
RFD_{90}, N/s							
Involved	2634 ± 1987	1672 ± 1340	–962 (–1664, –260)	.01	2396 ± 1912	–238 (–1045, 569)	.56
Uninvolved	2609 ± 1898	2333 ± 1611	–276 (–1005, 453)	.45	2678 ± 2070	69 (–753, 891)	.86
Mean difference (95% CI)	–25 (–829, 779)	661 (47, 1274)			282 (–543, 1107)		
P value	.95	.03			.49		

Abbreviations: CI, confidence interval; MVIC, maximal voluntary isometric contraction; RFD_{30}, rate of force development at 30% of MVIC; RFD_{50}, rate of force development at 50% of MVIC; RFD_{90}, rate of force development at 90% of MVIC.
**Values are mean ± SD unless otherwise indicated.*

The average amount of tibial anterior displacement during testing with the KT1000, with a load of 13.61 kg, was greater than 5 mm in all athletes at the postinjury/prereconstruction assessment, with a side-to-side difference of 6.2 ± 3.7 mm. At the 6- and 12-month postreconstruction assessments, the side-to-side differences at maximal loading were 2.5 ± 1.9 and 1.8 ± 1.2 mm, respectively. All differences were statistically significant ($P<.05$).

The results for MVIC and RFD_{30}, RFD_{50}, and RFD_{90} are summarized in **TABLE 1**. The 2-way ANOVA for the MVIC values revealed no significant interaction (F = 9.14, $P>.05$). At the 6-month postreconstruction assessment, the mean MVIC of the involved side was 97% of the value obtained at the baseline assessment (**TABLE 1**) and 96% of the value of the uninvolved side, which was also tested at 6 months postreconstruction. At the 12-month postreconstruction assessment, mean MVIC of the involved side was 104% of the baseline value (**TABLE 1**) and 98% of the MVIC of the uninvolved side, which was also tested at 12 months postreconstruction.

The 2-way ANOVA indicated a significant interaction (F = 38.75, $P<.01$) for RFD_{30} values. The subsequent post hoc analysis indicated no significant difference in RFD_{30} values between the involved and uninvolved limbs measured at baseline (preinjury) and at 12 months postreconstruction. However, there was a significant difference between limbs at 6 months postreconstruction (**TABLE 1**). Further post hoc analysis showed no significant differences between the RFD_{30} values for the uninvolved limb obtained at baseline and at 6 and 12 months postreconstruction (**TABLE 1**). For the involved limb, there was a significant difference in RFD_{30} values between baseline and 6 months, but not between baseline and 12 months.

At 6 months postreconstruction, the average RFD_{30} value for the involved side was only 80% of the baseline value (**TABLE 1, FIGURE 3**) and only 79% of the value of the uninvolved side, which was also measured at 6 months postreconstruction. At 12 months postreconstruction, the mean RFD_{30} value for the involved side was 98% of the baseline value and 97% of the value of the uninvolved side, which was also tested at 12 months postreconstruction (**TABLE 1**). Similarly, a significant in-

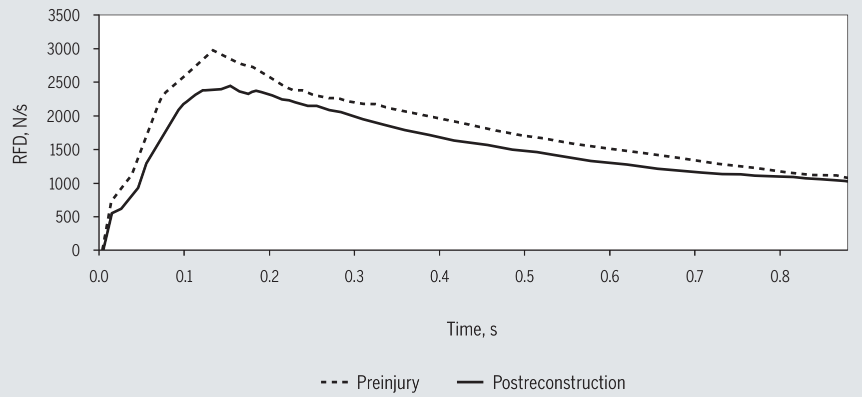

FIGURE 3. Representative data comparing the rate of force development (RFD)-time relationship between preinjury and 6 months post–anterior cruciate ligament reconstruction for an athlete performing an isometric leg-press strength test.

TABLE 2 Correlations (Pearson *r*) Between RFD Values and IKDC, Tegner, and KT1000 Scores at 6 Months Post–Anterior Cruciate Ligament Reconstruction*

	IKDC Score	Tegner Score	KT1000
RFD_{30}	0.123	0.290	0.131
RFD_{50}	0.144	0.240	0.148
RFD_{90}	0.201	0.198	0.172

Abbreviations: IKDC, International Knee Documentation Committee; RFD_{30}, rate of force development at 30% of maximal voluntary isometric contraction; RFD_{50}, rate of force development at 50% of maximal voluntary isometric contraction; RFD_{90}, rate of force development at 90% of maximal voluntary isometric contraction.
**P>.05 for all correlation coefficients (r).*

teraction (F = 33.44, $P<.01$) was observed for RFD_{50} values. Post hoc comparison demonstrated the same results as detailed above for the RFD_{30} values (**TABLE 1**).

The average RFD_{50} value at 6 months postreconstruction for the involved side was only 77% of the baseline value (**TABLE 1**, **FIGURE 3**) and only 79% of the value of the uninvolved side, which was also tested at 6 months postreconstruction. At 12 months postreconstruction, the average RFD_{50} value for the involved side was 93% of the baseline value and 92% of the value of the uninvolved side, which was also tested at 12 months postreconstruction (**TABLE 1**).

A significant interaction (F = 26.65, $P<.01$) was also observed for RFD_{90} values, with the post hoc comparison results being consistent with the RFD_{30} and RFD_{50} results (**TABLE 1**). The average RFD_{90} value at 6 months postreconstruction for the involved side was only 63% of the baseline value (**TABLE 1**, **FIGURE 3**) and only 72% of the value of the uninvolved side, which was also tested at 6 months postreconstruction. At 12 months postreconstruction, the average RFD_{90} value for the involved side was 91% of the baseline value and 89% of the value of the uninvolved side, which was also tested at 12 months postreconstruction (**TABLE 1**).

At 6 months postreconstruction, Pearson correlation coefficients indicated no significant association between RFD_{30}, RFD_{50}, and RFD_{90} and the IKDC, Tegner, or KT1000 scores (**TABLE 2**).

DISCUSSION

To our knowledge, this is the first study in which the RFD has been used to assess soccer players who have undergone an ACL reconstruction. This was also the first study to include preinjury MVIC and RFD data, as all players were evaluated prior to the start of the competitive season as part of their preseason standard evaluation. MVIC and RFD data for the involved lower extremity at 6 and 12 months post–ACL reconstruction were compared to preinjury values of the same lower extremity and those of the contralateral uninvolved limb at the same time points. This is a significant strength of this study, as the use of the contralateral limb as the sole comparison has been criticized by some authors,[43] who argue that patients who have undergone a unilateral ACL reconstruction have a bilateral deficit in voluntary quadriceps muscle activation for more than 2 years.

The present study found that RFD values measured at 6 months post–ACL reconstruction were still significantly lower than those measured before the ACL injury, indicating a significant residual deficit. This is in contrast to the scores for MVIC, which were very close to those obtained preinjury at the same time. The fact that the RFD had not returned to preinjury levels after 6 months of rehabilitation (the amount of time often recommended for recovery and return to sport post–ACL reconstruction[23,34]) is of concern. Previous studies conducted on individuals post–ACL reconstruction have emphasized maximal muscle strength assessment recorded as isometric or dynamic MVIC, with the recommendation that the strength of the operated limb be 85% to 90% of the nonoperated limb as a criterion for athletes to return to competitive sports activity.[29] However, as our results demonstrate, though MVIC had nearly fully returned to its preinjury value at 6 months, it took 12 months, including

20 weeks of training emphasizing RFD improvement, before the RFD values had returned to their preinjury levels. Therefore, reliance on MVIC criteria does not guarantee that RFD values have returned to preinjury levels.

Because some authors[7,48] have suggested that adequate muscle activity must occur within a 30-to-70-millisecond window from the onset of joint loading to effectively protect the ACL, the failure of this protective mechanism may expose the ACL to excessive forces and contribute to noncontact ACL injuries.[40] The authors of a previous study[9] showed that stiffness of the tendon-aponeurosis complex may account for up to 30% of the variance in voluntary RFD during the late phase of contraction (150-250 milliseconds), which roughly corresponds to the RFD_{50} in our study. Because we found significant differences in RFD values and not in MVIC values at 6 months post–ACL reconstruction, we believe that RFD could be a good predictor of the protection level offered to the ACL by the neuromuscular system. Our findings are supported by a previous study in which explosive activation in several human movements was found to be involved to a greater extent by the RFD than by the MVIC.[2,38] Moreover, the RFD, as well as the $T_{25\text{-}50}$ (the time required to go from 25% to 50% of MVIC) and other time-dependent parameters, were reported to be significantly correlated with explosive strength actions and vertical jumps.[30] Interestingly, RFD but not MVIC was related both to subjective knee function[24] and to maximal walking speed[39] in patients who underwent total hip arthroplasty.

Our study suggests that the restoration of ligamentous stability as assessed by the IKDC, Tegner, and KT1000 tests, and of maximal muscular strength as assessed by the MVIC test, are just some of the tests that athletes should undergo before they can safely return to sports activity. The findings of our study, which are consistent with data from other studies,[36,48] suggest that other factors, such as neuromuscular control, may influence the outcome after ACL reconstruction. Indeed, by assessing neuromuscular function using a hop test battery, Gustavsson and colleagues[16] found that only 1 of 10 subjects tested had restored hop performance 6 months after ACL reconstruction. Similar results were obtained by Augustsson and colleagues[6] when studying landing from a maximum 1-legged hop-for-distance test. In the study by Augustsson and colleagues,[6] patients who had undergone ACL reconstruction had a significantly reduced ability to produce a large amount of force quickly (ie, they produced lower muscular power) in the operated limb compared to the nonoperated limb.

Several studies have shown that producing a high level of force quickly is more important than just being able to produce a high level of force, and that explosive strength impairment is more sport specific and therefore a better reflection of the heavy demands imposed by sports.[2,22] The fact that the RFD is determined through this temporal compression of the recruitment sequence[12,26] could explain the positive training effect of explosive strength actions on RFD performance observed in our study at the 12-month follow-up. The assessment of maximal muscle strength and explosive muscle strength is fundamental to the performance of both athletic and daily activities,[35] and to the rehabilitation process. Actually, single-limb hop tests are often used to identify persistent limb asymmetries in athletes following ACL reconstruction.[28]

A limitation of our study is that our patient group was composed exclusively of male professional soccer players, and different results may be found in other athletic populations or in a sedentary population and with a different rehabilitation program. Another limitation is that the leg-press test used in this study 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. It may be of value to develop testing specific to the quadriceps and the hamstrings, because they both play an important role in stabilizing the knee joint.[37]

CONCLUSION

The results of this study demonstrated a significant deficit in the RFD at 6 months post–ACL reconstruction in a population of professional soccer players who had completed a typical standardized rehabilitation program. This deficit was present despite nearly full recovery of standard clinical outcome measures (IKDC, Tegner, KT1000, and MVIC) often used in deciding to return athletes to sport. Full recovery of the RFD was achieved 12 months post–ACL reconstruction, following 20 weeks of additional rehabilitation aimed toward recovery of the RFD. These results suggest that assessment of the RFD may provide another objective parameter of recovery in decisions regarding recovery and return to sports. ◉

KEY POINTS

FINDINGS: Deficits in the RFD remained 6 months postsurgery, despite full recovery of MVIC. Full recovery of the RFD was achieved 12 months postsurgery after 20 additional weeks of rehabilitation.

IMPLICATIONS: The results indicate that the RFD may need to be considered for the assessment of individuals post–ACL reconstruction as part of a battery of standardized tests to determine recovery and readiness for return to sport.

CAUTION: Because this study was conducted exclusively on male professional soccer players, our results require caution in their generalization to other populations of athletes.

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