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Short communication

Kinematic motion of the anterior cruciate ligament deficient knee during functionally high and low demanding tasks

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ABSTRACT

The purpose of this study was to determine whether mechanical adaptations were present in patients with anterior cruciate ligament (ACL)-deficient knees during high-demand activities. Twenty-two subjects with unilateral ACL deficiency (11 males and 11 females, 19.6 months after injury) performed five different activities at a comfortable speed (level walking, ascending and descending steps, jogging, jogging to a 90-degree side cutting toward the opposite direction of the tested side). Three-dimensional knee kinematics for the ACL-deficient knees and uninjured contralateral knees were evaluated using the Point Cluster Technique. There was no significant difference in knee flexion angle, but an offset toward the knee in less valgus and more external tibial rotation was observed in the ACL-deficient knee. The tendency was more obvious in high demand motions, and a significant difference was clearly observed in the side cutting motions. These motion patterns, with the knee in less valgus and more external tibial rotation, are proposed to be an adaptive movement to avoid pivot shift dynamically, and reveal evidence in support of a dynamic adaptive motion occurring in ACL-deficient knees.

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1. Introduction

Anterior cruciate ligament (ACL) injury is a major traumatic injury, and makes it difficult for athletes to continue or to begin sports activity participation without reconstruction surgery. Therefore, it is important to reveal how ACL deficiency affects joint mechanics and leads to functional disability. ACL injury leads to anterior–posterior instability and rotatory instability resulting in various adaptive movements. Decreased knee flexion in the stance phase of gait has been identified as an adaptive gait pattern in chronic ACL deficient patients (Rudolph et al., 1998; Torry et al., 2004). The lower flexion angles during stance in ACL deficient knees may be caused by a simultaneous contraction of the quadriceps femoris and hamstring muscles to achieve stability, and is known as the 'stiffening knee strategy'. Also, abnormalities in ankle muscular activity patterns during gait have been reported in chronic ACL deficiency (Lindstrom et al., 2010). However, ACL-deficient knee axial plane biomechanics may be influenced by mechanics other than muscular activation. Abnormal tibial rotation during gait in the ACL-deficient knee has been reported (Andriacchi and Dyrby, 2005; Georgoulis et al., 2003; Georgoulis et al., 2005; Gao and Zheng, 2010; Zhang et al., 2003). Fuentes et al. (2011) described that ACL-deficient patients walked with a reduced internal rotation knee moment, and described the gait pattern as a 'pivot shift avoidance gait'. The major problem for ACL-deficient patients is that they have limitations in or discomfort in performing more dynamic motions than gait. Therefore, understanding the influence of ACL deficiency in high-demand activities is essential for improving patient management. Several studies have investigated ACL-deficient knee mechanics during sports-related movements such as jogging and side step cutting or stair ascent or descent (Rudolph et al., 1998, 2000, 2001; Houck and Yack, 2003; Houck et al., 2005; 2007; Gao et al., 2012), but there is no study analyzing series of low demand and high demand tasks to reveal how the level of task affects the ACL deficient knee kinematics.

The purpose of this study was to evaluate three-dimensional knee kinematics during low-demand and high-demand activities in ACL-deficient knees, and to determine how knee kinematics change in patients with ACL injury. We hypothesized that the alteration in knee kinematics caused by ACL injury would be more apparent during high-demand activities than during low-demand activities.

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2. Materials and methods

The subjects consisted of 22 patients (11 females and 11 males) who were diagnosed as unilateral ACL injury with manual clinical examination and MRI. All patients planned to have ACL reconstruction, and underwent the surgery after the examination for this study. Patients with other knee ligament injuries, meniscus injury with Mink grade 2 or more, moderate or severe patellofemoral and tibiofemoral joint osteoarthritic changes, a history of lower limb surgical procedures on either limb, and those with other neuromuscular disease were excluded. The mean subject age was 22 (range, 17–31) years old. The average time post-injury was 19.6 (range, 2–120) months. The activity level of subjects was determined by Tegner Activity Score and was 7.2 (range, 3–9) points in average. The research protocol was approved by our institutional review board and informed consent was obtained from each subject prior to enrollment.

Subjects underwent motion analysis using six 120 Hz opto-electronic cameras (Pro-Reflex mcu120, Qualysis, Savedalen, Sweden), a multicomponent force plate at a synchronized frequency of 120 Hz (Type AM6110, Bertec, Columbus, OH, USA) and a control PC. The three-dimensional knee kinematics were obtained using the Point Cluster Technique (PCT) originally described by Andriacchi et al. (1998), in which a total of 21 light-reflective markers were placed on the iliac bone, thigh, shank and foot. A constant marker weighting was used to ensure that excessive non-rigid skin motion artifact has not occurred (Alexander and Andriacchi, 2001; Dyrby et al., 2004; Lathrop et al., 2011).

Each subject performed five different activities at a self-selected speed with bare feet: level walking (WK), ascending and descending steps (SA, SD), jogging (JG), and jogging to a 90-degree side cutting to the opposite side of the tested side (JC) (Table 1). After practicing these activities, two successful trials of three trials were recorded for each motion. If all three trials were successful, the second and third trials were used. The contralateral side of the ACL-deficient knees were also evaluated as a control.

Maximum vertical force (VF) and time length of the stance phase (TL) of the contralateral healthy knees were evaluated to determine the mechanical demand level of each activity. VF was calculated using inverse dynamics based on a local anatomical coordinate system placed on the tibia. VF and TL were statistically compared between the five activities using a single factor analysis of variance (ANOVA) with a significance level of $p=0.05$.

Knee flexion, valgus and tibial rotation angles with respect to the femur were evaluated in each subject. The data lengths were normalized by the time length of the stance phase, which is defined from 0% stance (the foot touched the force plate) to 100% stance (the foot lifted off of the plate), and the kinematics were analyzed at 5% intervals. A 5% value was chosen to detect time-dependent change due to the ACL deficiency during the activities.

The average knee flexion, valgus and tibial rotation angles were compared between the ACL-deficient side and the healthy side. A repeated-measures ANOVA with two within-subjects factors was used to test the hypotheses that these kinematic parameters were different between ACL-deficient and healthy contralateral knees. The two factors used were the knee status (ACL-deficient vs. contralateral) and time point (each 5% stance phase). A Bonferroni correction level of 0.017 was used in the ANOVA to account for the analysis of three kinematic parameters (flexion/extension, varus/valgus and internal /external rotation of tibia).

3. Results

Mechanical demands during jogging and side cutting were greater than other activities as the greater forces were applied to the knee in a shorter period during the two activities.

3.1. *Knee flexion/extension angle (Fig. 1)*

There were no differences in knee flexion-extension patterns between ACL-deficient and the contralateral knees during the five activities.

3.2. *Knee varus/valgus angle (Fig. 2)*

Overall, ACL-deficient knees tended to have a smaller valgus angle than the contralateral knees. The difference became more apparent during cutting activities. The valgus angle was an average of $\sim 5^\circ$ smaller in ACL-deficient knees during 90° cutting activities, and this difference was significant from just before the initial stance phase ($p=0.006$) and from 10% to 15% of the stance phase ($p=0.015$, 0.016). There was no significant difference in knee varus/valgus angle during the other activities.

3.3. *Tibial external/internal rotation (Fig. 3)*

ACL-deficient knees tended to maintain more tibial external rotation during all activities when compared to the contralateral knees. There was significantly less internal tibial rotation (more external tibial rotation) during cutting maneuver than on the healthy side at 15% of stance. The average difference in tibial rotation at that point was 4.6° ($p=0.017$). The peak internal rotation occurred at the end of the stance phase, and a significant difference was observed from 95% to 100% stance and just after the foot lifted off of the plate, with a difference of 6.0° ($p=0.013$–0.016).

4. Discussion

Our results suggest that alteration in three-dimensional knee kinematics due to ACL deficiency becomes more obvious during the high-demand activities. ACL-deficient knees had a tendency to show less valgus and more tibial external rotation during walking, stair activities and straight line jogging, and the differences were significant during cutting activities.

Side cutting activities are reported to apply greater torque to the knee than level walking or jogging. Houck et al. (2006) reported there were greater knee abduction (valgus) moments in side step cutting than walking. Besier et al. (2001) indicated that greater knee internal rotation moment occurred during side cutting than walking or running in healthy subjects. The reduction in the knee valgus angle during higher demand activities such as side cutting suggests that ACL-deficient patients tend to maintain the injured knee in a less abducted position to avoid greater valgus torque during the activity. Since there is greater mechanical load during side cutting than other activities, the load on the knee and the high speed motion associated with the tibial rotation caused an external rotation offset referred to the healthy side likely to avoid internal rotation moment. This occurred even though the amount of rotation angles was not different between activities.

The sagittal knee mechanics are associated with muscle activation in ACL deficient patients (Rudolph et al., 1998; Torry et al., 2004; Lindstrom et al., 2010), while the axial mechanics are more mechanically determined. This is because of the anatomy of the

Table 1
Detailed descriptions of activities in the current study.

Level walking (WK)	Walked toward the force plate at a self-selected speed and struck the force plate with the tested side foot.
Step ascent (SA)	A 21.5 cm, 32 cm deep step was placed on top of the center of the force plate next to a 43 cm tall box. The subject stood facing the 21.5-cm-tall step, then placed the tested foot on top of the 21.5 cm tall step. Next the subject placed the opposite side foot on top of the 43 cm tall box adjoining the 21.5 cm step.
Step descent (SD)	A 21.5 cm, 32 cm deep step was placed on top of the center of the force plate next to a 43 cm tall box. The subject stood on the 43-cm-tall box, stepped down onto the step with the tested side leg first and stepped down onto the ground with the opposite side leg.
Jogging (JG)	Jogged forward and struck the plate with the tested side foot at a self-selected speed.
Jogging to cutting (JC)	Jogged forward to the force plate, struck the force plate with the tested side foot and jumped to the opposite side of the tested foot facing forward at approximately 90°.

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