Dynamic Effect of Quadriceps Muscle Activation on Anterior Tibial Translation After Single-Bundle and Double-Bundle Anterior Cruciate Ligament Reconstruction

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Purpose: To examine differences in anterior tibial translation in 3 groups: single-bundle anterior cruciate ligament (ACL)—reconstructed, double-bundle ACL-reconstructed, and ACL-intact knees under gradual dynamic quadriceps muscle activation. **Methods:** Thirty male patients underwent successful single-bundle (n = 15) and double-bundle (n = 15) ACL reconstructions; 15 healthy controls were included in the study. Anterior tibial translation was assessed at 30° of knee flexion in the resting position (0% quadriceps activation) and under 50% and 100% of maximum quadriceps concentric contraction using an isokinetic dynamometer with the KT-2000 arthrometer securely attached to the participants' knees. **Results:** The 2 ACL-reconstructed groups were similar regarding International Knee Documentation Committee (IKDC), Knee Injury and Osteoarthritis Score (KOOS), Tegner, and Lysholm scores and preliminary isokinetic evaluation ($P = .38$). Quadriceps activation significantly affected anterior tibial translation ($P = .001$, $\alpha = 0.98$). In all 3 study groups, anterior tibial translation was significantly higher under 100% quadriceps activation compared with 0% contraction ($P = .01$) and 50% quadriceps activation ($P = .047$). There were no between-group differences in anterior tibial translation with 0%, 50%, or 100% quadriceps activation ($P = .46$). **Conclusions:** Under quadriceps muscle activation, anteroposterior knee laxity in ACL-intact and ACL-reconstructed knees is gradually increased. Single-bundle and double-bundle ACL-reconstructed knees show a similar increase in anterior tibial translation under gradual quadriceps contraction. When comparing different ACL reconstruction techniques in the experimental setting, dynamic, in addition to static, testing is advised to reach a comprehensive assessment of anteroposterior knee stability. **Level of Evidence:** Level III, retrospective comparative study.

Surgical reconstruction of the anterior cruciate ligament (ACL) aims to restore both anteroposterior and rotational knee laxity to normal, in addition to improving functionality and preventing the onset of osteoarthritis. Anatomic reconstruction of the ligament in respect to its native dimensions, collagen orientation, and insertion sites is currently considered the keystone to successful ACL reconstruction.[1] A double-bundle configuration and a more anatomic lateralized orientation of the single-bundle ACL-reconstructed graft have both been advocated to more effectively restore anteroposterior and rotational knee kinematics to normal when compared with the conventional single-bundle technique.[2-5]

To date, multiple studies have examined anterior tibial translation in ACL-intact, ACL-deficient, and ACL-reconstructed knees using KT arthrometer testing, magnetic resonance imaging, robotic simulators, and computer navigation.[6-9] Basic science studies have added significantly to our understanding of ACL function and kinematics, and static stability testing has offered an easy and reproducible way to compare different techniques. However, there is a growing consensus that in vivo human testing under dynamic loading conditions is warranted to more realistically approximate knee

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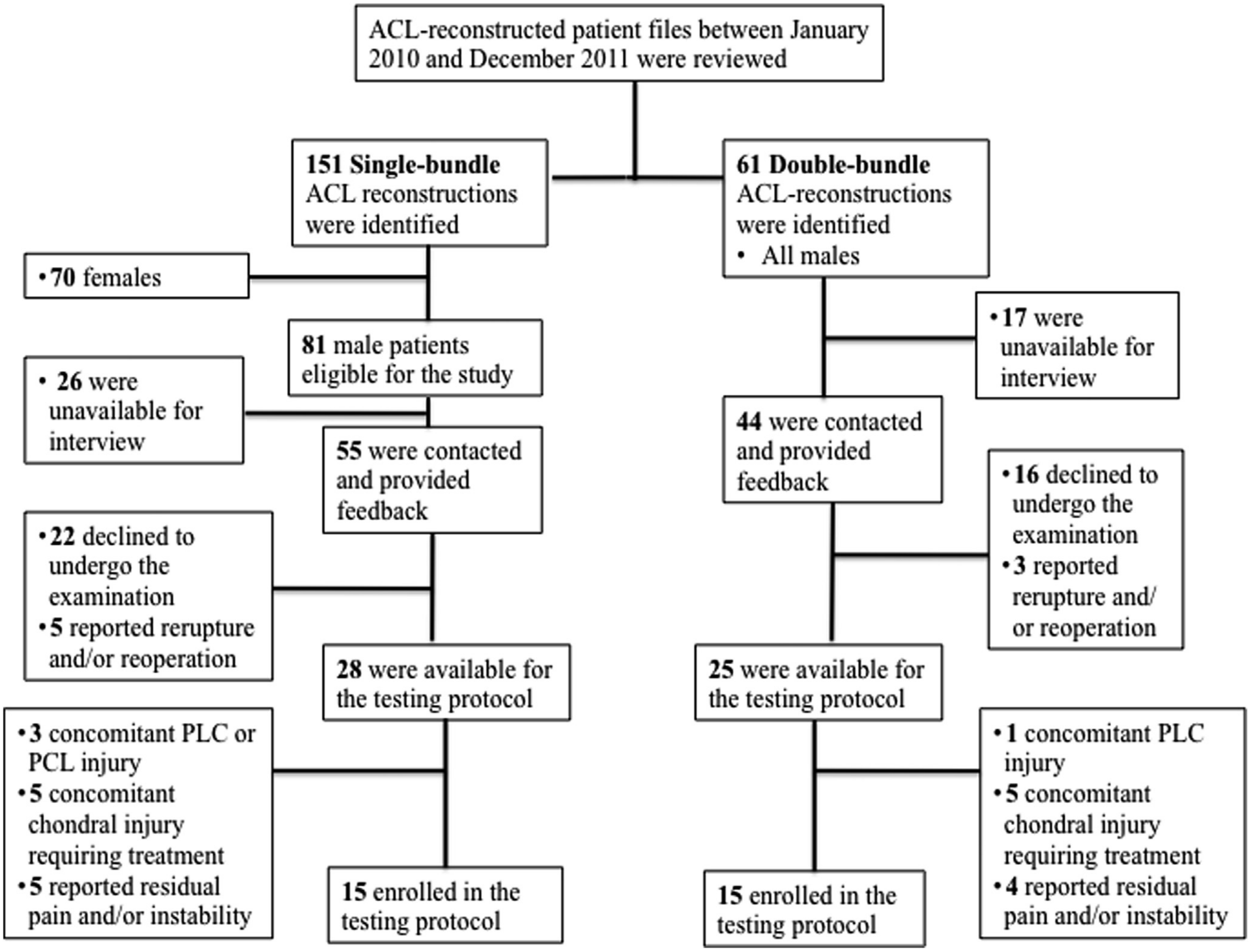

Fig 1. Flowchart describing the selection process of participants with single-bundle and double-bundle anterior cruciate ligament (ACL) reconstruction.

loading conditions and achieve more clinically relevant outcomes.[10] Although recent research has examined in vivo the rotational stability of single-bundle and double-bundle ACL-reconstructed knees under different pivoting and swinging maneuvers,[11,12] there is limited evidence on anteroposterior knee laxity under dynamic quadriceps contraction.[13,14]

The purpose of this study was, therefore, to examine differences in anterior tibial translation in 3 groups: single-bundle ACL-reconstructed knees, double-bundle ACL-reconstructed knees, and ACL-intact knees under gradual quadriceps muscle activation. Our primary hypothesis was that ACL-reconstructed knees would exhibit significantly increased anterior tibial translation compared with ACL-intact knees under gradual quadriceps activation. Our secondary hypothesis was that single- and double-bundle ACL-reconstructed knees would show similar anterior translation values under varying quadriceps loads.

Methods

Patient Selection

Patient files from a prospectively documented database comprising 151 single-bundle and 61 double-bundle procedures performed between January 2010 and December 2011 in our department were retrospectively reviewed for inclusion in the study (Fig 1). Inclusion criteria were ACL reconstructions with hamstring tendon autografts performed using either the single-bundle or double-bundle technique and with a successful surgical outcome as evidenced by patient feedback, side-to-side stability testing, and return to preinjury activity level. Exclusion criteria were other ligamentous (medial or lateral posterior cruciate), bone, and chondral injuries in the same knee, as assessed by magnetic resonance imaging and clinical examination (Fig 1). Ultimately, 15 single-bundle and 15 double-bundle ACL-reconstructed knees in male patients

Table 1. Baseline Patient Characteristics

Variable	Control (n = 15)	Single Bundle (n = 15)	Double Bundle (n = 15)	*P* Value
Age, yr	25.2 ± 1.3	24.1 ± 4.9	26 ± 4.6	.67
Body mass index, kg/m^2	23.4 ± 2.2	24.4 ± 2.9	23.9 ± 1.8	.73
Right/left knee	9/6	8/7	9/6	
Dominant/nondominant limb	7/8	7/8	7/8	
Follow-up, mo	–	19 ± 5.3	17.2 ± 4.9	.59
Meniscectomies	–	5	6	

NOTE. Data presented as mean ± SD unless otherwise indicated.

were included in the study. All the reconstructions were performed or directly supervised by the same surgeon (M.E.H.). The minimum interval between the surgery and the examination was 1 year. Fifteen participants with no history of lower limb trauma or neuromusculoskeletal deficit formed the control group. The 3 groups were similar regarding age, body mass index, limb dominance, and side tested. The ACL-reconstructed groups were also similar regarding side affected, associated meniscal injury, and duration of follow-up. All the participants signed an informed consent form approved by the institutional review board before the initiation of the study. Baseline patient and control data are presented in Table 1.

Surgical Technique

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 were addressed before the ACL reconstruction.

For the double-bundle technique, 2 separate femoral and 2 tibial tunnels were created using anatomic aimers (Acufex Anatomic ACL Guide System; Smith & Nephew Endoscopy, Andover, MA) with an appropriate offset. The femoral tunnel for the anteromedial bundle was drilled first through the anteromedial portal at 110° to 120° of knee flexion. The posterolateral tunnel was drilled through an accessory medial portal created with the knee flexed at 130°. 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 set at 50°. The grafts were inserted into the joint and secured on the femoral side with EndoButtons (Smith & Nephew Endoscopy) and on the tibial side with bioabsorbable interference screws reinforced by postfixation screws. The grafts were tensioned by manual power and fixed in the tibia at 10° of knee flexion for the posterolateral bundle and 45° for the anteromedial bundle.

For single-bundle ACL reconstructions, the single femoral tunnel was created through the anteromedial portal with the knee at 110° 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 ACL-reconstructed groups followed the same postoperative regimen.

Instrumentation and Testing Protocol

Clinical evaluation of the participants with ACL-reconstructed knees was performed by the leading author (A.T.) and preceded the isokinetic evaluation and knee laxity measurements. Knee range of motion and the outcomes of the Lachman, anterior drawer, and pivot-shift tests were recorded. 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 also obtained.

An isokinetic dynamometer (Cybex Humac Norm, CSMi, Stoughton, MA) was used for the baseline isokinetic evaluation and the subsequent testing procedure, which was performed by a single investigator (V.S.). 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. Gravitational corrections were made to account for the effect of limb weight on torque measurements. To maximize performance, verbal encouragement was given, whereas the dynamometer automatically provided feedback on the intensity and duration of exercise and total work production.

A baseline isokinetic examination was subsequently performed at 60°/s. The maximum voluntary concentric contraction (MVCC) of the quadriceps muscle was calculated with the knee at 30° of flexion. The KT-2000 arthrometer was then securely stabilized with straps on

Fig 2. The experimental setup with the right knee joint centered on the axis of rotation of the dynamometer and the KT-2000 securely attached to the participant's tibia.

the participant's knee (Fig 2). Based on the dynamometer curve, the participant performed isometric quadriceps contractions at the same knee flexion angle under 50% and 100% of the quadriceps MVCC, and the examiner recorded the maximum KT reading. Consequently, anterior tibial translation was assessed under 3 conditions: first, a KT arthrometer was used to measure translation by the traditional method with a maximum manually applied load at 30° of knee flexion. The participants then generated a 50% and 100% maximum isometric quadriceps contraction at the same knee flexion angle, and the KT arthrometer was used to measure anterior tibial translation again. Each participant performed at least 3 trials with appropriate rest intervals under these 3 testing conditions, and average values were calculated.

Statistical Analysis

All analyses were performed using SPSS, version 15, (SPSS, Chicago, IL). Baseline patient characteristics, functional scores, and KT-2000 side-to-side differences in the single-bundle, double-bundle, and control groups were compared using one-way analysis of variance. Repeated-measures analysis of variance was performed using anterior tibial translation as the dependent variable and patient group as the within-subject factor to explore within- and between-participant effects of quadriceps muscle activation on anterior tibial translation. When applicable, post hoc comparisons (using paired *t* tests within groups and independent samples *t* tests between groups) were computed to further explore the interaction. The α values for all comparisons made were calculated. The significance level was set at .05.

Table 2. Functional and KT-2000 Scores of the ACL-Reconstructed Knees

Knee Scores	Single Bundle (n = 15)	Double Bundle (n = 15)	*P* Value
KT-2000 side-to-side difference, mm	1.4 ± 1.1	1.2 ± 1.4	.61
Lysholm score	88.3 ± 7.6	86 ± 9.1	.72
Tegner score	6.8 ± 1.5	7 ± 1.4	.38
IKDC	77.6 ± 14.1	78.8 ± 12.4	.74
KOOS	80.5 ± 9.2	82.3 ± 9.8	.79

NOTE. Data presented as mean ± SD unless otherwise indicated.

IKDC, International Knee Documentation Committee; KOOS, Knee Injury and Osteoarthritis Score.

Results

The range of knee motion averaged 141.8 ± 9.3 and 139.8 ± 9.6 in the single-bundle and double-bundle groups, respectively. All participants with ACL-reconstructed knees achieved full knee extension. The anterior drawer, Lachman, and pivot-shift tests were negative for all ACL-reconstructed knees. IKDC, KOOS, Tegner, and Lysholm scores were similar between the 2 ACL-reconstructed groups (Table 2). KT-2000 side-to-side differences in anterior tibial translation were also similar between the 2 groups (Table 2).

The outcomes of isokinetic flexion/extension evaluation at 60°/s are shown in Table 3. Knee flexion and extension moments and knee flexion/extension moment ratios were similar in the 3 groups.

Mean ± standard deviation values of anterior tibial translation for the 3 study groups under different fractions of quadriceps activation are shown in Table 4. There was no significant difference in anterior tibial translation between single-bundle and double-bundle ACL reconstructions and controls when no quadriceps torque (0% contraction) was applied ($P = .46$; $\alpha = 0.39$). Quadriceps activation significantly affected anterior tibial translation ($P = .001$; $\alpha = 0.98$) (Fig 3). Specifically, with 50% quadriceps activation, anterior tibial translation did not increase significantly compared with 0% activation within the single-bundle ($P = .69$), double-bundle ($P = .12$), and control ($P = .17$) groups. However, a significant increase was noted from 50% to 100% of quadriceps activation within the single-bundle ($P = .01$), double-bundle ($P = .006$), and control ($P = .01$) groups. Similarly, anterior tibial translation was significantly higher under 100% quadriceps activation when compared with 0% activation within the single-bundle ($P = .047$), double-bundle ($P = .02$), and control ($P = .01$) groups. In contrast, no significant difference in anterior tibial translation was found in the 3 groups with either 50% ($P = .46$) or 100% ($P = .6$) quadriceps activation.

Discussion

In this study, anterior tibial translation values increased significantly within all 3 groups with 100% quadriceps muscle activation compared with 0% contraction. In contrast, anterior tibial translation was

Table 3. Isokinetic Evaluation at 60°/s

Variable	Control (n = 15)	Single Bundle (n = 15)	Double Bundle (n = 15)	*P* Value
Extension moment, N•mm/kg	185 ± 28	179 ± 57	196 ± 58	.39
Flexion moment, N•mm/kg	134 ± 31	132 ± 52	148 ± 45	.35
Flexion/extension ratio	0.74 ± 0.12	0.72 ± 0.17	0.71 ± 0.19	.78

NOTE. Data presented as mean ± SD unless otherwise indicated.

similar among the 3 groups with 0%, 50%, or 100% quadriceps activation.

The effect of quadriceps muscle contraction on ACL strain and anterior tibial translation in the ACL-intact and ACL-reconstructed knee has been evaluated previously.[15] The anterior vector of the quadriceps is considered the primary producer of anterior knee force throughout the knee's range of motion. In a cadaveric model, DeMorat et al.[15] established that aggressive quadriceps loading, with the knee in slight flexion, significantly increased anterior tibial translation and the risk of ACL injury. Using a musculoskeletal model of the knee, Pandy et al.[16] found that for isolated quadriceps contraction, forces on the ACL increased with increasing quadriceps force for all flexion angles between 0° and 80°. The ACL was unloaded at flexion angles greater than 80°. A relative in vivo comparison of anterior tibial translation between single-bundle and double-bundle techniques under dynamic quadriceps activation is still lacking. For this purpose, this study combined isokinetic dynamometry and KT-2000 testing, which we believe offered considerable advantages. First, it allowed a more accurate evaluation of quadriceps loads applied to the knee joint, which were calculated as a percentage of the participant's MVCC rather than in absolute numbers. Second, compared with cadaveric models, an in vivo assessment of anterior tibial translation takes into account the contribution of all static and dynamic knee stabilizers to the final outcome and therefore may reach more clinically relevant findings.

Biomechanical analysis has confirmed the distinct roles of the 2 ACL bundles in controlling anteroposterior laxity throughout the knee's range of motion. Transecting the anteromedial bundle alone significantly disturbed anterior stability at 60° and 90° of knee flexion. Isolated transection of the posterolateral bundle significantly increased anterior tibial translation at 30° of knee flexion.[17] In particular, the posterolateral bundle has been shown to predominantly resist anteroposterior and combined rotational loads near full extension.[18,19] Li et al.[20] found that when quadriceps loads were applied to the knee in vitro, in situ forces on the ACL peaked near 30° of knee flexion. Consequently, our testing protocol allowed a comparative evaluation of the contribution of reconstructing both ACL bundles and an equivalent graft configuration in dynamic anteroposterior stability by measuring the maximum tibial translation at a flexion angle at which the posterolateral bundle predominantly contributes in resisting tibial translation.

Findings of this study showed a similar increase in anterior tibial translation between single-bundle and double-bundle ACL-reconstructed knees under increasing fractions of quadriceps activation. Although standard deviation values in the double-bundle group were comparatively higher compared with the single-bundle group, differences did not reach statistical significance. The superiority of either technique in restoring anteroposterior tibial translation to normal is still debated. A most recent meta-analysis of 19 randomized controlled trials found the double-bundle technique superior regarding anteroposterior laxity along with rotational knee laxity compared with single-bundle reconstruction as evidenced by the Lachman and pivot shift tests and KT-1000 measurements.[2] Other clinical and biomechanical studies have not supported these findings.[21-23] In their series of human cadaveric studies, Markolf et al.[23] failed to show any advantage of either technique regarding in situ graft forces and knee laxity. However, studies of anteroposterior knee laxity, which have included double-bundle ACL reconstructions under in vivo dynamic loading conditions, are still limited. Recently, Hoshino et al.[24] reported the outcomes of an in vivo study that examined the tibiofemoral kinematics of single-bundle and double-bundle ACL-reconstructed knees during downhill treadmill running using dynamic stereo x-ray imaging. They found reduced anterior tibial translation in both groups and concluded that kinematic variables were not restored to normal after either ACL-reconstruction technique.

Our findings showed a significant increase in anterior tibial translation of both ACL-intact and

Table 4. Anterior Tibial Translation Values (mean ± standard deviation) Under Gradual Quadriceps Activation for the 3 Study Groups

Quadriceps activation	Control, mm (n = 15)	Single Bundle, mm (n = 15)	Double Bundle, mm (n = 15)	*P* Value
0%	3.1 ± 1.7	4.8 ± 3.2	4.4 ± 2.9	.46
50%	3.7 ± 2.36	4.6 ± 3.05	5.8 ± 4.06	.46
100%	4.9 ± 2.74	5.9 ± 3.67	6.8 ± 4.4	.6

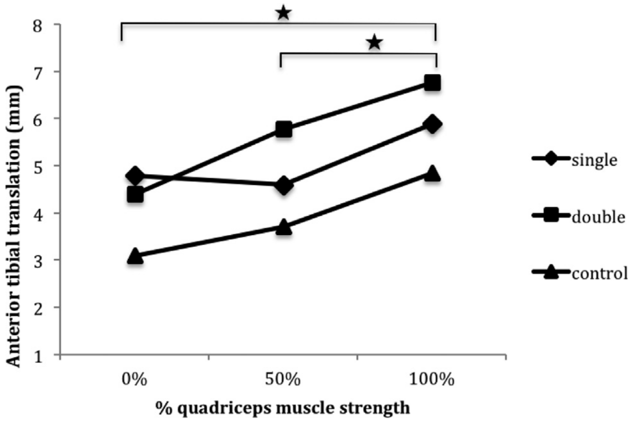

Fig 3. Anterior tibial translation under different degrees of quadriceps muscle activation. In all groups, the values increased significantly with increasing muscle strength. *Statistically significant (P <.05).

ACL-reconstructed knees with 100% of quadriceps activation compared with 0% contraction. Similar to our findings, Papannagari et al.[14] using radiostereometry found that although anterior knee laxity was restored during KT-1000 arthrometer testing, ACL reconstruction did not restore normal knee kinematics under weight-bearing loading conditions. Only single-bundle ACL reconstructions using bone—patellar tendon—bone autografts were included in this study. Findings of our study showed that anteroposterior knee laxity significantly increased from 50% to 100% of quadriceps torque but not from 0% to 50%, suggesting that it is in the state of full quadriceps activation that anteroposterior knee laxity is significantly amplified and potentially exhibits differences if present. Recent research on rotational knee laxity after ACL reconstruction has found significant differences between the single-bundle and double-bundle techniques under varying simulated knee loading conditions, such as under lower limb muscular fatigue.[11] Actual dynamic testing may well induce knee extensor and flexor fatigue while performing consecutive MVCCs. Therefore, our study suggests that similar to rotational knee laxity testing, dynamic, in addition to static, in vivo experiments are warranted to achieve a comprehensive comparison of anteroposterior knee stability between different ACL reconstruction techniques.

A drawback of the configuration used in this study involved the conflicting effect of the KT-2000 device (because of its weight) against anterior translation of the proximal tibia. At every knee flexion angle, the device's weight produced a component of torque that opposed the anterior translation of the proximal tibia caused by quadriceps contraction. It is clear that this component is null at the 90° knee-flexion position and increases toward knee extension. However, the device's weight affected all study participants evenly, and the torque produced by the quadriceps sufficiently generated significant differences in anterior tibial translation compared with the resting position. Therefore, it was considered that no additional adjustments or calculations were required. However, it could be stated that the amount of anterior displacement calculated for all study groups in the resting position was lower compared with earlier reports, such as those of Howell et al.[25] in 1990 and Myrer et al.[26] in 1996. Although more recent clinical studies have reported anteroposterior translation values similar to our findings (e.g., Ferretti et al.[8] in 2008 found 3.7 ± 1.4 of anteroposterior translation after single-bundle ACL reconstruction), it is possible that the configuration discussed earlier has influenced the values calculated in the resting position, particularly because KT-2000 testing with maximum manual power was performed without dynamometer confirmation of the anterior force applied.

Limitations

Our study may be limited by the fact that only male participants were included. Differences between sexes in quadriceps muscle force during weight-bearing knee flexion have already been established in vitro.[27] However, it has been our preference in our institution to perform the double-bundle technique mainly in male patients with hamstring tendon autografts of adequate size, and consequently the number of female patients undergoing double-bundle ACL-reconstructions in our department was limited. Another limitation of our study is the small number of participants and the fact that only post hoc power analysis was performed. Because small groups of patients with successful ACL reconstructions from a larger database were enrolled in the study, selection bias may have ensued. Conversely, the inclusion of 3 study groups obviously strengthens our findings. Finally, validation of our study methodology was not performed. However, Howell et al.[25] published a study using a clearly similar methodology in 1990.

Conclusions

Under quadriceps muscle activation, anteroposterior knee laxity in ACL-intact and ACL-reconstructed knees is gradually increased. Single-bundle and double-bundle ACL-reconstructed knees show a similar increase in anterior tibial translation under dynamic conditions. In the experimental setting, when comparing different ACL reconstruction techniques, dynamic, in addition to static, testing is advised to reach a comprehensive assessment of anteroposterior knee stability.

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