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Impaired Quadriceps Rate of Torque Development and Knee Mechanics After Anterior Cruciate Ligament Reconstruction With Patellar Tendon Autograft

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Background: Rate of torque development (RTD) measures the ability of a muscle to produce torque quickly. Decreased quadriceps RTD may impair performance of sporting tasks after surgery. Currently, little is known about variations in quadriceps RTD between anterior cruciate ligament (ACL)–reconstructed and noninjured limbs.

Purpose: To determine the differences in RTD of the quadriceps, the rate and timing of knee extensor moment (KEM) development, and knee flexion excursion during running after ACL reconstruction with patellar tendon autograft.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: This study involved 21 patients (11 female) 6 months after ACL reconstruction with patellar tendon autograft (median [IQR]: age, 18 [16-20] years; mass, 68.18 [61.34-75] kg; height, 1.74 [1.66-1.78] m). Patients performed four 5-second maximal voluntary isometric strength trials of both limbs on an isokinetic dynamometer. RTD was calculated as the mean slope of the torque-time curve between 20% and 80% of total time to peak torque. Then, patients underwent 3-dimensional motion analysis while running on an instrumented treadmill at a self-selected running speed (mean ± SD, 2.68 ± 0.28 m/s). The rate of knee extensor moment (RKEM) was calculated as the mean slope of the moment curve between 10% and 30% of stance phase. Between-limb comparisons were determined with a paired *t* test for peak KEM, RKEM, knee flexion excursion during 10% to 30% of stance, and time to generate KEM.

Results: In the reconstructed limb, deficits in the peak rate of quadriceps torque development compared with the noninjured limb existed both isometrically (RTD, 257.56 vs 569.11 Nm/s; $P < .001$) and dynamically (RKEM, 16.47 vs 22.38 Nm/kg·m·s; $P < .001$). The reconstructed limb also generated a KEM later in the stance phase compared with the noninjured limb (11.37% vs 9.61% stance; $P < .001$) and underwent less knee flexion excursion (15.5° vs 19.8°; $P < .001$).

Conclusion: After ACL reconstruction with patellar tendon autograft, patients have lower RTD and RKEM in the reconstructed limb. Deviations in RTD and the timing of the KEM can change the way the knee is loaded and can potentially increase injury risk and future development of posttraumatic osteoarthritis. Rehabilitation should consider exercises designed to improve RTD and prepare the limb for the demands of sport performance.

Keywords: knee extensor moment; running; loading; excursion; ACL reconstruction; quadriceps rate of torque development

More than 250,000 anterior cruciate ligament (ACL) tears occur annually.[15,26] Surgical reconstruction requires a lengthy period of postoperative rehabilitation, after which 37% to 56% of individuals do not return to sport.[7,8,27] While the reasons for this are multifactorial, one limiting factor is the incomplete return of quadriceps strength, which may persist for up to 4 years after surgery.[9,21,24,31,32,35,43] Decisions on readiness to return to sport after an ACL reconstruction are made, in part, by comparing the operative limb to the nonoperative limb for symmetry in quadriceps strength, function, and mechanics.[23,27,28,38,42] While measurements of peak quadriceps strength have proven valuable, they typically do not reflect how the quadriceps functions during critical times of dynamic activity. Noncontact ACL tears occur quickly

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(<50 milliseconds), while the quadriceps requires more than 300 milliseconds to reach peak torque production.[2,41] For this reason, alternative methods to measure quadriceps function are needed that capture the ability of the quadriceps to generate force quickly.

Measuring rate of torque development (RTD) of the quadriceps instead of peak strength has been proposed as a potential method to assess how quickly the muscle can generate force.[2,6] Additionally, examining differences in early- and late-phase RTD may provide insight into whether reductions in RTD are due to neural or muscular changes.[3] To date, few studies have focused on this variable after ACL reconstruction. One study found diminished RTD after an ACL reconstruction despite a full recovery of peak maximum isometric quadriceps strength.[6] While informative, this study used a leg press machine with the subjects performing an isometric contraction. This testing method does not isolate the quadriceps, as the hip extensors and ankle plantar flexors can contribute to the torque produced. More recently, Jordan et al[20] used isometric knee extension to determine quadriceps RTD in 8 elite alpine ski racers after ACL reconstruction and found that RTD and peak torque were impaired in the reconstructed limb more than 2 years after surgery. While informative, the small and highly specific sample limits the study's generalizability. Thus, a need remains to define quadriceps RTD after an ACL reconstruction in a wider population.

Since the quadriceps muscles are the primary active stabilizers of the knee joint during dynamic tasks,[10] the ability of these muscles to generate force during such tasks could lend important insights into the altered mechanics often observed after ACL reconstruction that potentially predispose the patient to posttraumatic osteoarthritis.[5,19] Little is known of quadriceps RTD during dynamic functional tasks such as running. Because of the timing demands of dynamic tasks, these activities require that muscles generate torque rapidly for safe and optimal performance.[4,37] For this reason, RTD may be a suitable measurement of quadriceps function and may reflect the ability of the quadriceps to generate torque during functional and sports tasks.

Although the knee extensor moment (KEM) is a surrogate measure of all forces across the knee, the contribution of the quadriceps is one of the largest modifiable components.[45] Therefore, determining the RTD of the KEM may provide insight into how the quadriceps muscles function during dynamic activity. Moreover, little is known regarding the differences in timing of the KEM. Alterations in the onset of the KEM could modify the loading pattern in the knee joint during early stance. Impaired RTD could potentially delay the timing of the KEM and result in altered knee mechanics. Reduced knee flexion angle during early stance phase has been reported in walking, but this relationship was not seen in running.[14,30] To date, knee flexion excursion, defined as the difference between maximum and minimum knee flexion angle during stance phase, has been relatively understudied during running and may affect the ability of the quadriceps to stabilize the knee joint and attenuate shock during higher level tasks.[4,13,19]

Therefore, the purposes of this study were to determine whether there are reductions in RTD of the quadriceps, to determine between-limb differences in the rate and timing of KEM development, and to determine between-limb differences in sagittal plane knee mechanics after an ACL reconstruction. We hypothesized that the reconstructed limb would have a lower RTD, lower rate of KEM (RKEM), and decreased knee flexion excursion.

METHODS

Study Patients

After the protocol was approved by the university institutional review board, 21 recreational athletes (11 female patients, 10 male patients; median [IQR]: age, 18 [16-20] years; mass, 68.18 [61.34-75] kg; height, 1.74 [1.66-1.78] m) with an ACL reconstructed by use of a patellar tendon autograft were enrolled in the study and provided their written informed consent. The patients reported a mean ± SD presurgery Tegner activity scale rating of 9 ± 1. An a priori power analysis based on previously published data[20] (α = .05, β = .90) revealed a need for a minimum of 11 subjects for adequate statistical power to detect a 300-Nm/s difference in RTD. All participants were tested 6 months after surgery, after having completed rehabilitation, and were cleared to return to sport by a physician. Concurrent meniscus repair or meniscectomy may have been performed at the time of reconstruction, but potential subjects were excluded if total knee dislocation occurred at time of injury. All ACL reconstructions were performed by 1 of 2 surgeons from the same orthopaedic practice. Each patient underwent a standardized rehabilitation protocol, with a 4- to 6-week period of reduced weightbearing for those with concurrent meniscectomy. Return-to-sport decisions were made based on performance of a battery of functional testing, including hop testing, Y balance test, and strength within 80% of nonoperative limb.

Rate of Torque Development

Patients performed four 5-second maximal voluntary isometric knee extension strength trials of both the operative and nonoperative limb using a Biodex System 3 isokinetic dynamometer with a sampling rate of 30 Hz (Biodex Medical Systems Inc). An initial practice trial was allowed for each limb to familiarize the patient with the task and device. Patients were securely situated in the dynamometer by use of shoulder, lap, and thigh straps to ensure that joint motion did not influence the isometric contraction. All trials were performed with the knee at 90° and the hip at 85° of flexion. Maximal oral encouragement was provided to facilitate full effort. Custom MATLAB code (MathWorks Inc) was used to calculate the mean slope of the torque-time curve between 20% and 80% of total time between the onset of the trial and peak torque (Figure 1). Additionally, the time-torque curve was divided into 2 phases, 0 to 100 milliseconds (RTD1) and 100 to 200 milliseconds (RTD2), to examine differences in neurologic and

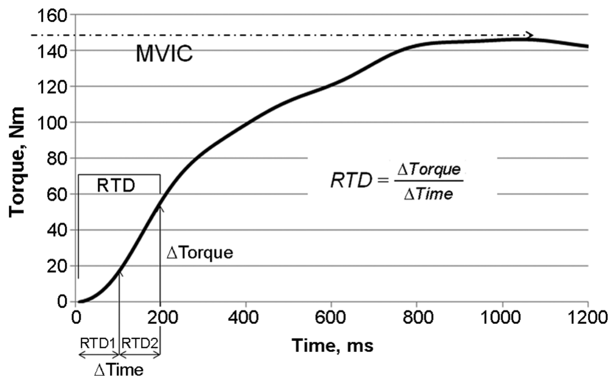

Figure 1. Torque-time graph from a single patient. The rate of torque development (RTD) is the slope of the torque-time curve from the initiation of torque production to the respective time threshold. RTD1 = 0-100 milliseconds, RTD2 = 100-200 milliseconds, RTD = 0-200 milliseconds. MVIC, maximal voluntary isometric contraction.

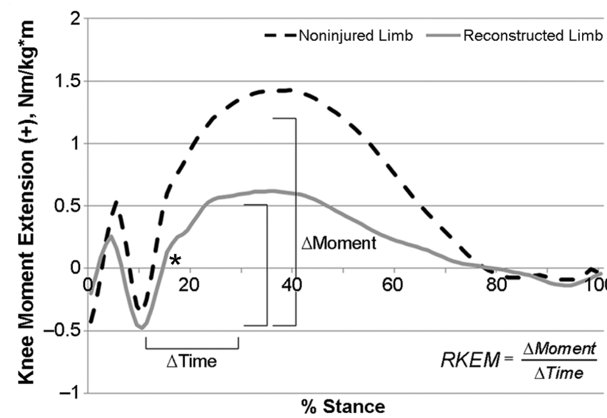

Figure 2. Sagittal plane knee moment from a single patient demonstrating differences between the anterior cruciate ligament–reconstructed and noninjured limbs. Rate of knee extensor moment (RKEM) is the slope of the moment-time curve between 10% and 30% of the stance phase during running. *Time (percentage of stance) of achievement of knee extensor moment.

muscular contributions to knee extensor torque, respectively (Figure 1).[3] Early-phase RTD (0-100 milliseconds) is influenced by muscle fiber type, while late-phase RTD (100-200 milliseconds) is thought to be more influenced by neural drive.[1,2,11,17] Data from each trial were extracted individually, and a mean was established for each limb for each patient.

3-Dimensional Motion Analysis

Fifty-six reflective markers—32 on anatomic landmarks and 24 as tracking clusters—were placed on each participant according to a previously established configuration.[29] The anatomic landmarks were placed on the following locations: sternal notch, spinous process of C7, right and left superior acromion processes, posterior L5/S1, right and left superior iliac crests, right and left greater trochanters, right and left posterior superior iliac spine, right and left anterior superior iliac spines, right and left medial and lateral distal tibia, right and left medial and lateral proximal tibia, right and left medial and lateral malleoli, right and left fifth metatarsal heads, right and left first metatarsal head, right second metatarsal head, and right and left distal foot. Tracking clusters were attached to rigid plates and secured to bilateral thigh and shank. Each plate contained 4 markers. Three tracking markers were secured to the rearfoot of each shoe to identify proximal, distal, and lateral heel locations. To differentiate the left and right limbs, 2 additional tracking markers were placed on the right anterior thigh and shank. All participants wore neutral running shoes (New Balance 662; New Balance Athletic Shoe Inc) to minimize potential alterations in mechanics due to footwear. After running a warm-up for 5 minutes, the participant ran at a self-selected test speed (mean ± SD, 2.68 ± 0.28 m/s) while marker trajectories were recorded by use of a 10-camera motion analysis system (Motion Analysis Corp) sampling at 200 Hz. Force-plate data were simultaneously recorded from an instrumented Bertec treadmill (Bertec) sampling at 1200 Hz.

Visual3D software (C-motion) was used to filter the data, calculate knee joint angles, and perform inverse dynamics to calculate knee joint moments. Marker trajectories were filtered at 8 Hz and the force data at 35 Hz by use of a fourth-order, low-pass, zero-lag Butterworth filter. The biomechanical model used has been previously described,[29] in which angles and moments were calculated using Cardan XYZ angles referencing the distal segment to the proximal. The moments were normalized with respect to body mass and height. Custom MATLAB code was used to extract sagittal plane knee moment curves and sagittal plane knee angles. Knee moments from individual strides were analyzed for each limb in each patient. Peak KEM, percentage stance of KEM onset, and RKEM were extracted from each stride. Percentage stance of KEM onset was defined as the time percentage of the stance phase in which the KEM is greater than zero and remains above zero for the duration of the stance phase. RKEM was defined as the change in KEM divided by stance duration between 10% and 30% of stance, which corresponds to the most linear phase of KEM (Figure 2).

Statistical Analysis

Comparisons between the operative and nonoperative limbs were made using SPSS software (IBM Corp) to perform 2-tailed paired t tests to compare RTD, RTD1, RTD2, RKEM, percentage stance to KEM, peak KEM, and sagittal plane knee excursion. Statistical significance was defined as $P \leq .05$.

RESULTS

There was a significant difference between the reconstructed and noninjured limbs for all variables of interest

TABLE 1
Between-Limb Comparisons: Reconstructed vs Noninjured[a]

Variable	Reconstructed Limb	Noninjured Limb	*P* Value (Paired *t* Test)
RTD1, Nm/s	302.40 ± 169.80 (225.11-379.69)	620.71 ± 223.83 (518.82-722.60)	<.001[b]
RTD2, Nm/s	178.10 ± 102.00 (131.67-224.52)	411.57 ± 141.83 (347.01-476.13)	<.001[b]
RTD, Nm/s	257.56 ± 147.1 (190.60-324.52)	569.11 ± 180.68 (486.87-651.35)	<.001[b]
Knee flexion excursion, deg	15.5 ± 5.23 (13.12-17.88)	19.83 ± 4.14 (17.95-21.71)	<.001[b]
Rate of KEM, Nm/kg·m·s	16.47 ± 5.38 (14.02-18.92)	22.38 ± 5.32 (19.96-24.80)	<.001[b]
% stance to KEM[c]	11.37 ± 1.95 (10.48-12.26)	9.61 ± 1.59 (8.89-10.33)	<.001[b]

[a]Results are reported as mean ± SD (95% CI). KEM, knee extensor moment during running; RTD, quadriceps rate of torque development, 0-200 milliseconds; RTD1, quadriceps rate of torque development, 0-100 milliseconds; RTD2, quadriceps rate of torque development, 100-200 milliseconds.
[b]Significant at α = .05.
[c]Time (in percentage of stance) to achievement of KEM.

(Table 1). RTD, RTD1, and RTD2 were 55%, 51%, and 57% slower, respectively, in the reconstructed limb compared with the noninjured limb ($P < .001$) (Table 1). Additionally, the reconstructed limb demonstrated the following differences compared with the injured limb: 4.5° ± 3.5° less knee flexion excursion during the stance phase of running ($P < .001$), 26% reduced RKEM ($P < .001$), and 15% more time to onset of KEM during stance ($P < .001$) (Table 1 and Figure 2).

DISCUSSION

The purpose of this study was to determine the between-limb differences in RTD of the quadriceps and the KEM during running after an ACL reconstruction with patellar tendon autograft. We found that the reconstructed limb had a significantly lower RTD of the quadriceps compared with the nonreconstructed limb. Differences between limbs were also seen during running, with decreased RKEM and delayed time to generation of KEM in the reconstructed limb. These results suggest that alterations in quadriceps functional abilities persist in both the static and dynamic RTD condition, which could have implications for long-term joint health and return to sport readiness.

The reduction in RTD of the quadriceps is consistent with previous reports that showed decreased quadriceps RTD up to 2 years after surgery.[6,20,22] The percentage reduction was greater in our findings (55% reduction between limbs) compared with those found in previous studies (28% and 29% reduction between limbs) at 6 months after surgery and 23% reduction 2 years after surgery.[6,20,22] However, direct comparisons between this work and others are not fully possible because of the use of an isometric leg press machine to determine RTD in the previous study.[6] This measurement may have included contributions from the hip extensors and ankle plantar flexors, potentially depressing the full impact of reduced quadriceps RTD.[6] Another possible factor is the type of athlete used in the study. For example, previous studies used professional athletes, whereas we included recreational athletes. Despite differences in the methods and patient populations, all of these studies reported impairment in the RTD at the time of return to sport, supporting its use to measure patient functional progress. In fact, a recent report found that quadriceps RTD collected at 3 months after surgery correlated with the patients' self-reported knee function.[18] Thus, future work should consider the use of RTD as part of return to sport testing for athletes after an ACL reconstruction.

Our results demonstrate significant reductions in both early-phase (RTD1) and late-phase (RTD2) quadriceps RTD. Two potential contributors to RTD are neural drive and intrinsic contractile properties of the muscle.[1-3,16] For example, RTD1 is believed to be more dependent on contractile properties of muscle such as the myosin-heavy chain composition of type IIa and IIx fibers.[11,17] In support of this, a moderate relationship has been reported between voluntary RTD and twitch-evoked RTD, suggesting that muscle fiber type composition contributes to the ability of muscle to generate torque within the first 40 milliseconds of contraction.[3] Previous work has found that RTD2 is influenced more by neural drive via increased motor unit firing rate, which is believed to increase force summation and lead to more rapid development of isometric force.[1,2] Another study showed that increases in RTD can occur even after peak isometric force is attained.[12] Previous findings link increases in maximal isometric strength through resistance training with increases in RTD 150 to 250 milliseconds after onset of muscle contraction, which overlaps with RTD2 in our sample.[2,16] As most dynamic movements require torque production within shorter time frames, 50 to 150 milliseconds, early-phase RTD may be of greater interest.[41] Heavy resistance training has been demonstrated to improve both early- and late-phase RTD through increased neural drive, increased motor unit firing, and increased muscle strength.[2,16,44] Thus, interventions targeted at improving muscle force during earlier phases of quadriceps contraction may mitigate impairments in quadriceps RTD overall.

We have also extended the findings of deficits in RTD to dynamic activities such as running. We have found that both the onset and rate of the KEM are delayed in the ACL-reconstructed limb (Figure 2). The delay in the onset of the KEM reduces the time available for the quadriceps to generate an extensor moment to control knee flexion and absorb the knee load. Similarly, impaired RKEM demonstrates additional reductions in the ability of the quadriceps to generate an extensor moment. Interestingly, the delayed time to develop the KEM occurs during the period of the initial impact peak. Previous work by Radin et al[36] showed that a lack of quadriceps contraction at heel strike resulted in higher impact forces in humans, a loading mechanism that led to joint damage in an animal model. The reduced RKEM possibly further impairs load attenuation. These findings support previous work linking reduced knee extensor strength and altered gait pattern as possible contributors to accelerated development of posttraumatic osteoarthritis.[4,19] However, further research is needed to define whether these factors contribute greater risk for injury and decrements in long-term joint health.

One difficulty in studying between-limb differences in a population with a unilateral injury lies in accounting for the physiologic changes that occur in the noninjured limb while the injured limb recovers. Studies can be designed to partially control for this by including a healthy control group. While comparing patients with a control group highlights absolute differences after ACL reconstruction, the between-limb comparison gives us a relative difference within the individual, which is important in running. In a cyclic activity like running, motion of one limb can affect motion in the other as both limbs are engaged in the activity and asymmetries may contribute to unequal forces and movement patterns. Between-limb mechanical asymmetries have been reported in dynamic activities after ACL reconstruction including running,[30] jumping,[33] and cutting.[25] Also, one study showed that between-limb differences, especially in sagittal plane knee moments, that were present during jump landings after initial ACL reconstruction were predictive of second ACL injury.[34] Additionally, decisions regarding return to sport are often based on normalizing between-limb differences.[23,27,28,38,42] Thus, between-limb differences give the clinician an understanding of the relative difference between the limbs, which can have implications for future injury risk and ability to return to sport safely.

There are limitations to the findings of this study. First, the data were collected 6 months after ACL reconstruction. Although the findings reported in this paper are consistent with RTD reduction at 1 and 2 years after reconstruction, the findings related to RKEM and the timing of the KEM cannot be generalized to individuals more than 6 months after reconstruction. Additionally, this study included only patients who underwent a reconstruction with a patellar tendon autograft. While the effects of graft type on RTD have not been established, the procedure to harvest the patellar tendon graft may impair the quadriceps of an ipsilateral bone–patellar tendon–bone autograft differently than an allograft and hamstring graft. Because of pain and structural changes in the patella in harvesting an ipsilateral patellar tendon graft, ACL reconstructions that use a contralateral patellar tendon autograft have demonstrated improved between-limb symmetry for quadriceps strength and knee range of motion.[39,40] These findings indicate that the graft harvest site may play a role in torque production of the quadriceps independent of the presence of an ACL reconstruction.

Future studies should examine the relationship between RTD and knee mechanics during running and sport-specific tasks such as landing and cutting. Additionally, investigating the mechanics of dynamic sporting activities in an ACL-reconstructed group with normal RTD compared with a group with impaired RTD would provide better clarity regarding the role of RTD of the quadriceps in functional and sporting activities. Impairments in quadriceps RTD have been reported as long as 2 years after reconstruction; however, the expected time course and chronicity of impaired quadriceps RTD are unknown.[20] Additional knowledge about the expected duration of and the effect of reduced RTD on performance and mechanics will aid clinicians and researchers in addressing this impairment.

CONCLUSION

We have shown that the RTD of the quadriceps, rate and timing of KEM, and knee flexion excursion have not normalized between limbs at 6 months after ACL reconstruction with patellar tendon autograft and may be contributing factors to unsuccessful return to sport and long-term joint health. These results suggest that additional attention should be paid to restoring normal RTD and between-limb gait mechanics before a patient is cleared to return to sport participation.

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REFERENCES

1. Aagaard P, Magnusson PS, Larsson B, Kjaer M, Krustrup P. Mechanical muscle function, morphology, and fiber type in lifelong trained elderly. *Med Sci Sports Exerc*. 2007;39(11):1989-1996.
2. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol (1985)*. 2002;93(4):1318-1326.
3. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur J Appl Physiol*. 2006;96(1):46-52.
4. Andriacchi TP, Koo S, Scanlan SF. Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee. *J Bone Joint Surg Am*. 2009;91(suppl 1):95-101.
5. Andriacchi TP, Mundermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng*. 2004;32(3):447-457.

6. Angelozzi M, Madama M, Corsica C, et al. Rate of force development as an adjunctive outcome measure for return-to-sport decisions after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012;42(9):772-780.
7. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *Br J Sports Med*. 2014;48(21):1543-1552.
8. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45(7):596-606.
9. Beynnon BD, Johnson RJ, Naud S, et al. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. *Am J Sports Med*. 2011;39(12):2536-2548.
10. Blackburn TA, Craig E. Knee anatomy: a brief review. *Phys Ther*. 1980;60(12):1556-1560.
11. Bottinelli R, Canepari M, Pellegrino MA, Reggiani C. Force-velocity properties of human skeletal muscle fibres: myosin heavy chain isoform and temperature dependence. *J Physiol*. 1996;495(Pt 2):573-586.
12. Buller AJ, Lewis DM. The rate of tension development in isometric tetanic contractions of mammalian fast and slow skeletal muscle. *J Physiol*. 1965;176:337-354.
13. DeVita P, Hortobagyi T, Barrier J. Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. *Med Sci Sports Exerc*. 1998;30(10):1481-1488.
14. Di Stasi SL, Logerstedt D, Gardinier ES, Snyder-Mackler L. Gait patterns differ between ACL-reconstructed athletes who pass return-to-sport criteria and those who fail. *Am J Sports Med*. 2013;41(6):1310-1318.
15. Frank CB, Jackson DW. The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am*. 1997;79(10):1556-1576.
16. Hakkinen K, Alen M, Komi PV. Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiol Scand*. 1985;125(4):573-585.
17. Harridge SD, Bottinelli R, Canepari M, et al. Whole-muscle and single-fibre contractile properties and myosin heavy chain isoforms in humans. *Pflugers Arch*. 1996;432(5):913-920.
18. Hsieh CJ, Indelicato PA, Moser MW, Vandenborne K, Chmielewski TL. Speed, not magnitude, of knee extensor torque production is associated with self-reported knee function early after anterior cruciate ligament reconstruction [published online July 16, 2014]. *Knee Surg Sports Traumatol Arthrosc*. doi:10.1007/s00167-014-3168-1.
19. Ingersoll CD, Grindstaff TL, Pietrosimone BG, Hart JM. Neuromuscular consequences of anterior cruciate ligament injury. *Clin Sports Med*. 2008;27(3):383-404, vii.
20. Jordan MJ, Aagaard P, Herzog W. Rapid hamstrings/quadriceps strength in ACL-reconstructed elite Alpine ski racers. *Med Sci Sports Exerc*. 2015;47(1):109-119.
21. Keays SL, Newcombe PA, Bullock-Saxton JE, Bullock MI, Keays AC. Factors involved in the development of osteoarthritis after anterior cruciate ligament surgery. *Am J Sports Med*. 2010;38(3):455-463.
22. Knezevic OM, Mirkov DM, Kadija M, Nedeljkovic A, Jaric S. Asymmetries in explosive strength following anterior cruciate ligament reconstruction. *Knee*. 2014;21(6):1039-1045.
23. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. *Sports Med*. 2004;34(4):269-280.
24. Lautamies R, Harilainen A, Kettunen J, Sandelin J, Kujala UM. Isokinetic quadriceps and hamstring muscle strength and knee function 5 years after anterior cruciate ligament reconstruction: comparison between bone-patellar tendon-bone and hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(11):1009-1016.
25. Lee SP, Chow JW, Tillman MD. Persons with reconstructed ACL exhibit altered knee mechanics during high-speed maneuvers. *Int J Sports Med*. 2014;35(6):528-533.
26. Majewski M, Susanne H, Klaus S. Epidemiology of athletic knee injuries: a 10-year study. *Knee*. 2006;13(3):184-188.
27. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther*. 2006;36(6):385-402.
28. Myer GD, Schmitt LC, Brent JL, et al. Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. *J Orthop Sports Phys Ther*. 2011;41(6):377-387.
29. Noehren B, Sanchez Z, Cunningham T, McKeon PO. The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain. *Gait Posture*. 2012;36(3):596-599.
30. Noehren B, Wilson H, Miller C, Lattermann C. Long-term gait deviations in anterior cruciate ligament-reconstructed females. *Med Sci Sports Exerc*. 2013;45(7):1340-1347.
31. Oiestad BE, Holm I, Gunderson R, Myklebust G, Risberg MA. Quadriceps muscle weakness after anterior cruciate ligament reconstruction: a risk factor for knee osteoarthritis? *Arthritis Care Res (Hoboken)*. 2010;62(12):1706-1714.
32. Palmieri-Smith RM, Thomas AC, Wojtys EM. Maximizing quadriceps strength after ACL reconstruction. *Clin Sports Med*. 2008;27(3):405-424, vii-ix.
33. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med*. 2007;17(4):258-262.
34. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978.
35. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. *Arch Orthop Trauma Surg*. 2014;134(10):1417-1428.
36. Radin EL, Yang KH, Riegger C, Kish VL, O'Connor JJ. Relationship between lower limb dynamics and knee joint pain. *J Orthop Res*. 1991;9(3):398-405.
37. Rouis M, Coudrat L, Jaafar H, et al. Assessment of isokinetic knee strength in elite young female basketball players: correlation with vertical jump [published online November 6, 2014]. *J Sports Med Phys Fitness*.
38. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012;42(9):750-759.
39. Shelbourne KD, Beck MB, Gray T. Anterior cruciate ligament reconstruction with contralateral autogenous patellar tendon graft: evaluation of donor site strength and subjective results. *Am J Sports Med*. 2015;43(3):648-653.
40. Shelbourne KD, Urch SE. Primary anterior cruciate ligament reconstruction using the contralateral autogenous patellar tendon. *Am J Sports Med*. 2000;28(5):651-658.
41. Stone MH, Sands WA, Carlock J, et al. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res*. 2004;18(4):878-884.
42. Thomee R, Kaplan Y, Kvist J, et al. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(11):1798-1805.
43. Tourville TW, Jarrell KM, Naud S, Slauterbeck JR, Johnson RJ, Beynnon BD. Relationship between isokinetic strength and tibiofemoral joint space width changes after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42(2):302-311.
44. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol*. 1998;513(pt 1):295-305.
45. Winter DA. *Biomechanics and Motor Control of Human Movement*. 3rd ed. Hoboken, NJ: John Wiley & Sons; 2005.