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Effect of anticipation on knee kinematics during a stop-jump task

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1 **ABSTRACT**

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

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

11 **Study design:** Cohort study

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

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

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

27 restored knee rotational stability from an impaired level.

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

29 **INTRODUCTION**

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

44

45 The movement of functional test should be specific to the purpose of study. Several
46 kinematics studies, which employed different dynamic movements, investigated
47 patients with unilateral ACL injury. Andriacchi and Dyrby³ reported that the external
48 rotation and anterior translation were different between ACL deficient and intact knees
49 in swing phase during walking. On treadmill running, tibial rotation increased with
50 speed in both injured and normal knees⁵. The differences between the knees,
51 however, were not significant. Waite and coworkers³³ suggested that low demand
52 activity such as walking and running did not produce sufficient stress to initiate knee
53 instability in ACL deficient knee. In a study of assessing functional stability with a high
54 demanding movement, tibial rotation was found not to be restored after single bundle

55 ACL reconstruction with hamstring or patellar tendon autograft¹². In the current study,
56 a pivoting task was used to evaluate the effect of anatomical double bundle ACL
57 reconstruction.

58

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

74

75 **METHOD**

76 **Subject:** Ten male subjects (age = 27.2 ± 4.7 yr, height = 1.76 ± 0.1 m, body mass =
77 69.1 ± 9.2 kg) with unilateral ACL injury (six right knees and four left knees) were
78 recruited in the study. All the subjects were recruited in our sports clinic. When
79 patients were confirmed with unilateral ACL rupture, they were scanned with exclusion
80 criteria. ACL rupture was confirmed either by arthroscopy, magnetic resonance

81 imaging or clinical examination. Exclusion criteria included the presence of bone
82 fractures, complex meniscal injury, ligamentous injuries of the involved knee and
83 previous surgery on either knee. All subjects reported knee joint instability during
84 sports and were suggested to receive surgical treatment. All injuries were
85 sport-related and all subjects participated at least one time per week in their sports
86 before the injury. The preoperative and postoperative clinical data was shown in Table
87 1. The university ethics committee approved the study. Informed consents were
88 obtained from each subject before the study.

89

90 **Surgical technique:** In all subjects, anatomical double bundle ACL reconstructions
91 were performed by two authors who have more than 10 years experiences in
92 performing ACL reconstruction. The operating knee was put on the operating table
93 with a foot rest and lateral thigh support at 90 degrees of flexion. The operation was
94 performed after inflating the tourniquet. The hamstring grafts (gracilis and
95 semi-tendinosus) were harvested through an incision over the ipsilateral tibia and
96 braided with ultrabraid 2 (Smith and Nephew Endoscopy, Massachusetts, USA) to
97 each tendon grafts. A diagnostic arthroscopy was performed by using the anterolateral
98 and anteromedial portals. After confirming the rupture of anteromedial (AM) and
99 posterolateral (PL) bundles, the ACL stump was debrided and the foot prints of AM
100 and PL bundles were identified and marked by radiofrequency probe. The footprint of
101 the ACL was identified by locating the lateral intercondylar ridge and the lateral
102 bifurcate ridge as suggested by previous studies^{17,24}. The AM femoral tunnel was
103 prepared through the anteromedial portal with the aid of a 6 mm offset guide, the
104 guide pin was placed at the footprint of AM bundle and reamed to 4.5mm diameter for
105 the passage of the endobutton (Smith and Nephew Endoscopy, Massachusetts, USA).
106 It was further reamed to 6mm or 7mm diameter and the integrity of the outer cortex

107 was preserved. The diameter and length of the tunnel depended on the graft size and
108 the patient anatomy. After creating the tunnel for AM bundle, the knee was then flexed
109 to 110 degrees. An accessory anteromedial portal was created according to the
110 guidance of a spinal needle which was used to aim the footprint of the PL bundle. A
111 2.4 mm guide pin was inserted according to the footprint of the PL bundle. The PL
112 femoral tunnel, which varied from 5mm to 6mm in diameter, was then created through
113 the accessory anteromedial portal by the endobutton reamer and the 5mm or 6 mm
114 reamer. The bone bridge between the two tunnels was at least 2mm. For the tibial
115 tunnels of AM and PL bundles, 45° and 55° tibial jig (Smith and Nephew Endoscopy,
116 Massachusetts, USA) was used respectively. The ACL remnant was used as a guide
117 to identify the footprint of ACL. The tibial tunnel of PL bundle was created by inserting
118 a 2.4 mm guide pin through a 55 degrees tibial jig. The guide pin was aimed to the
119 footprint of ACL and around 6mm to 7mm anterior to the PCL. Another 2.4 mm guide
120 pin was inserted through 45 degrees tibial jig, aimed around 9mm away (anterior and
121 medial) from the guide pin for PL tunnel. According to the size of the graft, it was then
122 further reamed to 5 or 6 mm and 6 or 7 mm in diameter for the PL and AM tibial
123 tunnels respectively. The bone bridge between the two tibial tunnels was aimed for
124 around 2mm. A double throws Gracilis and semitendinosis tendons were used for PL
125 and AM bundle reconstructions respectively. Graft passage was completed for the PL
126 bundle followed by the AM bundle. On the femoral side, PL bundle was fixed by 15mm
127 Endobutton loop (Smith and Nephew Endoscopy, Massachusetts, USA), while AM
128 bundle was fixed by 15mm or 20mm Endobutton loop. The PL bundle was tensioned
129 at 15° of flexion and the AM bundle at 60° of flexion. On the tibial side, bioabsorbable
130 interference screws were used to fix each bundle individually and staples were used
131 to fix both grafts over the medial surface of tibia. The arthroscopic image and

132 postoperative x-ray picture was shown in Figure 1. After ACL reconstruction, all
133 patients completed a standard rehabilitation program³⁰.

134

135 **Experimental procedure:** All subjects were assessed before and after ACL
136 reconstruction with a follow-up of 10.3 ± 3.9 months. An optical motion analysis
137 system with eight cameras (VICON 624, UK) was used to record the three
138 dimensional rotation movements of lower extremities at 120Hz capturing frequency.
139 The system was calibrated on the same day of testing and the mean residual was less
140 than 1mm. If not, the system was recalibrated. Synchronized force-plate (AMTI OR6-7,
141 Massachusetts, USA) data was collected at the centre of the capture volume at
142 1080Hz. A fifteen-marker model⁶ was adopted to collect lower limb kinematics during
143 movements. Skin reflective markers with 9mm diameter were placed at anatomical
144 landmarks including anterior superior iliac spines (ASIS), sacrum, greater trochanter,
145 femoral epicondyle, tibial tubercle, lateral malleolus, heel and fifth metatarsal head on
146 both limbs. Anthropometric data including body mass, ASIS breadth, thigh and calf
147 length, midthigh and calf circumference, knee diameter, foot breadth and length,
148 malleolus height and diameter were measured for kinematics calculation. The
149 reliability of the overall procedure was reported to be less than 2.4 degrees for within
150 day measures³⁴.

151

152 **Experimental task:** Before performing the movement, a trial of standing anatomical
153 position was recorded. Every subject was instructed by the same tester to stand with
154 both feet in shoulder width and align the shank and foot segment to a neutral position.
155 This calibration file provided a definition of zero degree for all segmental movements.
156 Both limbs were tested individually. The subjects were asked to leave off a platform,
157 which was 40cm height and placed 10cm behind the force plate, and land with both

158 feet on the ground, with only the testing foot on the force-plate. After the foot contact,
159 the subjects pivoted 90 degrees to the lateral side of testing leg, which also acted as
160 the core leg during pivoting. The subjects were instructed to run away with their
161 maximum effort for three steps after completing the pivoting movement (Figure 2).

162

163 **Data collection and reduction:** The evaluation period was defined from the first foot
164 contact to the take-off of the testing leg on the ground. A foot contact was determined
165 by the force plate when the vertical ground reaction force exceeded 5% of the
166 subject's body weight. Three dimensional coordinates of every marker were exported
167 from the VICON software. Together with the anthropometric measurements, the knee
168 joint kinematics was then calculated⁶. All calculations were conducted using self
169 compiled program (Mathworks, Massachusetts, USA). The main dependent variable
170 in the current study was range of tibial rotation during pivoting movement, which was
171 defined as the difference between the lowest tibial internal rotation after landing and
172 the highest tibial internal rotation within the foot contact period²⁹.

173

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

180

181 **RESULTS**

182 During the pivoting phase, the tibia internally rotated to a maximum degree (Figure 3).

183 For the range of tibial rotation, there was a significant ($P=0.005$) increase in the

184 deficient knee (12.6 ± 4.5 degrees) when compared to the intact knee (7.9 ± 3.1
185 degrees) pre-operatively. This increased tibial rotation significantly ($p=0.035$)
186 decreased to 8.9 ± 3.0 degrees in the reconstructed knee and did not differ to that of
187 intact knee (8.2 ± 2.6 degrees) after ACL reconstruction (Figure 4). Since there was
188 no significant difference between the reconstructed knee and the intact knee after
189 reconstruction, power analysis was conducted (true difference: 2 degrees; correlation:
190 0.27) and the statistical power was reported to be 0.81 between the two groups.

191

192 **DISCUSSION**

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

198

199 Our findings supported previous studies^{7,12,29,31} that showed knee rotational instability
200 of ACL deficient knee and reconstructed knee with single bundle technique. In two
201 studies^{12,29} with similar protocol to the present study, the tibial rotation of deficient
202 knee was significantly higher than that of intact knee. While those subjects were
203 instructed to walk followed by the pivoting movement, our subjects were instructed to
204 run instead. We believed that the task in our study provided a higher rotational stress
205 to the knee. However, the increased tibial rotation found in the current study was not
206 as high as that in these two previous studies. It might be due to the difference in the
207 time from injury to assessment. The subjects recruited in this study were acute injury
208 cases and those in the two studies were chronic injury cases. The subjects in this
209 study might perform cautiously in the preoperative assessment. Another studies

210 employing different functional activities such as downhill running³¹ and single leg
211 hopping⁷ also showed abnormal rotational motion after ACL reconstruction. When
212 comparing the study design, all the subjects in our study were assessed prospectively
213 before and after ACL reconstruction. The variations between study group and control
214 group were minimized to affect the result as contralateral intact knee was used as a
215 control.

216

217 Anatomic ACL reconstruction¹⁵ aims to reconstruct the original ACL with normal
218 kinematics in all six degree of freedom, including mediolateral and anteroposterior
219 translation, and axial rotation. However, in vitro^{4,19,35} and in vivo^{7,12,29,31} studies showed
220 that tibial rotation was not restored by single bundle ACL reconstruction. One of the
221 reasons suggested that only AM bundle was replicated, resulting in insufficient
222 rotational control to the knee. In the current study, all subjects were treated with
223 anatomical double bundle ACL reconstruction, in which both AM and PL bundles were
224 reconstructed to mimic the original ACL anatomy. In addition to the AM bundle, PL
225 bundle might provide a role in the stabilization of the knee against a combined rotatory
226 load¹¹. When evaluating double bundle ACL reconstruction with a high demanding
227 movement in this study, the significant decrease in range of tibial rotation of the
228 reconstructed knee suggested the effectiveness of rotational control of such
229 anatomical reconstruction. To better demonstrate the superiority of double bundle
230 technique as well as the effect of PL bundle, future study with large scale randomized
231 controlled trial comparing the effect of single bundle and double bundle ACL
232 reconstruction on functional stability was suggested.

233

234 Functional test should be the ultimate step for evaluating ACL reconstruction since it
235 involves real-life loading that human joints are exposed to in daily activity or even

236 sport motion. Although dynamic functional test was commonly employed⁹, previous
237 studies, however, mainly focused on functional performance. Muscle strength was
238 one of the performance indexes during rehabilitation, in which there were positive
239 association between thigh muscles and functional outcome of the knee²⁵. Other
240 functional tests such as vertical jump, figure of eight and stairs running were used as
241 assessment after ACL reconstruction²⁸. All these functional outcomes were expressed
242 as strength and ability that a patient would achieve. Instead, joint functional stability
243 should be investigated through function test such as running³¹ and jumping⁷. In the
244 present study, a high demanding sport movement was used to investigate the effect of
245 anatomical double bundle ACL reconstruction on knee rotational stability. The stability
246 was expressed as tibial rotation during a pivoting movement and the result of
247 excessive rotation before ACL reconstruction was in line with previous study²⁸.
248 Functional test with motion analysis would be a good tool to evaluate patients with
249 knee instability, such as after knee ligamentous injury.

250

251 The limitation in the present study involved known drawbacks of motion analysis,
252 including the movement of skin markers²⁷. During the procedure, the inter-tester error
253 was minimized by having the same technician placing the skin markers and
254 measuring all anthropometric data. A standing offset trial to define zero degree for all
255 segmental movements was collected to avoid subtle misalignment of the knee joint.
256 Moreover, it was reported that tibial rotation was reliably measured in a similar
257 previous study³⁴. Typical error values ($<2.9^{\circ}$) were less than the usual group
258 differences in rotational excursion reported in the literature. Furthermore, to avoid
259 variation in the complicated surgical technique¹⁴ between different surgeons, two
260 experienced orthopaedic surgeons preformed all reconstructions in this study. Lastly,

261 to avoid unnecessarily subject variations the current study employed a prospective
262 cohort design, in which the same injury knee was compared before and after the
263 reconstruction. The intact knee of the same individual was used as a control.

264

265 **CONCLUSION**

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

270 **FIGURE CAPTIONS**

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

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

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

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

287 **TABLE CAPTIONS**

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

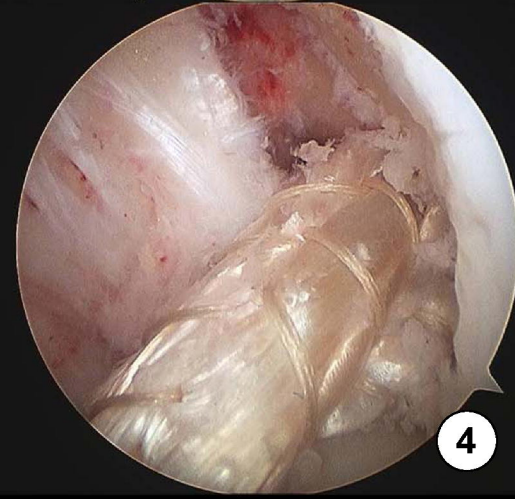
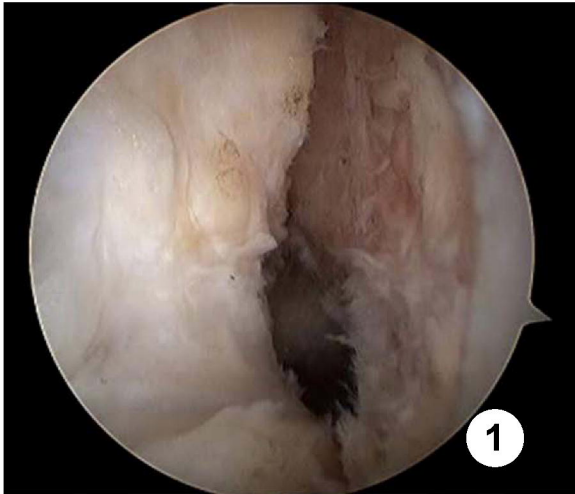
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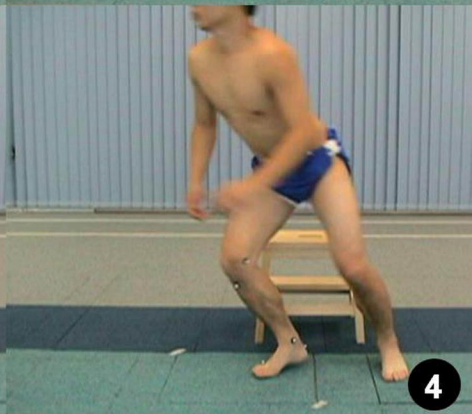
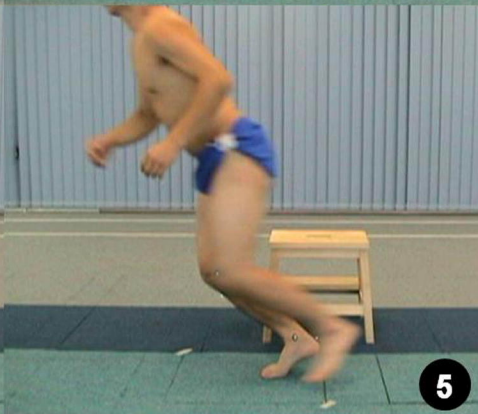
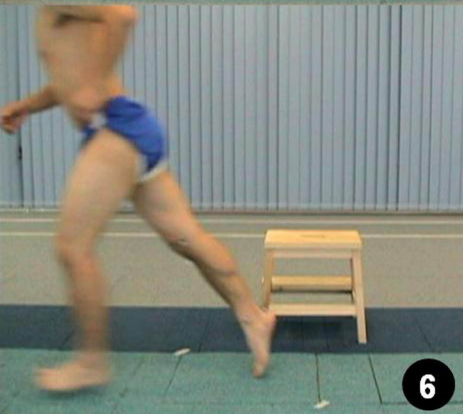
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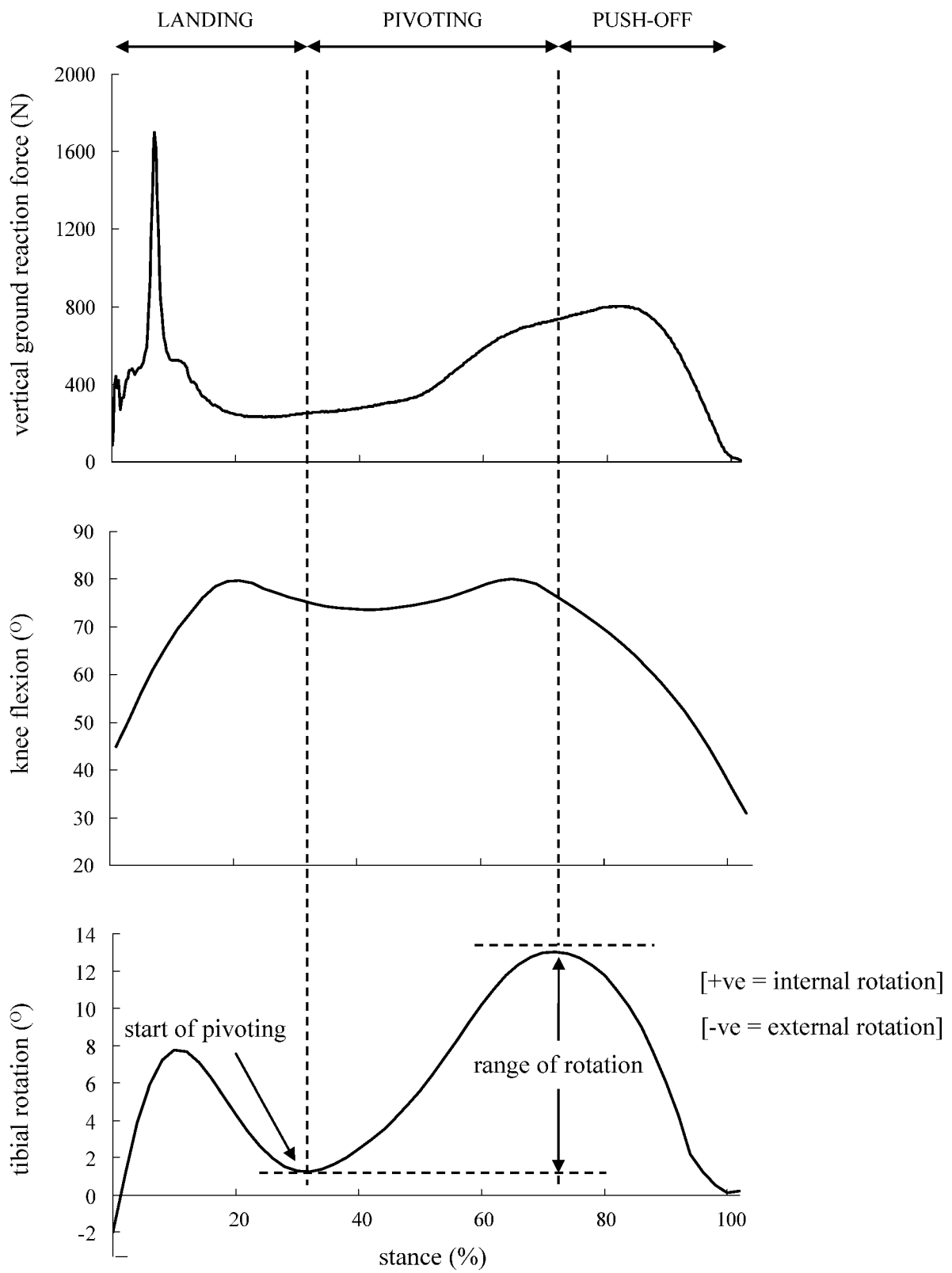
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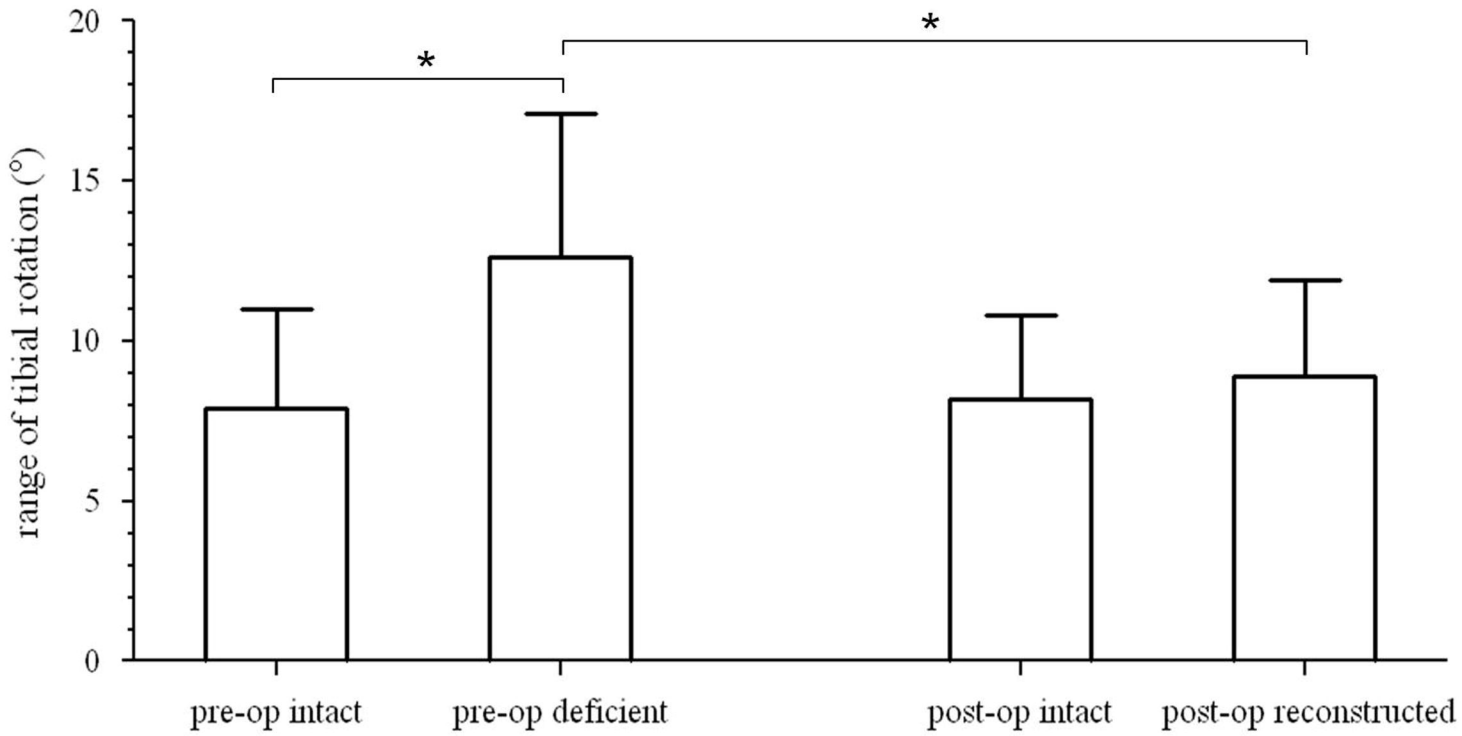
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Subject	Injured knee	Time from injury to pre-op assessment (month)	Time from surgery to post-op assessment (month)	Preoperative assessment						Postoperative assessment					
				IKDC	Lysholm	KT1000 (mm)*	Lachman test	Anterior drawer test	Pivot shift 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.