ABSTRACT

Background: The restoration of knee rotational stability after anatomical double bundle anterior cruciate ligament (ACL) reconstruction has been demonstrated in cadaveric model and passive stress test on human, but not yet in dynamic functional biomechanical test performed by human subjects.

Purpose: The purpose of the current study was to prospectively investigate the range of tibial rotation of ACL deficient and reconstructed knees during a pivoting task. It was hypothesized that there would be a significant increase in tibial internal rotation of ACL deficient knee compared to the contralateral knee, and the increased rotation would be returned to normal after anatomical double bundle ACL reconstruction.

Study design: Cohort study

Methods: Ten male subjects with unilateral ACL injury performed a high demanding jump-landing and pivoting task before and after ACL reconstruction with mean follow up of 11 months. The range of tibial rotation of the injured, reconstructed and intact knees during the pivoting movement was measured by an optical motion analysis system. Paired t-tests were performed to investigate any significant difference between the two limbs pre-operatively and post-operatively, and within the injured limb before and after the surgical treatment. Statistical significance was set at $p<0.05$ level.

Results: The range of tibial rotation was higher in ACL deficient knee than the intact knee pre-operatively ($p<0.05$). The increased rotation was reduced in the reconstructed knee after ACL reconstruction when compared to the deficient knee ($p<0.05$). There was no significant difference in the tibial rotation between the intact knee and the reconstructed knee post-operatively ($p>0.05$).

Conclusion: By assessing with a dynamic functional pivoting movement, we demonstrated that the anatomical double bundle ACL reconstruction successfully

restored knee rotational stability from an impaired level.

Keywords: Kinematics, rotational instability, rotation, ACL, double bundle

INTRODUCTION

Anterior cruciate ligament (ACL) injury leads to knee instability, mainly in anterior-posterior (AP) translation and axial internal-external rotation. It has been well documented that excessive tibial rotation would follow an ACL excision in cadaveric model[1,8,20]. Clinically, knee instability before and after ACL reconstruction is often examined subjectively by pivot shift test, in which passive valgus and internal rotation stresses are applied to the knee[18,22]. Recently, mechanical devices were developed for objective and biomechanical assessment of knee rotational laxity[21,26]. They provided an easy and non-invasive way by applying a controlled torque to the knee joint, and documenting the knee rotational abnormality. However, these clinical and biomechanical tests were measuring the passive knee joint laxity with relaxed muscles. When a patient performs a dynamic functional movement after returning to sport, it is not only the ligaments but also the muscle contractions that provide the joint stability. There is a need to conduct functional performance test to evaluate the dynamic joint stability during high demanding tasks.

The movement of functional test should be specific to the purpose of study. Several kinematics studies, which employed different dynamic movements, investigated patients with unilateral ACL injury. Andriacchi and Dyrby[3] reported that the external rotation and anterior translation were different between ACL deficient and intact knees in swing phase during walking. On treadmill running, tibial rotation increased with speed in both injured and normal knees[5]. The differences between the knees, however, were not significant. Waite and coworkers[33] suggested that low demand activity such as walking and running did not produce sufficient stress to initiate knee instability in ACL deficient knee. In a study of assessing functional stability with a high demanding movement, tibial rotation was found not to be restored after single bundle

ACL reconstruction with hamstring or patellar tendon autograft[12]. In the current study, a pivoting task was used to evaluate the effect of anatomical double bundle ACL reconstruction.

In-vitro studies showed that anatomical double bundle ACL reconstruction using hamstring graft restored both AP translation and axial rotation stability[23,37]. With this current technique, clinical studies reported good restoration of joint stability and patient-reported outcomes after a short-term follow-up[10,32]. Moreover, a few studies[2,13,16,36], which used subjective clinical tests and questionnaires for evaluation, compared between double bundle and single bundle ACL reconstruction. However, among these studies, there is limited knowledge of rotational stability as investigated by objective assessment after anatomical double bundle ACL reconstruction. On the other hand, there were studies[29,31], using dynamic functional activity, reported that single bundle ACL reconstruction could not restore rotational stability. Therefore, the purpose of the current study was to prospectively investigate the range of tibial rotation of ACL deficient and reconstructed knees during a high demanding task. The contralateral intact knee was used as a control. It was hypothesized that there would be a significant increased tibial rotation in ACL deficient knee and it would be returned to normal after anatomical double bundle ACL reconstruction.

METHOD

Subject: Ten male subjects (age = 27.2 ± 4.7yr, height = 1.76 ± 0.1m, body mass = 69.1 ± 9.2kg) with unilateral ACL injury (six right knees and four left knees) were recruited in the study. All the subjects were recruited in our sports clinic. When patients were confirmed with unilateral ACL rupture, they were scanned with exclusion criteria. ACL rupture was confirmed either by arthroscopy, magnetic resonance imaging or clinical examination. Exclusion criteria included the presence of bone fractures, complex meniscal injury, ligamentous injuries of the involved knee and previous surgery on either knee. All subjects reported knee joint instability during sports and were suggested to receive surgical treatment. All injuries were sport-related and all subjects participated at least one time per week in their sports before the injury. The preoperative and postoperative clinical data was shown in Table 1. The university ethics committee approved the study. Informed consents were obtained from each subject before the study.

Surgical technique: In all subjects, anatomical double bundle ACL reconstructions were performed by two authors who have more than 10 years experiences in performing ACL reconstruction. The operating knee was put on the operating table with a foot rest and lateral thigh support at 90 degrees of flexion. The operation was performed after inflating the tourniquet. The hamstring grafts (gracilis and semi-tendinosus) were harvested through an incision over the ipsilateral tibia and braided with ultrabraid 2 (Smith and Nephew Endoscopy, Massachusetts, USA) to each tendon grafts. A diagnostic arthroscopy was performed by using the anterolateral and anteromedial portals. After confirming the rupture of anteromedial (AM) and posterolateral (PL) bundles, the ACL stump was debrided and the foot prints of AM and PL bundles were identified and marked by radiofrequency probe. The footprint of the ACL was identified by locating the lateral intercondylar ridge and the lateral bifurcate ridge as suggested by previous studies[17,24]. The AM femoral tunnel was prepared through the anteromedial portal with the aid of a 6 mm offset guide, the guide pin was placed at the footprint of AM bundle and reamed to 4.5mm diameter for the passage of the endobutton (Smith and Nephew Endoscopy, Massachusetts, USA). It was further reamed to 6mm or 7mm diameter and the integrity of the outer cortex was preserved. The diameter and length of the tunnel depended on the graft size and the patient anatomy. After creating the tunnel for AM bundle, the knee was then flexed to 110 degrees. An accessory anteromedial portal was created according to the guidance of a spinal needle which was used to aim the footprint of the PL bundle. A 2.4 mm guide pin was inserted according to the footprint of the PL bundle. The PL femoral tunnel, which varied from 5mm to 6mm in diameter, was then created through the accessory anteromedial portal by the endobutton reamer and the 5mm or 6 mm reamer. The bone bridge between the two tunnels was at least 2mm. For the tibial tunnels of AM and PL bundles, 45° and 55° tibial jig (Smith and Nephew Endoscopy, Massachusetts, USA) was used respectively. The ACL remnant was used as a guide to identify the footprint of ACL. The tibial tunnel of PL bundle was created by inserting a 2.4 mm guide pin through a 55 degrees tibial jig. The guide pin was aimed to the footprint of ACL and around 6mm to 7mm anterior to the PCL. Another 2.4 mm guide pin was inserted through 45 degrees tibial jig, aimed around 9mm away (anterior and medial) from the guide pin for PL tunnel. According to the size of the graft, it was then further reamed to 5 or 6 mm and 6 or 7 mm in diameter for the PL and AM tibial tunnels respectively. The bone bridge between the two tibial tunnels was aimed for around 2mm. A double throws Gracilis and semitendinosis tendons were used for PL and AM bundle reconstructions respectively. Graft passage was completed for the PL bundle followed by the AM bundle. On the femoral side, PL bundle was fixed by 15mm Endobutton loop (Smith and Nephew Endoscopy, Massachusetts, USA), while AM bundle was fixed by 15mm or 20mm Endobutton loop. The PL bundle was tensioned at 15° of flexion and the AM bundle at 60° of flexion. On the tibial side, bioabsorbable interference screws were used to fix each bundle individually and staples were used to fix both grafts over the medial surface of tibia. The arthroscopic image and postoperative x-ray picture was shown in Figure 1. After ACL reconstruction, all patients completed a standard rehabilitation program[30].

Experimental procedure: All subjects were assessed before and after ACL reconstruction with a follow-up of 10.3 ± 3.9 months. An optical motion analysis system with eight cameras (VICON 624, UK) was used to record the three dimensional rotation movements of lower extremities at 120Hz capturing frequency. The system was calibrated on the same day of testing and the mean residual was less than 1mm. If not, the system was recalibrated. Synchronized force-plate (AMTI OR6-7, Massachusetts, USA) data was collected at the centre of the capture volume at 1080Hz. A fifteen-marker model[6] was adopted to collect lower limb kinematics during movements. Skin reflective markers with 9mm diameter were placed at anatomical landmarks including anterior superior iliac spines (ASIS), sacrum, greater trochanter, femoral epicondyle, tibial tubercle, lateral malleolus, heel and fifth metatarsal head on both limbs. Anthropometric data including body mass, ASIS breadth, thigh and calf length, midthigh and calf circumference, knee diameter, foot breadth and length, malleolus height and diameter were measured for kinematics calculation. The reliability of the overall procedure was reported to be less than 2.4 degrees for within day measures[34].

Experimental task: Before performing the movement, a trial of standing anatomical position was recorded. Every subject was instructed by the same tester to stand with both feet in shoulder width and align the shank and foot segment to a neutral position. This calibration file provided a definition of zero degree for all segmental movements. Both limbs were tested individually. The subjects were asked to leave off a platform, which was 40cm height and placed 10cm behind the force plate, and land with both feet on the ground, with only the testing foot on the force-plate. After the foot contact, the subjects pivoted 90 degrees to the lateral side of testing leg, which also acted as the core leg during pivoting. The subjects were instructed to run away with their maximum effort for three steps after completing the pivoting movement (Figure 2).

Data collection and reduction: The evaluation period was defined from the first foot contact to the take-off of the testing leg on the ground. A foot contact was determined by the force plate when the vertical ground reaction force exceeded 5% of the subject's body weight. Three dimensional coordinates of every marker were exported from the VICON software. Together with the anthropometric measurements, the knee joint kinematics was then calculated[6]. All calculations were conducted using self compiled program (Mathworks, Massachusetts, USA). The main dependent variable in the current study was range of tibial rotation during pivoting movement, which was defined as the difference between the lowest tibial internal rotation after landing and the highest tibial internal rotation within the foot contact period[29].

Data analysis: Paired t-tests were performed to investigate any significant difference between the two limbs pre-operatively and post-operatively, and within the injured limb before and after the anatomical double bundle ACL reconstruction. Power analysis was conducted if there was no significant difference between the reconstructed knee and the intact knee after reconstruction. The level of significance and study power were set at 0.05 and 0.8 respectively.

RESULTS

During the pivoting phase, the tibia internally rotated to a maximum degree (Figure 3). For the range of tibial rotation, there was a significant (P=0.005) increase in the deficient knee (12.6 ± 4.5 degrees) when compared to the intact knee (7.9 ± 3.1 degrees) pre-operatively. This increased tibial rotation significantly (p=0.035) decreased to 8.9 ± 3.0 degrees in the reconstructed knee and did not differ to that of intact knee (8.2 ± 2.6 degrees) after ACL reconstruction (Figure 4). Since there was no significant difference between the reconstructed knee and the intact knee after reconstruction, power analysis was conducted (true difference: 2 degrees; correlation: 0.27) and the statistical power was reported to be 0.81 between the two groups.

DISCUSSION

In this study, the increased tibial rotational movement in ACL deficient knee and the restoration of this movement after ACL reconstruction were demonstrated. The different between intact and deficient knees of the current study supported the first hypothesis while the decreased tibial rotation and the adequate statistical power also support the second hypothesis of this study.

Our findings supported previous studies[7,12,29,31] that showed knee rotational instability of ACL deficient knee and reconstructed knee with single bundle technique. In two studies[12,29] with similar protocol to the present study, the tibial rotation of deficient knee was significantly higher than that of intact knee. While those subjects were instructed to walk followed by the pivoting movement, our subjects were instructed to run instead. We believed that the task in our study provided a higher rotational stress to the knee. However, the increased tibial rotation found in the current study was not as high as that in these two previous studies. It might be due to the difference in the time from injury to assessment. The subjects recruited in this study were acute injury cases and those in the two studies were chronic injury cases. The subjects in this study might perform cautiously in the preoperative assessment. Another studies employing different functional activities such as downhill running[31] and single leg hopping[7] also showed abnormal rotational motion after ACL reconstruction. When comparing the study design, all the subjects in our study were assessed prospectively before and after ACL reconstruction. The variations between study group and control group were minimized to affect the result as contralateral intact knee was used as a control.

Anatomic ACL reconstruction[15] aims to reconstruct the original ACL with normal kinematics in all six degree of freedom, including mediolateral and anteroposterior translation, and axial rotation. However, in vitro[4,19,35] and in vivo[7,12,29,31] studies showed that tibial rotation was not restored by single bundle ACL reconstruction. One of the reasons suggested that only AM bundle was replicated, resulting in insufficient rotational control to the knee. In the current study, all subjects were treated with anatomical double bundle ACL reconstruction, in which both AM and PL bundles were reconstructed to mimic the original ACL anatomy. In addition to the AM bundle, PL bundle might provide a role in the stabilization of the knee against a combined rotatory load[11]. When evaluating double bundle ACL reconstruction with a high demanding movement in this study, the significant decrease in range of tibial rotation of the reconstructed knee suggested the effectiveness of rotational control of such anatomical reconstruction. To better demonstrate the superiority of double bundle technique as well as the effect of PL bundle, future study with large scale randomized controlled trial comparing the effect of single bundle and double bundle ACL reconstruction on functional stability was suggested.

Functional test should be the ultimate step for evaluating ACL reconstruction since it involves real-life loading that human joints are exposed to in daily activity or even sport motion. Although dynamic functional test was commonly employed[9], previous studies, however, mainly focused on functional performance. Muscle strength was one of the performance indexes during rehabilitation, in which there were positive association between thigh muscles and functional outcome of the knee[25]. Other functional tests such as vertical jump, figure of eight and stairs running were used as assessment after ACL reconstruction[28]. All these functional outcomes were expressed as strength and ability that a patient would achieve. Instead, joint functional stability should be investigated through function test such as running[31] and jumping[7]. In the present study, a high demanding sport movement was used to investigate the effect of anatomical double bundle ACL reconstruction on knee rotational stability. The stability was expressed as tibial rotation during a pivoting movement and the result of excessive rotation before ACL reconstruction was in line with previous study[28]. Functional test with motion analysis would be a good tool to evaluate patients with knee instability, such as after knee ligamentous injury.

The limitation in the present study involved known drawbacks of motion analysis, including the movement of skin markers[27]. During the procedure, the inter-tester error was minimized by having the same technician placing the skin markers and measuring all anthropometric data. A standing offset trial to define zero degree for all segmental movements was collected to avoid subtle misalignment of the knee joint. Moreover, it was reported that tibial rotation was reliably measured in a similar previous study[34]. Typical error values (<2.9°) were less than the usual group differences in rotational excursion reported in the literature. Furthermore, to avoid variation in the complicated surgical technique[14] between different surgeons, two experienced orthopaedic surgeons preformed all reconstructions in this study. Lastly, to avoid unnecessarily subject variations the current study employed a prospective cohort design, in which the same injury knee was compared before and after the reconstruction. The intact knee of the same individual was used as a control.

CONCLUSION

It was concluded that there was an increased tibial rotation in ACL deficient knee. By using a dynamic functional biomechanical assessment in this study, we demonstrated that the reconstructed knee by anatomical double bundle ACL reconstruction successfully restored functional knee rotational stability during a pivoting movement.

FIGURE CAPTIONS

Figure 1: The arthroscopic images (1, ACL footprint of femoral side at 90 degrees of knee flexion; 2, femoral tunnels at 110 degrees of knee flexion, viewed from anteromedial portal; 3, tibial tunnels created by insertion 2 guide pins by tibial jig at 55 and 45 degrees for PL and AM bundles respectively; 4, graft passage viewed from anterolateral portal) and postoperative x-ray picture of the anatomical double bundle ACL reconstruction.

Figure 2: The video sequence (1, initial position; 2, jumping; 3, landing; 4, pivoting; 5, push-off; 6, running) of the jump-landing and pivoting task, assessing the right knee of the patient.

Figure 3: Vertical ground reaction force (top), knee flexion (middle) and tibial rotation (bottom) during the entire stance phase of the high demanding jump-landing and pivoting task from one typical ACL deficient knee.

Figure 4: Range of tibial rotation during pivoting movement before and after ACL reconstruction. Asterisks (*) indicate a significant difference suggested by paired t-test ($p=0.005$ for pre-op intact and pre-op deficient; $p=0.035$ for pre-op deficient and post-op reconstructed).

TABLE CAPTIONS

Table 1: Preoperative and postoperative clinical data of all subjects.

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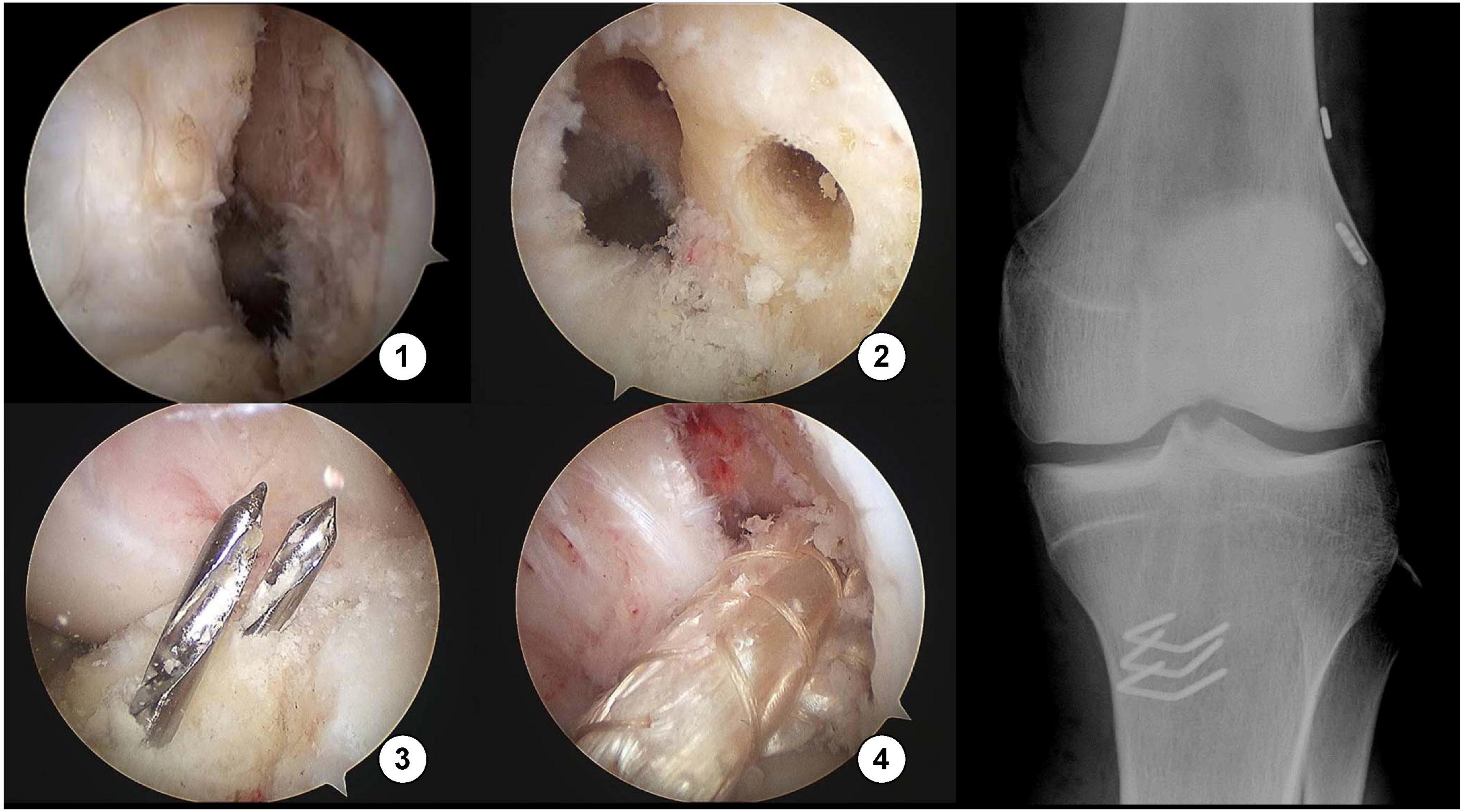
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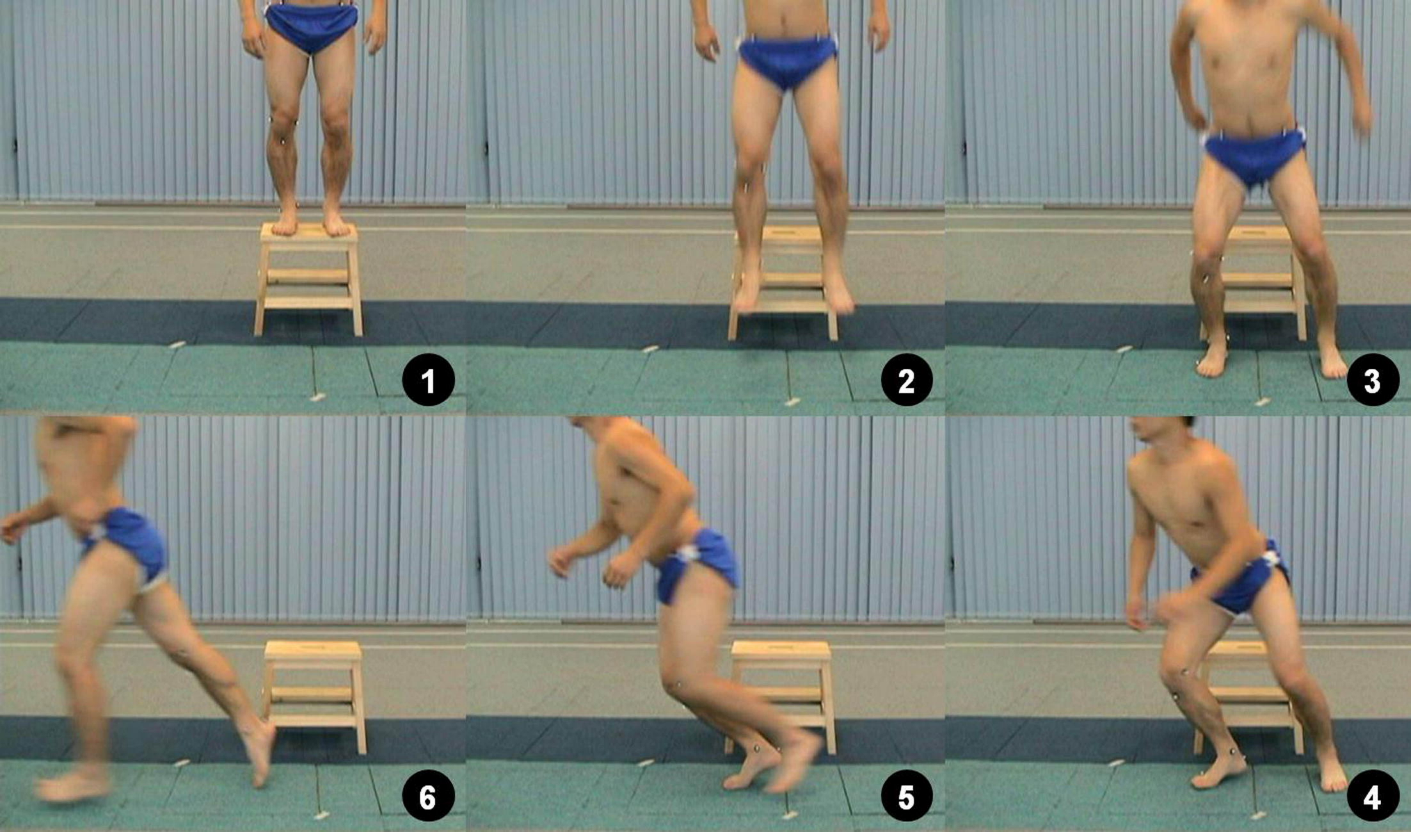
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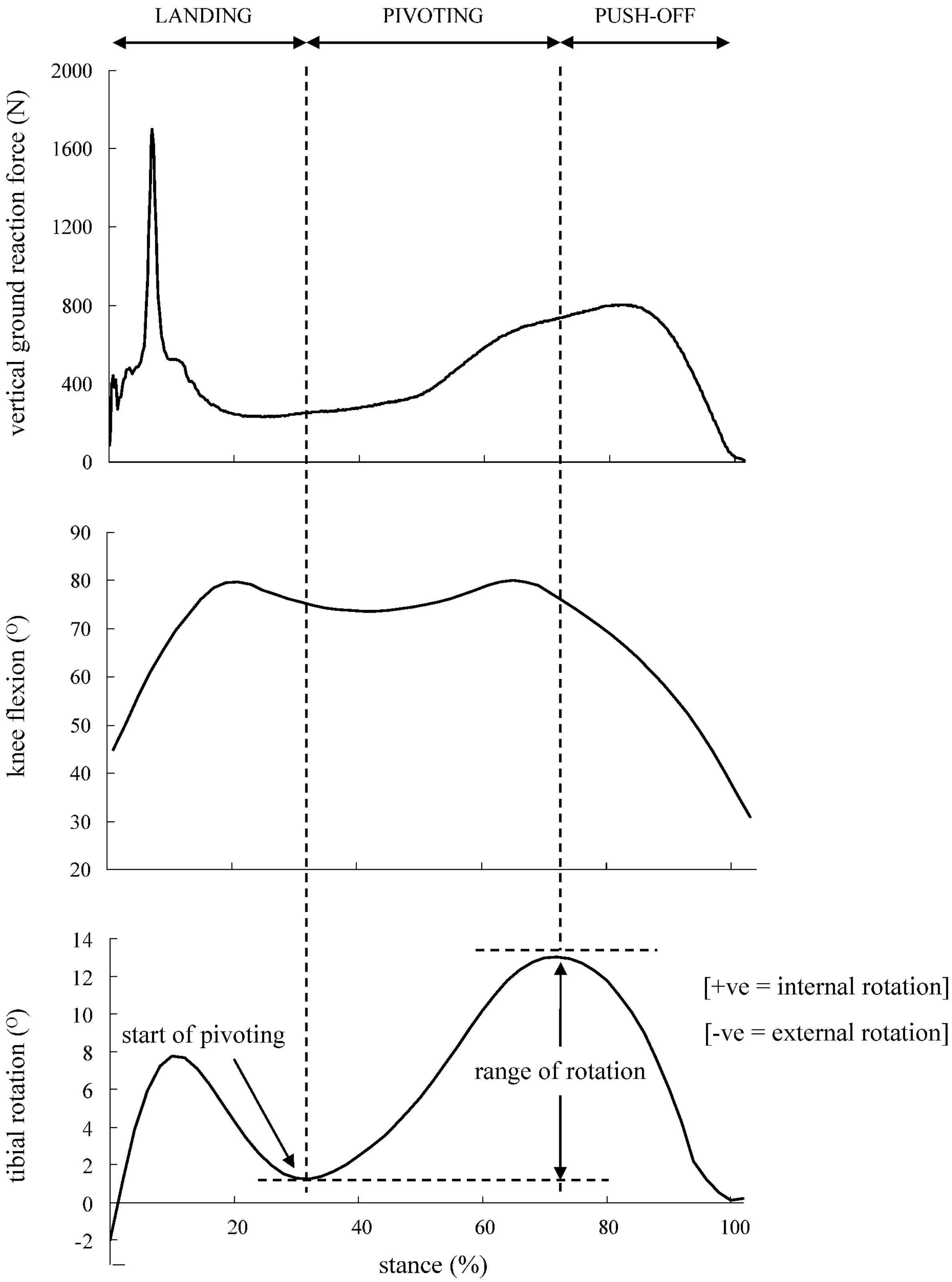
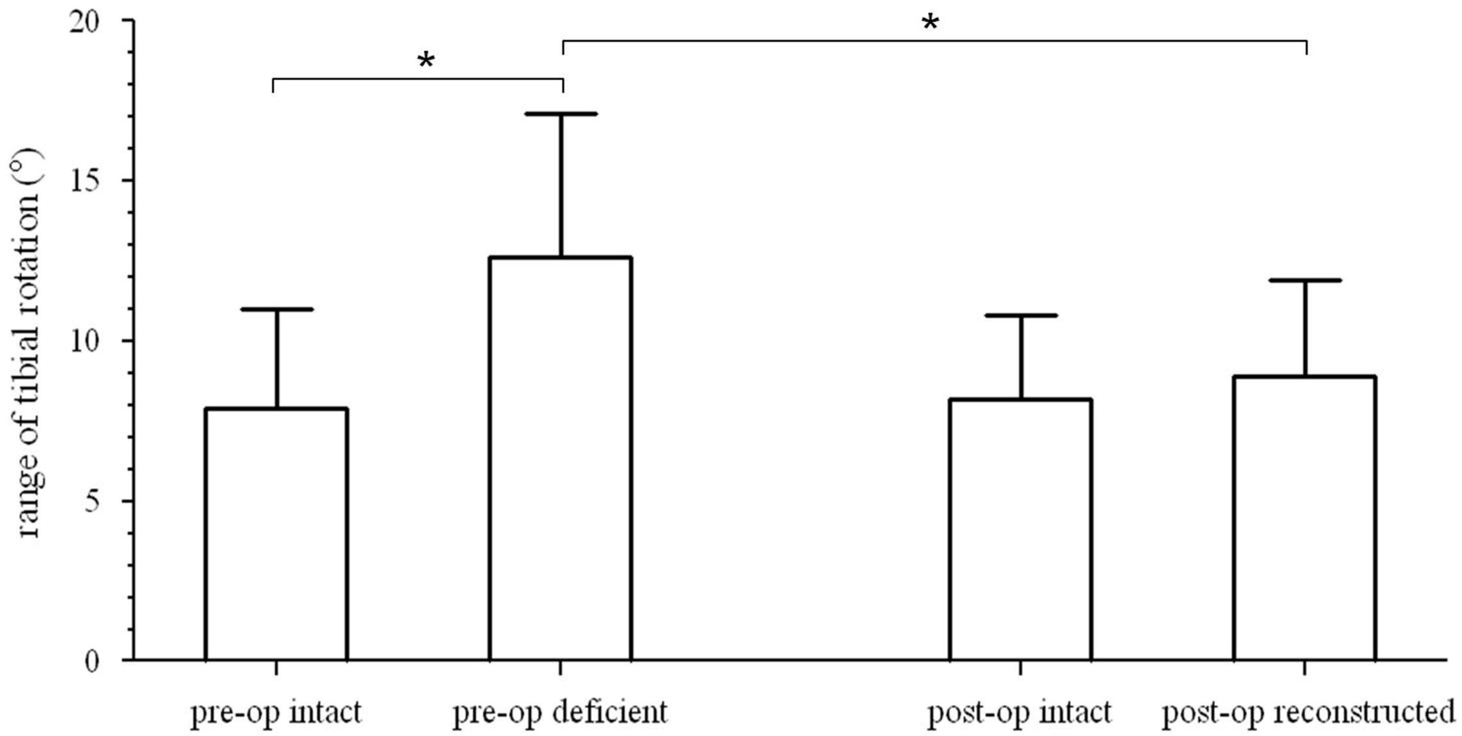


LANDING
PIVOTING
PUSH-OFF
vertical ground reaction force (N)
2000
1600
1200
800
400
0
knee flexion (°)
90
80
70
60
50
40
30
20
tibial rotation (°)
14
12
10
8
6
4
2
0
-2
start of pivoting
range of rotation
[+ve = internal rotation]
[-ve = external rotation]
20
40
60
80
100
stance (%)



range of tibial rotation (°)
0
5
10
15
20
*
*
pre-op intact
pre-op deficient
post-op intact
post-op reconstructed

Subject	Injured knee	Time from injury to pre-op assessment (month)	Time from surgery to post-op assessment (month)	Preoperative assessment						Postoperative assessment					
				IKDC	Lysholm	KT1000 (mm)*	Lachman test	Anterior drawer test	Pivot shift test	IKDC	Lysholm	KT1000 (mm)*	Lachman test	Anterior drawer test	Pivot shift test
Lui MW	L	11	7	47.1	90	8.5	3	2	2	100	99	1.5	0	0	0
Lam SP	R	3	18	74.7	85	4.5	3	3	2	100	100	0	0	0	0
Lam WK	L	5	10	74.7	85	5.5	3	2	2	79.3	99	1.5	0	0	0
Chan SY	L	4	12	74.7	80	2.5	3	3	2	80.5	100	2.5	0	0	0
Mak KL	R	9	7	74.7	85	8.5	3	2	3	74.8	90	3	1	1	0
Lam CK	R	5	15	79.3	84	0	3	2	2	100	98	1	0	0	0
Lam C	L	5	7	69	80	3.5	2	2	1	100	100	1.5	0	1	1
Fung SW	R	4	12	73.6	80	4.5	3	3	2	93.3	98	1.5	0	0	0
Chan CK	R	2	7	73.6	75	5.5	3	3	3	100	100	1	0	0	0
Yu CY	R	3	8	66.7	85	7	3	3	2	93.3	90	6	1	1	1
Mean(SD)	-	5.1(2.8)	10.3(3.9)	70.8(9.0)	82.9(4.2)	5.0(2.6)	-	-	-	92.1(10.1)	97.4(4.0)	2.0(1.6)	-	-	-

* Difference between both knees at 30 lb anterior force.