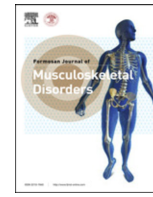
Formosan Journal of Musculoskeletal Disorders 3 (2012) 43–49

Contents lists available at SciVerse ScienceDirect

Formosan Journal of Musculoskeletal Disorders

journal homepage: www.e-fjmd.com



Original Article

Dynamic functional performance and kinematic analysis of the rotational patterns of single- versus double-bundle anterior cruciate ligament reconstruction

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A R T I C L E I N F O

Article history:
Received 31 July 2011
Received in revised form
4 January 2012
Accepted 18 January 2012
Available online 17 May 2012

Keywords:
anterior cruciate ligament
kinematic
pivoting
rotational stability

A B S T R A C T

Background: The evaluation of anterior cruciate ligament (ACL) reconstruction has typically focused on the restoration of rotatory stability. Some studies have compared single-bundle and double-bundle ACL reconstruction using subjective clinical tests and questionnaires, but these studies only provide limited data on rotational stability. The purpose of this study is to determine the rotational patterns that present during high-demand pivoting tasks and to evaluate any difference in kinematic rotational patterns between patients who have undergone single- or double-bundle ACL reconstruction.
Materials and Methods: Twenty-four males were divided into four groups for this study: intact, ACL deficient, single-bundle reconstructed, and double-bundle reconstructed. Kinematic data were collected using a 10-camera optoelectronic motion analysis system while the participants performed high-demand landing and pivoting tasks. The evaluation period was defined as the time from when the tested foot made contact with the ground to takeoff, and the range of tibial rotation was measured.
Results: Rotation was significantly reduced in the single-bundle ACL reconstructed knees ($7.8^\circ \pm 3.4^\circ$) and double-bundle ACL reconstructed knees ($7.5^\circ \pm 2.6^\circ$) in comparison with ACL-deficient knees ($13.5^\circ \pm 3.7^\circ$; $p < 0.05$). There was no significant difference in terms of tibial rotation between the intact knees ($6.5^\circ \pm 3.5^\circ$) and the single-bundle or double-bundle ACL reconstructed knees after >2 years of follow up ($p > 0.05$).
Conclusion: By using a dynamic functional biomechanical assessment, we demonstrate that the single-bundle ACL reconstruction technique using a composite hamstring tendon graft and the double-bundle ACL reconstruction technique can adequately restore excessive tibial rotation during high-demand activities such as landing and pivoting.

1. Introduction

The anterior cruciate ligament (ACL) restrains anterior tibial translation and also plays an important role in maintaining rotational stability. For ACL-deficient knees, single-bundle ACL reconstruction has been the standard surgical option for eliminating excessive anterior tibial translation. However, recent biomechanical studies have shown that single-bundle reconstruction cannot completely restore rotatory stability[1,2] or improve biomechanical disadvantages (even though a clinical procedure that anatomically reconstructs two functional bundles was reported by Yasuda et al[3]), but some studies have reported no clinically significant difference between double- and single-bundle ACL reconstructions.[4,5]

Knee joint laxity, including anterior tibial translation and rotational stability, can be subdivided into static laxity and dynamic laxity.[6] Static instability can be tested by manual clinical tests such as the anterior drawer test, Lachman test for anterior tibial translation, and the pivot-shift test for rotational stability, or by using a device such as KT-1000 (Medmetric, San Diego, CA, USA). In addition, some mechanical devices have been designed for the objective and biomechanical evaluation of knee rotational static laxity.[7,8] However, these static tests measure passive knee joint stability without muscle activity. When a patient performs dynamic functional activities after returning to daily sport, it is not only the ligaments but also the muscle contractions that provide knee joint stability; therefore, dynamic functional tests are needed to evaluate dynamic joint stability.

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doi:10.1016/j.fjmd.2012.03.002

Various kinematics studies have measured different dynamic movements in patients with ACL injuries and reconstructed knees. In 2005, Waite et al[9] suggested that low-demand activities do not produce sufficient stress to initiate knee instability in the ACL-deficient knee, but Georgoulis et al[10] reported that tibial rotation is not restored during high-demand movements after ACL reconstruction. Although many studies have compared single- and double-bundle ACL reconstruction using subjective clinical tests and questionnaires that evaluate the final functional outcome, there are limited data on rotational stability as an objective assessment of outcome. Therefore, because the purpose of this study was to evaluate the rotational patterns, we chose high-demand pivoting tasks to evaluate any differences between the kinematic rotation patterns in patients who underwent single- and double-bundle ACL reconstruction.

2. Materials and methods

Four groups were included in the study. Five healthy gender-, age-, height-, and mass-matched participants who had never been diagnosed with any kind of orthopedic or neurologic condition were recruited to participate in the healthy control group (mean age: 25.8 years; mean mass: 74.5 kg; mean height: 1.73 m). Five male participants (mean age: 23.4 years; mean mass: 73.7 kg; mean height: 1.72 m) with ACL-deficient knees were also included in the ACL-deficient control group. The ACL-deficient subjects had sustained an isolated unilateral ACL injury, as confirmed using magnetic resonance imaging (MRI) and a clinical evaluations. They had sustained the injuries more than 1 year before testing (mean time: 16.8 months). Rupture was also arthroscopically confirmed when they underwent ACL reconstruction. Seven male patients (mean age: 26.7 years; mean mass: 75.5 kg; mean height: 1.73 m) were included in the single-bundle reconstruction group, and seven male patients (mean age: 26.3 years; mean mass: 74.3 kg; mean height: 1.72 m) were included in the double-bundle reconstruction group (Table 1).

Table 1
Patient characteristics.

No.	Age (y)	Height (m)	Weight (kg)
Healthy control			
1	24	1.69	71.3
2	27	1.74	75.2
3	24	1.72	77.3
4	25	1.74	68.8
5	29	1.76	79.9
Mean	25.8	1.73	74.5
Deficient control			
1	23	1.71	75.2
2	22	1.69	72.6
3	23	1.68	69.4
4	25	1.75	77.8
5	24	1.77	73.5
Mean	23.4	1.72	73.7
Single-bundle			
1	27	1.69	73.4
2	26	1.74	77.8
3	27	1.75	74.6
4	28	1.71	75.3
5	25	1.73	75.4
6	26	1.76	75.9
7	28	1.73	76.1
Mean	26.7	1.73	75.5
Double-bundle			
1	27	1.68	69.2
2	26	1.74	77.4
3	26	1.71	70.3
4	25	1.75	78.2
5	26	1.70	74.7
6	27	1.72	74.6
7	27	1.74	75.7
Mean	26.3	1.72	74.3

In the two reconstructed groups, meniscal damage was also present at the time of injury in some cases. In all cases, the level of meniscal damage was <25% and no repair procedure had been performed. The mean duration of the postoperation evaluation period was 36 months (24–50 months) for the single-bundle group and 32 months (24–48 months) for the double-bundle group. The patients in the two reconstruction groups all received the same rehabilitation protocol and demonstrated successful rehabilitation. They were all able to resume sport-related activities or military training, such as parachute training and the running of obstacle courses. Before any data were collected, each patient received a clinical evaluation. For the ACL-reconstructed groups, negative Lachman testing and pivot-shift test results indicated that knee joint stability was restored. During this evaluation, Lysholm scores were obtained for both groups. In addition, anterior tibial translation was evaluated in both groups using the K-1000 knee arthrometer (Table 2).

3. Surgical technique

The ACL reconstructions were performed on each patient by one surgeon who had >10 years of experience performing ACL reconstructions. The operation was performed after inflating the tourniquet. The hamstring grafts (gracilis and semitendinosus tendons) were harvested through an incision over the ipsilateral tibia. Once adequate sedation was achieved, the patient was positioned supine on the operating table. A physical examination under anesthesia was then performed, and the involved and uninvolved knees were compared. Both the degree and quality of the endpoint were determined using the Lachman and drawer tests, respectively. Additionally, the presence and magnitude of the pivot-shift phenomenon was assessed. A well-padded pneumatic tourniquet was placed as proximal as possible to the thigh of the operative extremity. The nonoperative extremity was then positioned with both the hip and knee flexed, and the hip was both abducted and externally rotated. The foot on the operating table was dropped, and the operative extremity was placed at the level of the tourniquet. Anatomic landmarks were delineated on the skin using a marking pen, and standard anteromedial and anterolateral portals were established on the joint line adjacent to the borders of the patellar tendon. Arthroscopic evaluation included the assessment of the suprapatellar pouch, patellofemoral joint, medial and lateral gutters, and medial and lateral compartments to determine the presence of any chondral or meniscal injuries and to confirm any suspected ligamentous pathology.

4. Single-bundle reconstruction

The tibial tunnel was first drilled at a position slightly posterior to the center of the anatomic ACL footprint in order to avoid impinging on the extension. An adequate reamer (with a diameter 1 mm larger than the graft size) was used for reaming the tibial cortex. After the drill bit was removed, it was replaced with a 7-mm core-reamer guide wire. In addition, the bone block was removed from the tibial tunnel using a 7-mm core-reamer (Arthrex GmbH, Karlsfeld/Munchen, Germany). The bone block was cut into two pieces, one of which was sutured to the femoral end of the graft while the other was sutured to the tibial end. Notchplasty was unnecessary for most cases except those with a narrow notch. An appropriate femoral location was chosen using an aiming guide, and a drill-guide wire was introduced from the outside through the

Table 2
Clinical data on reconstruction patients.

No.	Side	Postoperation (mo)	IKDC[α]	Lysholm	KT-1000 (mm)	Lachman	Pivot-shift	Graft size (mm)	
Single									
1	L	48	98	95	1.7	0	0	11	
2	R	37	92	90	1.9	0	0	10	
3	L	24	90	88	2.5	0	0	10	
4	L	36	91	89	2.5	1	0	9	
5	R	50	95	90	1.8	0	0	10	
6	R	32	92	88	1.8	0	0	11	
7	R	25	95	88	2.5	1	0	10	
Mean		36	93.2	89.67	2.1				
Double								**AM**[β]	**PL**[γ]
1	L	24	97	90	1.5	0	0	8	7
2	L	48	98	93	1.5	0	0	8	6
3	R	36	89	87	2.0	0	0	8	7
4	R	24	90	87	1.4	0	0	8	7
5	L	30	94	90	1.0	0	0	8	7
6	R	36	91	87	1.6	0	0	8	6
7	L	26	91	88	1.5	0	0	8	7
Mean		32	92.8	88.82	1.5				

[α] International Knee Documentation Committee.
[β] Anteromedial (AM)bundle.
[γ] Posterolateral (PL)bundle.

tibial tunnel. The femoral tunnel was created from the inside-out using a cannulated reamer. Following the creation of the tunnel, an adequately sized tunnel dilator was introduced from the tibial tunnel to the femoral tunnel in order to smooth both of the tunnels and to test for lateral wall or roof impingement. Then, a TransFix tunnel hook (Arthrex, Naples, FL, USA) was inserted through the tibial tunnel and positioned into the femoral socket. Next, the prepare procedure and the graft were simultaneously pulled away from the knee, advancing the graft through the tibial tunnel and into the femoral tunnel. The graft was fixated to the femur using a Bio-TransFix pin (Arthrex, Naples, FL, USA), and biodegradable interference screws were used for tibial fixation.

5. Double-bundle reconstruction

For the double-bundle technique, the anteromedial (AM) femoral tunnel was first prepared through the AM portal and then the posterolateral (PL) femoral tunnel was created through the accessory AM portal. The bone bridge between the two tunnels was at least 2 mm. The two tibial tunnels were created using entry points that were separated by a distance of 1–1.5 cm, and these tunnels intra-articularly converged on the ACL ligament's footprint. The appropriately sized EndoButton CL (Smith & Nephew Endoscopy, Andover, MA, USA), as determined by the AM and PL tunnel lengths, was then attached at the end of each graft. When the tunnels were ready, the PL bundle was first positioned, followed by the AM bundle. The AM bundle was secured at 20° of flexion and the PL bundle was fixed at full extension. The graft was then checked for impingement and the knee was examined for range of motion and stability using the Lachman test.

6. Instrumentation procedures

We next examined these patients during landing and subsequent pivoting, which are demanding activities considered by many researchers to represent high-level sport activities. An optical motion analysis system (Vicon T40, Vicon Motion Systems Limited, United Kingdom) with 10 cameras was used to record the three-dimensional rotational movements of the lower extremities. Skin reflective markers (diameter: 9 mm) were placed at anatomic landmarks, including the anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial and lateral femoral epicondyle, tibial tubercle, fibular head, lateral malleolus, medial malleolus, heel, and the fifth metatarsal head of both limbs (Fig. 1). Synchronized force plate data were used to determine the capture volume.

The dynamic test was administered by a physical therapist. The patient was instructed to warm up using a defined protocol and practiced the actions twice. During the landing and pivot-running test, each patient was asked to jump off a platform (50 cm in height and 10 cm behind the force plate) and to land as naturally as possible with both feet on the force plate. After contact, they were to pivot 90° to the lateral side of the leg being tested, which acted as the core leg during pivoting. Subsequently, they were instructed to run away with maximum effort for four steps after completing the pivoting movement (Fig. 2). None of the participants reported any pain or discomfort during the experiment. The three-dimensional coordinates of every marker were exported using VICON software (Vicon NEXUS, United Kingdom), and the knee joint kinematics were then calculated.

The evaluation period was defined as the moment the foot made contact with the ground through takeoff. A three-dimensional model of the markers was reconstructed using VICON software. All calculations were conducted using a self-compiled program. The main dependent variable was the range of tibial rotation during pivoting, as defined as the difference between the lowest tibial internal rotation after landing and the highest tibial internal rotation within the foot contact period.[11]

Based on our study, the dependent variable examined in the present study was the maximum range of tibial rotation during the identified evaluation period. The dependent t test was used to compare the ACL-reconstructed leg with the contralateral intact leg within the single- and double-bundle groups. Subsequently, one-way analysis of variance was performed to compare the dependent variable in each of the four groups (single- and double-reconstruction groups and the deficient and healthy control groups) using post hoc comparisons. The level of statistical significance was set to $p < 0.05$.

7. Results

All of the participants in the two ACL-reconstructed groups were satisfied with the functional outcome of the surgery. The modified Lysholm score was 89.67 (range: 85–93) for the single-bundle ACL

Fig. 1. Test setup. The entire retroreflective marker set used to collect motion data on the lower extremities is shown.

reconstructed group and 88.82 (range: 84–93) for the double-bundle ACL reconstructed group. All of the reconstructed knees regained objective stability, demonstrating negative Lachman and pivot-shift test results.

The calculated range of movement that was used as the dependent variable was also determined (Fig. 3). During the pivoting phase of the landing and pivot-running test, the range of tibial rotation was higher in ACL-deficient knees ($13.5^\circ \pm 3.7^\circ$) than the healthy knees ($6.5^\circ \pm 3.5^\circ$). Increased rotation was significantly reduced in the single-bundle ACL reconstructed knees ($7.8^\circ \pm 3.4^\circ$) and the double-bundle ACL reconstructed knees ($7.5^\circ \pm 2.6^\circ$; $p < 0.05$). There was no postoperative significant difference in terms of tibial rotation between the intact knee and the single-bundle or double-bundle ACL reconstructed knees after >2 years ($p > 0.05$; Fig. 4).

8. Discussion

In this study, we found increased tibial rotation in ACL-deficient knees and restoration of this status was confirmed after ACL reconstruction using both the single- and double-bundle techniques. This difference between healthy and deficient knees supports the notion that the ACL plays a major role in knee joint stabilization, whereas the decreased tibial rotation and adequate statistical power of the two reconstructed groups support the notion that the reconstruction procedure adequately eliminates any defect.

Some *in vitro* research[2,16,17]has indicated that tibial translation is restored after ACL reconstruction but that tibial rotation is not improved. Anatomic ACL reconstruction aims to reconstruct the original ACL and restore normal kinematics across all six degrees of freedom, including axial rotation, and double-bundle reconstruction, in which the AM and PL bundles are both reconstructed, aims to restore the original ACL anatomy. In theory, anatomic double-bundle reconstruction has several advantages over single-bundle reconstruction and can provide a structure that more closely resembles the normal ACL. Muneta et al[18] reported their clinical results after performing the double-bundle procedure with a 2-year follow-up period on 54 patients, demonstrating good anterior stability with no serious complications. This technique, however, has not been dynamically investigated. The ACL has a three-dimensional structure that consists of collagen fibrils that respond differently to various torsional stresses in the knee; however, graft tissues are structurally different from the normal ACL morphology. The graft tissue gradually changes to become an apparently normal ACL through a remodeling process that occurs over a long period of time,[18–20] but it seems very unlikely that the graft will regain the normal three-dimensional structure with normal mechanical properties, regardless if the single- or double-bundle graft is performed. This is a problem that needs to be resolved.

In two studies that used protocols that were similar to the present study,[11,12] the tibial rotation of the deficient knee was significantly higher than that of the intact knee. In the study by Lam et al,[13] participants were instructed to run after the pivoting movement, similar to our study, and their conclusion indicated that double-bundle ACL reconstruction successfully restores knee rotational stability from an impaired level. Other studies that employed different functional activities, such as downhill running[14] and single-leg hopping,[15] have demonstrated abnormal rotational motion after ACL reconstruction. In our study, the single- and double-bundle reconstructed groups demonstrated post-operative knee rotational stability for >2 years. However, the increased tibial rotation found in our study was not as high as that found in any of the previous studies, perhaps because of differences in the assessment periods and the different study designs of the control groups. In our study, the variations between the study and control groups were minimized because the contralateral intact knee was used as a control and we the designed the healthy/deficient control groups for further comparative evaluations. Because we did not measure muscle strength in the current study, however, we can only speculate on the plausibility of this relationship. During the task, we did not factor in the jump height or double-limb support during landing, which absorbs impact, or knee joint flexion in the uninjured limb; however, we believe that these factors would have a minor effects in relation to muscle strength.

A possible explanation for the results of this study may be the positioning of the graft placement in single-bundle group. In the

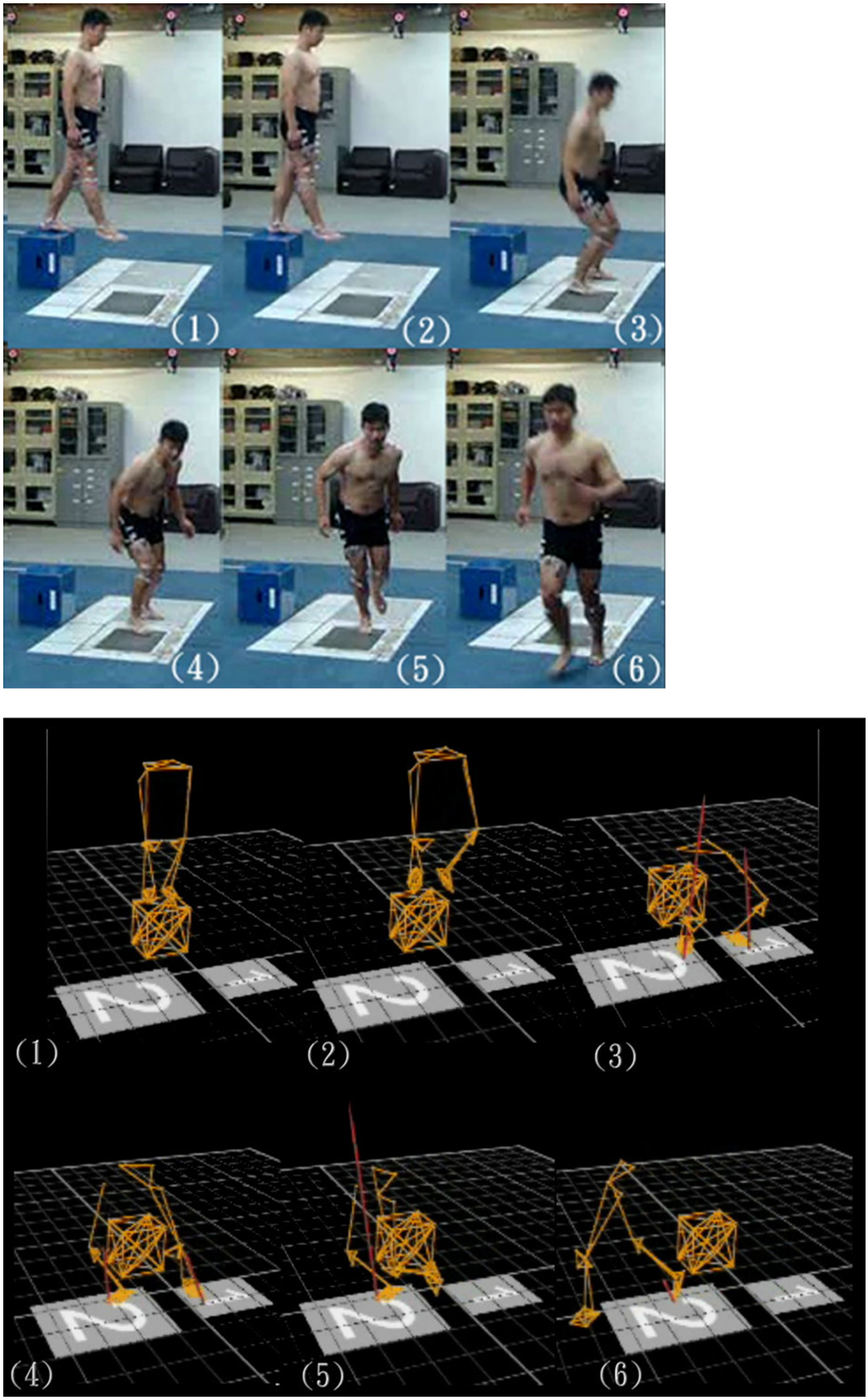

Fig. 2. Photo series showing the experimental procedure and measurement of the right knee during 1) the starting position at the initial height, 2) jumping, 3) landing, 4) pivoting, 5) push-off, and 6) running.

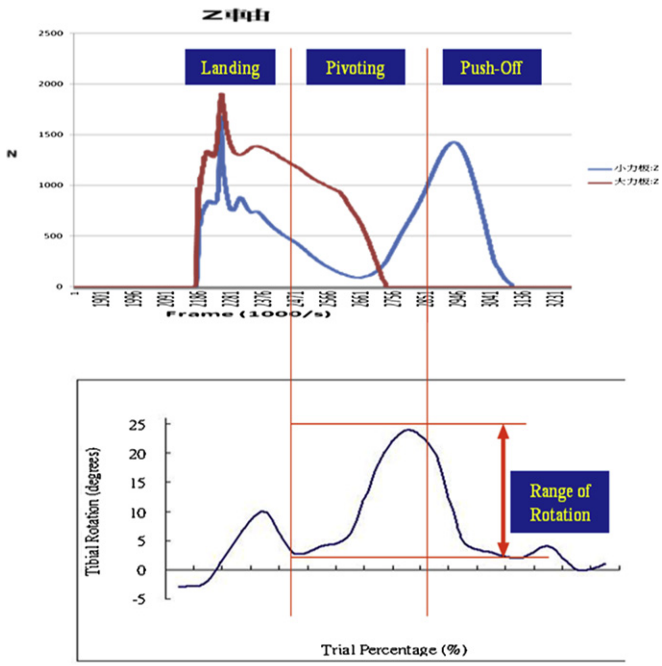

Fig. 3. Tibial internal-external rotation curve (below) of the kinematic data collected from an ACL-deficient knee through the entire experimental period. Rotational waveforms showing the forces involved during the landing, pivoting, and push-off running phases in comparison with vertical ground reaction forces (above). The focus of this study was to measure the forces involved during the pivoting phase and to record the range of rotation.

study by Woo et al,[2] the authors indicated that *in vitro* tibial rotation is not restored after ACL reconstruction when the femoral tunnel has been placed at the 11-o'clock position in order to replicate the AM bundle (not the PL bundle), thereby resulting in inadequate resistive ability to rotational force. Scopp et al[26] and Loh et al[17] have also shown that oblique tunnel placement in the femur is more appropriate than standard femoral tunnel placement, withstanding the effects of rotation, and reported that oblique femoral tunnel placement at the 10-o'clock position results in less internal tibial rotation in comparison with standard femoral tunnel placement. In our single-bundle group, we placed the femoral tunnel between the 10–11-o'clock position and a slightly wider graft size provided better coverage of the footprint of the native ACL, possibly allowing the tibia to withstand more rotational torque.

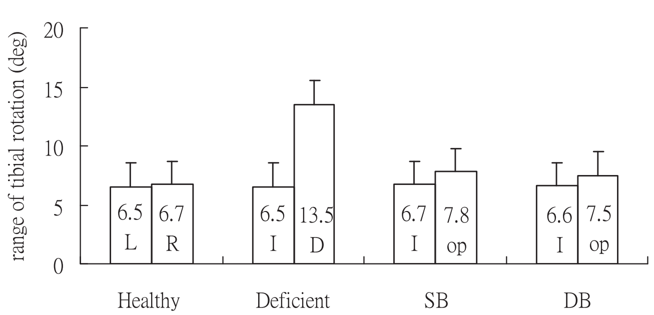

Fig. 4. Bar graph showing the mean and standard deviation values of the maximum range of motion involved in tibial internal-external rotation during the pivoting period in each of the four groups. Significant reductions are noted between the two reconstructed groups (single bundle: $7.8° \pm 3.4°$; double bundle: $7.5° \pm 2.6°$) in comparison with the deficient group ($p < 0.05$). No significant postoperative differences between the intact knees and the single-bundle or double-bundle ACL reconstructed knees were noted after >2 years of follow up ($p > 0.05$).

Several kinematic studies have employed different functional movements to evaluate patients with unilateral ACL injuries, such as vertical jumping, figure-8 movements, and the running of stairs.[21] However, the movement of a functional test should be specific to the purpose of study and involve real-life loading that is similar to the stresses human joints are exposed to during daily activities or sport-related motion. Instead, joint functional stability should be investigated through function tests such as running[14] or jumping.[15] In the present study, a high-demand sports movement was used to investigate the effects of single- and double-bundle ACL reconstruction on knee rotational stability. Stability was expressed as tibial rotation during a pivoting movement, and the results of excessive rotation before ACL reconstruction was in line with the results of a previous study.[21]

The limitations of the present study include the known drawbacks of motion analysis, including movement of the skin markers.[22] However, the marker model has been validated[23] and employed by other researchers to study similar movements.[11,24,25] During the procedure, operative error was minimized by having the same technician place the skin markers. Moreover, tibial rotation was reliably measured in a similar previous study.[24] In the present study, we used a high-demand movement to investigate the effects of the reconstructed ligament on knee rotational stability, and we consider functional testing with motion analysis to be a good tool for evaluating patients with knee joint instability after knee ligamentous injury. Moreover, it should be mentioned that our primary measured outcome (range of tibial rotation) is not a clinically relevant short-term outcome such as Lysholm or KT-1000 scoring. However, our *in vivo* model and our measurements can be used to assess surgical procedures and rehabilitation protocols with regard to rotational knee stability during dynamic activities.

9. Conclusion

By using a dynamic functional motion assessment, we are able to demonstrate that the single-bundle ACL reconstruction technique using a composite hamstring tendon graft and the double-bundle ACL reconstruction technique are adequate for restoring tibial rotation for high-demand activities such as landing and subsequent pivoting. Long-term follow-up studies are needed that focus on the effects of ACL reconstruction and the restoration of tibial rotation to preinjury levels via postoperative neuromuscular adaptations.

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