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Effect of Fatigue on Tibial Rotation After Single- and Double-Bundle Anterior Cruciate Ligament Reconstruction

A 3-Dimensional Kinematic and Kinetic Matched-Group Analysis

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Background: Fatigue is an extrinsic factor adversely affecting joint proprioception and neuromuscular response, thereby increasing anterior cruciate ligament (ACL) strain and injury risk. The effectiveness of the single- and double-bundle techniques for ACL reconstruction to control residual rotational knee laxity under fatigue has not been examined.

Hypothesis: Fatigue results in a significant increase in tibial rotation angles and moments in both ACL-intact and single- and double-bundle ACL-reconstructed knees. The 2 groups with ACL-reconstructed knees will show no significant differences in tibial rotation angles and moments either pre- or postfatigue.

Study Design: Controlled laboratory study.

Methods: Twenty-four male patients who underwent successful single-bundle (n = 12) or double-bundle (n = 12) ACL reconstructions and 10 matched healthy controls were subjected to a standard lower limb muscle fatigue protocol using an isokinetic dynamometer. Three-dimensional motion analysis was used to measure tibial rotation and rotational knee moments in the pre- and postfatigue states, during a swinging maneuver on the weightbearing leg from a standing position with the knee in extension.

Results: Tibial rotation of the single-bundle group significantly increased postfatigue (prefatigue 22° ± 10° vs 29° ± 15° postfatigue, $P = .015$). In contrast, the double-bundle group showed similar tibial rotation values pre- and postfatigue (16° ± 6° vs 18° ± 4°, $P = .22$). The double-bundle group showed a trend toward decreased tibial rotation values pre- and post-fatigue compared with controls (22 ± 4 and 23 ± 4) ($P = .065$ and .08, respectively). In the prefatigue state, rotational moments (N·mm/Kg) of the single-bundle (339 ± 148) and double-bundle (317 ± 97) groups were significantly lower than that of controls (465 ± 134) ($P = .05$ and .03, respectively). In the postfatigue state, an increase was observed in rotational moments of the single-bundle (388 ± 131) and double-bundle (408 ± 187) groups compared with prefatigue values, whereas a decrease was noted in the control group (411 ± 117).

Conclusion: Single-bundle ACL-reconstructed knees demonstrate a reduced ability to resist rotational loads under fatigue. Double-bundle reconstructed knees had significantly better control of tibial rotation when fatigued. However, they demonstrate an excessive, yet not significant, reduction in tibial rotation compared with the intact knee, suggesting a possible overcorrection in rotational laxity.

Keywords: anterior cruciate ligament; fatigue; double-bundle; tibial rotation

The double-bundle technique for anterior cruciate ligament (ACL) reconstruction was introduced in an attempt to anatomically replicate the native ACL with respect to its dimensions, collagen orientation, and insertion sites and consequently optimize knee stability after ACL reconstruction.[19,30] Accumulated evidence from studies performed under varying testing conditions has implied that the novel technique better restores knee kinematics to normal compared with the conventional single-bundle one.[8,16,23,33] Other studies, however, have failed to show any advantage of the double-bundle technique in controlling either anteroposterior or rotational knee laxities.[7,14,28,29]

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TABLE 1
Baseline Patient Characteristics[a]

	Control Group (n = 10)	Single-Bundle Group (n = 12)	Double-Bundle Group (n = 12)
Age, y	22.1 ± 1	25.2 ± 6.6	28 ± 5.4
Body mass index, kg/m^2	24.9 ± 2.1	26 ± 3	23.8 ± 1.8
Right/left knee, No.	6/4	7/5	7/5
Dominant/nondominant limb, No.	5/5	7/5	6/6
Follow-up, mo	—	18 ± 6.8	16.8 ± 5.7
Meniscectomies, No.	—	5	6

[a] Values are expressed as mean ± standard deviation unless otherwise indicated. —, not applicable.

Fatigue is an extrinsic factor affecting the neuromusculoskeletal system, defined as a failure to maintain the required force or power production after prolonged exercise.[27] It adversely affects joint proprioception and neuromuscular response through afferent and efferent pathways.[6,32] Signaling of peripheral muscular mechanoreceptors and central processing of proprioceptive signals are weakened, resulting in diminished joint position sense.[24] In addition, muscle fibers show a decreased ability to absorb power when fatigued.[11] As a consequence, motor programming for precision movements and reflex muscle contraction are impaired, thereby compromising dynamic joint stability. Studies have shown that fatigue can increase anterior tibial translation in healthy knees by a mean 35.5% as well as internal tibial rotation during crossover cutting.[17,32]

To date, epidemiological and biomechanical studies have investigated the effect of fatigue on lower limb kinematics and the risk of muscular or knee ligament trauma. The literature has indicated an increased incidence of ACL injuries occurring during the later portion of games in numerous contact and noncontact sports.[4] In addition, biomechanical testing has shown alterations in knee kinematics and motor control strategies after fatigue during landing and stop-jump tasks, including increased anterior tibial shear forces and strains on the ACL.[1,13] Altered neuromuscular control and postural stability deficits were found to predict reinjury risk after ACL reconstruction.[18] These findings suggested a causative effect of fatigue on ACL injury.

Despite recent advances, limited data still exist regarding the effect of fatigue on knee kinematics after ACL reconstruction. In particular, although considerable attention has been drawn lately on rotational stability after ACL reconstruction, the effectiveness of single- and double-bundle techniques to control residual rotational knee laxity under fatigue has not been examined.

The purpose of this study was to investigate the differences in tibial rotation between single- and double-bundle ACL reconstructions after lower limb muscle fatigue. Given the apparent association of muscle fatigue with ACL strain and risk of injury, our primary hypothesis was that fatigue results in a significant increase in tibial rotation angles and moments in both ACL-intact and ACL-reconstructed knees. A secondary hypothesis was that the 2 groups of patients with ACL-reconstructed knees would show no significant differences in tibial rotation angles and moments either pre- or postfatigue.

MATERIALS AND METHODS

Patient Selection Criteria

For a comparative matched-group analysis, 12 male patients with single-bundle and 12 with double-bundle hamstring tendon ACL reconstructions were selected out of a database comprising 212 prospectively documented cases of single-bundle (n = 151) and double-bundle (n = 61) ACL reconstructions performed between January 2008 and December 2009. Matching criteria were age, body mass index, side affected, limb dominance, associated meniscal injury, time of follow-up, and successful surgical outcome, as evidenced by patient feedback, side-to-side stability testing, and return to preinjury activity level. Exclusion criteria were other ligamentous (posterior cruciate, medial or lateral) injuries; bone and chondral lesions in the same knee, as assessed by magnetic resonance imaging (MRI) and clinical examination; and any history of pain or trauma to the contralateral knee. The minimum interval between the surgery and the examination was 1 year. A matched control group was also formed by 10 volunteers with a negative history of lower limb trauma or neuromusculoskeletal deficit. Institutional review board approval was obtained before the initiation of the study, and each participant signed an informed consent form. Baseline patient and control data regarding the matching criteria for the study are presented in Table 1.

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Surgical Technique

All the reconstructions were performed or directly supervised by the same surgeon (MEH). The gracilis and semitendinosus tendons were harvested through a 2.5-cm longitudinal incision over the pes anserinus with the knee flexed to 90°. Diagnostic arthroscopy was performed through standard anteromedial and anterolateral portals. Associated meniscal or chondral lesions identified were addressed before the ACL reconstruction.

The technique of double-bundle ACL reconstruction has previously been described in detail.[3] In brief, 2 separate femoral and 2 tibial tunnels were created using anatomic aimers (Acufex Anatomic ACL Guide System; Smith & Nephew Endoscopy, Andover, Massachusetts) with an appropriate offset. The semitendinosus and gracilis tendon grafts were doubled separately to create the anteromedial (AM) and posterolateral (PL) bundles, respectively. The femoral tunnel for the AM bundle was drilled first through the anteromedial portal at 110° to 120° of knee flexion. The PL tunnel was drilled through an accessory medial portal created with the knee flexed at 130°. The bone bridge between the 2 tunnels was carefully inspected through the AM portal to ensure that no tunnel communication had occurred. Both femoral and tibial tunnels were drilled through the center of the insertion sites of the native bundles. For the tibial tunnels, the inclination of the anatomic aimer was originally set at 50°. The grafts were inserted to the joint and secured with EndoButtons (Smith & Nephew Endoscopy, Andover, Massachusetts) on the femoral side and bioabsorbable interference screws and postfixation screws on the tibial side. The typical length of the EndoButtons for the AM and PL bundles was 20 and 15 mm, respectively. The grafts were tensioned manually and fixed in the tibia at 10° of knee flexion for the PL and 45° for the AM bundle.

For the single-bundle technique, the 2 tendons were doubled and sutured together to form a quadruple graft. The single femoral tunnel was created through the anteromedial portal with the knee at 110° of flexion and was placed between the insertions of the native ACL bundles to provide a more horizontal graft orientation. The tibial tunnel was drilled in the center of the tibial footprint with the drill guide set at 50°. The same fixation devices were used as for the double-bundle ACL reconstruction. The graft was manually tensioned and fixed at 15° of knee flexion. Both groups with reconstructed knees followed the same postoperative regimen.

Data Collection

An isokinetic dynamometer (Cybex Humac Norm; CSMi, Stoughton, Massachusetts) was used for initial isokinetic evaluation and the induction of the fatigue protocol. The dynamometer was calibrated weekly according to the manufacturer's instructions. The participants were stabilized with straps placed along the trunk, waist, and thigh to limit the contribution of other muscle groups. The resistance pad was placed proximal to the ankle joint. The axis of rotation of the dynamometer was aligned with the knee joint axis of rotation at 90° of knee flexion. The functional range of knee motion was set electronically between 0° and 90° of flexion to prevent hyperextension and hyperflexion accordingly. Gravitational corrections were made to account for the effect of limb weight on torque measurements. To maximize performance, oral encouragement was given, whereas the dynamometer automatically provided feedback on the intensity and duration of exercise, as well as total work production.

An optoelectronic 3-dimensional motion analysis system (Vicon; OMG, Oxford, UK) was used to track the motion of the lower extremities. The system used 10 T-40 cameras (4 megapixels), sampling at a frequency of 100 Hz. A total of 24 retro-reflective skin markers (9 mm) were attached to the pelvis and lower extremities of each patient according to the model described by Schwartz and Rozumalski.[20] This model is initially based on the standard Davis model for calculating statically the approximate positions of the lower limb joints[2] but subsequently uses a cluster of markers to functionally optimize the knee and hip joint centers and axes of rotation. This method has been shown to provide precise hip and knee joint centers of rotation (within 1-3 mm and 3-9 mm, respectively) and knee axes alignment (within a deviation of 2°).[20]

A force platform (Bertec 4060-15; Bertec Corp, Columbus, Ohio), flush mounted in the center of the calibrated volume, was synchronized with the motion analysis system to collect ground-reaction force (GRF) data at a sampling frequency of 1000 Hz. Only the pivoting leg was on the force plate during each trial. Kinematic data were smoothed using a Woltring quantic splines filter (Vicon). Kinematic, anthropometric, and GRF data were combined to calculate joint loading. Knee joint moment was normalized to body mass.

Testing Procedure

Clinical evaluation of the participants with ACL reconstructions preceded the kinematic and kinetic evaluation. Clinical examination included range-of-motion assessment and the Lachman, anterior drawer, and pivot-shift tests. Side-to-side differences in anterior knee laxity were measured using the KT-2000 arthrometer at 30° of knee flexion. The International Knee Documentation Committee (IKDC), Knee Injury and Osteoarthritis Outcome (KOOS), Lysholm, and Tegner scores were obtained.

The experimental protocol was the same for every participant and was performed before and after the application of the fatigue protocol. The purpose was to apply substantial rotational loading to the knee joint. From a standing position and with the foot under examination planted on the force plate, the participants executed a swinging movement of the opposite leg (clockwise or anticlockwise), thereby performing a pivoting maneuver of the standing leg (Figure 1). One trial included 5 repetitions of touchdown-swing-touchdown of the swinging leg, simulating a maximum knee internal rotation toward a maximum knee external rotation movement of the supporting leg and

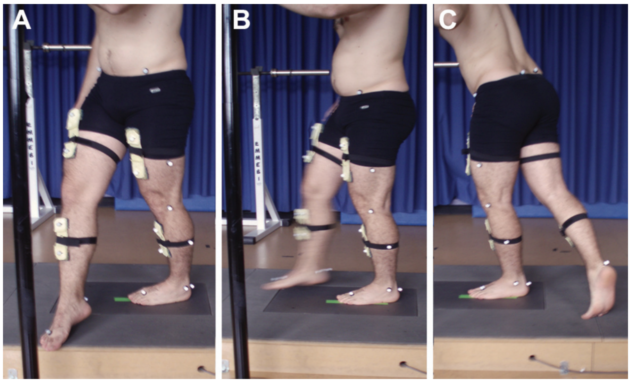

Figure 1. Touchdown (A), swinging (B), and touchdown of the contralateral limb (C) to induce consecutive internal and external rotational stress to the supporting knee.

vice versa. The maneuver was performed at self-selected speed with the knee at full extension. When performing the maneuver, the participants at all times gripped a vertical bar to maintain their balance. Familiarization with the experimental setting was performed before the fatigue protocol, and the participants defined a self-selected speed. They were instructed to keep the supporting foot landed and pivot with maximum intensity, within safe limits for their knees, to achieve maximum knee rotational loading. Trials that did not fulfill the defined criteria were eliminated after video and foot kinematic data inspection.

Fatigue Protocol

Before the induction of fatigue, an isokinetic evaluation was performed at 60° of knee flexion. The participants were then asked to perform 5 consecutive maximum voluntary concentric knee flexions/extensions. The highest torque value for knee flexion and extension was recorded and used for the quantification of muscle fatigue (baseline torque). After a 1-minute period of rest, the participants were asked to perform consecutive maximum concentric flexions/extensions until the torque measured for both muscle groups dropped below 50% of the baseline torque. They were then given the same period of rest and resumed the procedure as many times as needed until the first 5 repetitions were all below 50% of the baseline torque, which signified the completion of the protocol. During the fatigue protocol, the participants maintained the skin markers on their lower extremities. They then immediately performed the pivoting maneuver in the exact manner as for the prefatigue procedure and completed the examination within 20 minutes.

Statistical Analysis

Statistical analysis was performed using the SPSS version 15 software package (SPSS, Inc, an IBM Company, Chicago, Illinois). The 2 variables evaluated were the maximum range of internal-external tibial rotation and maximum knee rotational moment. The Kolmogorov-Smirnov test was performed to examine the normality of distribution of the examined variables (minimum $P = .07$), and consequently parametric tests were used for comparisons. One-way analysis of variance (ANOVA) was used to examine the differences between the control, single-bundle, and double-bundle groups in baseline patient characteristics, functional scores, and KT-2000 arthrometer measurements. Two-way repeated-measures ANOVA was performed using tibial rotation and rotational moment as the dependent variables and patient group as the within-subject factor. The Mauchly test was performed to examine sphericity (minimum $P = .12$) and the above-mentioned repeated-measures ANOVA tests were interpreted with sphericity assumed. Pairwise comparisons were computed to further explore the interaction. Power analysis was also performed. The significance level was set at $P < .05$.

RESULTS

Clinical Examination

Knee flexion averaged 135.2° ± 8.3° and 133.8° ± 9.4° in the single- and double-bundle groups, respectively. All patients with ACL-reconstructed knees achieved full knee extension. The anterior drawer, Lachman, and pivot-shift tests were negative for all patients with ACL-reconstructed knees. The IKDC, KOOS, Tegner, and Lysholm scores were not significantly different between the 2 groups with ACL-reconstructed knees (minimum $P = .26$; Table 2). Similarly, side-to-side differences in anterior tibial translation between the groups, as measured by the KT-2000 arthrometer, were not significant ($P = .61$; Table 2).

Isokinetic Evaluation

Isokinetic flexion/extension evaluation data at 60° of knee flexion are depicted in Table 3. Knee flexion and extension moments, as well as knee flexion/extension moment ratios, were not significantly different between the 3 groups (minimum $P = .18$). Flexion/extension moment ratios in the single- and double-bundle groups with ACL-reconstructed knees were 72% and 73%, respectively. Knee flexion and extension moments of the affected side (expressed as a percentage of the unaffected knee) were also not significant between the groups with ACL-reconstructed knees ($P = .69$ and .45, respectively).

Kinematic and Kinetic Evaluation

A total of 164 trials were available for kinematic and kinetic data analysis (mean 4.8 per participant). Tibial rotation and rotational moment values of the 3 groups in the pre- and postfatigue states are depicted in Table 4. In the prefatigue state, tibial rotation was not significantly different across the 3 groups ($P = .22$, observed power $a = 0.46$). The double-bundle group showed the lowest tibial rotation values, whereas the single-bundle group was

TABLE 2
Functional and KT-2000 Arthrometer Scores of the Patients With ACL-Reconstructed Knees[a]

	Single-Bundle Group (n = 12)	Double-Bundle Group (n = 12)
KT-2000 arthrometer side-to-side difference, mm	1.5 ± 1.1	1.1 ± 1.8
Lysholm score	91.3 ± 8.2	92 ± 9
Tegner score	6.6 ± 1.6	7.1 ± 1.5
IKDC	79.3 ± 16.2	80.2 ± 14.6
KOOS	81.3 ± 11.2	83.3 ± 10.2

[a] Values are expressed as mean ± standard deviation. IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Outcome Score.

TABLE 3
Isokinetic Evaluation at 60° of Knee Flexion[a]

	Control Group (n = 10)	Single-Bundle Group (n = 12)	Double-Bundle Group (n = 12)
Extension moment, N·mm/kg	183 ± 30	177 ± 69	213 ± 38
Flexion moment, N·mm/kg	132 ± 27	130 ± 63	156 ± 35
Flexion/extension ratio	0.72 ± 0.13	0.72 ± 0.12	0.73 ± 0.12
Extension moment, % of the unaffected knee	—	0.84 ± 0.31	0.92 ± 0.04
Flexion moment, % of the unaffected knee	—	0.93 ± 0.4	0.98 ± 0.12

[a] Values are expressed as mean ± standard deviation. —, not applicable.

TABLE 4
Tibial Rotation and Rotational Moment Values for the Examined Maneuver[a]

	Control Group (n = 10)	Single-Bundle Group (n = 12)	Double-Bundle Group (n = 12)
Tibial rotation, deg			
Prefatigue	22.35 ± 4.15	22.15 ± 10.01	16.45 ± 6.66
Postfatigue	22.97 ± 4.26	29.1[b] ± 15.63	18.05 ± 4.09
Rotational moment, N·mm/kg			
Prefatigue	465.3 ± 133.8	339.2[c] ± 147.9	317.9[c] ± 97.1
Postfatigue	410.9 ± 116.8	387.6 ± 130.8	407.9 ± 187.2

[a] Values are expressed as mean ± standard deviation.
[b] Significant at the .05 level compared with prefatigue values of the same group.
[c] Significant at the .05 level compared with prefatigue values of the control group.

closest to the controls. Fatigue significantly affected tibial rotation (P = .05, a = 0.54). Specifically, tibial rotation in the single-bundle group significantly increased compared with the prefatigue state by 31.4% (P = .015, a = 0.83). In contrast, the double-bundle and control groups showed no significant increase in tibial rotation in the postfatigue state (P = .6, a = 0.57 and P = .85, a = 0.49, respectively). Postfatigue tibial rotation of the single-bundle group was also significantly higher compared with the double-bundle group (P = .03, a = 0.74). Compared with controls, tibial rotation values in the double-bundle group were not significantly decreased both pre- and postfatigue (P = .065, a = 0.61 and P = .08, a = 0.59, respectively).

Fatigue did not affect significantly the rotational moments applied on the knee joint (P = .41, a = 0.56). On average, rotational moments increased by 14.1% and 28.3% postfatigue in the single- and double-bundle groups, respectively. In contrast, the control group showed a decrease in rotational moment by a mean 11.7%. In the prefatigue state, rotational moments of the control group were significantly higher compared with both the single-bundle (P = .05, a = 0.72) and double-bundle (P = .03, a = 0.82) groups. In the postfatigue state, rotational moments were not significantly different across the 3 groups (P = .93, a = 0.47).

DISCUSSION

The current study investigated the effect of lower limb muscle fatigue on tibial rotation in single- and double-bundle ACL-reconstructed knees using 3-dimensional (3-D) motion analysis. A significant increase was found postfatigue in the tibial rotation of the single-bundle group. In contrast, the double-bundle group showed similar tibial rotation values pre- and postfatigue. However, compared with controls, the double-bundle group showed a trend toward decreased tibial rotation values in both conditions. Rotational moments in the groups with ACL-reconstructed knees were not significantly different from prefatigue moments in any group.

Tibial rotation in this study was examined during a swinging maneuver, which was purposed to impose significant rotational stress to the knee and included consecutive internal and external rotational loading. Similar kinematic studies have employed cutting and pivoting maneuvers during which the knee joint was stressed at external rotation to simulate everyday or athletic activities.[9] We believe that the maneuver used in this study presents several advantages. First, it incorporates internal rotational stress of the knee, which most closely replicates the mechanism of noncontact ACL injury. Previous biomechanical studies, employing fatigue, have shown increases in internal but not external tibial rotation in ACL-intact knees during landing and crossover cutting tasks.[13,17] A second advantage of this maneuver would be that a cumulative evaluation of both internal and external tibial rotation during the same maneuver could better exhibit transverse plane residual knee laxity and consequently elicit potential differences, if present, between the 2 groups with ACL-reconstructed knees.

A standard fatigue protocol was employed to induce and maintain lower extremity muscle fatigue for postfatigue tasks. Consecutive maximum concentric knee flexions/extensions were used to induce adequate muscle fatigue of the lower extremities. Fatigue threshold was defined as a 50% decrease in the subject's maximum strength. Multiple protocols have been applied in previous studies, focusing either on localized or general fatigue.[1,15,27] The latter employs repetitive whole-body aerobic exercise to induce volitional exhaustion, which simulates regular athletic activity. General fatigue has been shown to decrease knee proprioception by adversely affecting central processing of afferent signals in addition to causing dysfunction of peripheral mechanoreceptors.[15] In contrast, the localized fatigue protocol applied here offered the advantage of objectively monitoring and quantifying the fatigue induced specifically to the quadriceps and hamstring muscles of each participant, which are known to contribute to the dynamic stabilization of the knee joint.[17,25]

Tibial rotation of the single-bundle group was significantly increased postfatigue compared with prefatigue and postfatigue values of the remaining 2 groups. There is a scarcity of studies in the literature examining the kinematics of ACL-reconstructed knees under lower limb muscular fatigue. Findings of this study are the first to demonstrate a comparable advantage of double-bundle ACL reconstructed knees to control tibial rotation when fatigued. Given that previous studies using similar instrumentation and testing conditions did not identify any differences in tibial rotation between the 2 techniques as did prefatigue testing in this study,[28,29] our findings highlight the role of fatigue in impairing rotational laxity control in single-bundle reconstructions.

However, our study demonstrated that tibial rotation values of the double-bundle group exhibited a trend toward being lower compared with controls both pre- and postfatigue. A growing body of recent evidence supports these findings. Using an MRI-compatible torsional loading device, Hemmerich et al[5] found that although the single-bundle reconstruction did not affect rotational laxity compared with contralateral or preoperative groups, the double-bundle technique excessively reduced internal laxity at 30° of knee flexion. In cadaveric studies, Markolf et al[12] and Musahl et al[16] demonstrated an overcorrection in tibial rotation of double-bundle ACL-reconstructed knees under variable simulated loading conditions. Employing 3-D motion analysis, Tsarouhas et al[28] also confirmed in vivo a decrease in tibial rotation values of the double-bundle group compared with controls during a pivoting maneuver from a standing position. To our knowledge, currently existing studies have not provided any insights on the potential clinical relevance of this finding.

In the prefatigue state, maximum knee rotational moments of the 2 groups with ACL-reconstructed knees were significantly lower compared with controls. It is unclear whether this can be attributed to a deficit in internal-external rotators muscular activity or to a protective compensation due to reduced confidence in the nonfatigued state. In a biomechanical study, Segawa et al[21] found decreased isokinetic strength in internal and external rotation of ACL-reconstructed knees using semitendinosus and gracilis autografts compared with the intact side 12 months after surgery. Similar isokinetic studies have found internal tibial rotation deficits even after an average of 51 months after hamstring tendon ACL reconstruction.[31] Significantly, lower rotational moments were found using motion analysis in the affected sides of single- and double-bundle ACL-reconstructed knees compared with their intact counterparts during a maneuver that combined pivoting and stair ascending.[29] The semitendinosus and gracilis muscles contribute to internal tibial rotation,[22] and therefore decreased postsurgical rotational moments are attributed to harvesting these 2 tendons. A rotational strength deficit after hamstring tendon harvest was also confirmed when hamstring and patellar tendon autograft ACL reconstructions were compared.[26] Of note, although there was an almost 2-fold increase in rotational moment of double-bundle ACL-reconstructed knees compared with single-bundle ones, tibial rotation showed only a minor increase postfatigue, reinforcing the assumption that the single-bundle technique demonstrates a comparably reduced ability to withstand rotational loads under fatigue and possibly depends more on the muscle for stability.

A limitation of this study was that it did not include female patients with ACL-reconstructed knees. Numerous studies in the literature have demonstrated differences in lower limb neuromuscular control and landing strategies in female compared with male subjects, which were considered accountable for the increased risk of ACL injury in female patients.[10,13] It would therefore be intriguing to investigate the effect of fatigue on rotational knee kinematics of female patients with single- and double-bundle ACL-reconstructed knees. However, we believe that hamstring tendons of adequate size for autograft ACL reconstruction are mainly available in male patients. Consequently, female patients undergoing double-bundle ACL reconstruction in our department were limited and, therefore, the study groups were matched to include only male participants. Additional limitations of this study were the number of participants included, the short-term follow-up, the relative inaccuracy of gait analysis systems, and the fact that a single functional activity was examined, which potentially limits the generalizability of the study.

CONCLUSION

Single-bundle ACL-reconstructed knees demonstrate a reduced ability to resist rotational loads under fatigue. Double-bundle reconstructed knees better control tibial rotation when fatigued. However, the latter demonstrate a trend toward an excessive reduction in tibial rotation compared with the intact knee, suggesting an overcorrection in rotational laxity.

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