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Comparison of kinematics of ACL-deficient and healthy knees during passive flexion and isometric leg press ☆

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ABSTRACT

Background: Studying the kinematics of the ACL deficient (ACLD) knees, during different physiological activities and muscle contraction patterns, can improve our understanding of the joint's altered biomechanics due to ACL deficiency as well as the efficacy and safety of the rehabilitations exercises.
Methods: Twenty-five male volunteers, including 11 normal and 14 unilateral ACLD subjects, participated in this study. The kinematics of the injured knees of the ACLD subjects was compared with their intact knees and the healthy group during passive flexion and isometric leg press with the knees flexed from full extension to 45° flexion, with 15° intervals. An accurate registration algorithm was used to obtain the three dimensional kinematical parameters, from magnetic resonance images.
Results: The ACL deficiency mainly altered the tibial anterior translation, and to some extent its internal rotation, with the change in other parameters not significant. During leg press, the anterior translation of the ACLD knees was significantly larger than that of the normal knees at 30° flexion, but not at 45°. Comparison of the anterior translations of the ACLD knees during leg press with that of the passive flexion revealed improved consistency (CVs changed from 1.2 and 4.0 to 0.6 and 0.6, at 30° and 45° flexion, respectively), but considerable larger translations (means increased by 6.2 and 4.9 mm, at 30° and 45° flexion, respectively).
Conclusion: The simultaneous contraction of the quadriceps and hamstrings during leg press, although reduces the knee laxity, cannot compensate for the loss of the ACL to restore the normal kinematics of the joint, at least during early flexion.

1. Introduction

Anterior cruciate ligament (ACL) injury is one of the most prevalent and debilitating problems faced by knee patients and clinicians [1]. The stabilizing functions of the ACL, to limit the anterior tibial translation and to control the tibial axial rotation [2,3], are believed to be critical for maintaining the normal knee kinematics. Aberrant joint loading, due to the altered kinematics of the ACL deficient (ACLD) knees, has been considered responsible, at least in part, for the degenerative changes in the articular cartilage and the progressive development of knee osteoarthritis [4,5].

A thorough understanding of the effects of the ACL deficiency on the knee kinematics is essential to evaluate the efficacy of the surgical and rehabilitation treatment procedures and to prevent secondary devastating complications. *In vitro* cadaveric studies [6,7] have provided some insight into the kinematical behavior of the ACLD knees under controlled conditions. However, they are unable to accurately simulate the effects of weight bearing and muscles contraction on the joint kinematics. The *in-vivo* kinematics of the joint might be assessed using medical imaging modalities, e.g., magnetic resonance imaging (MRI), which provide direct visualization of the position and hence the relative motion of the bones, noninvasively. The previous MRI studies of the knee kinematics, however, have often addressed only two or three of the joint kinematical parameters [8–10] and/or analyzed its contact pattern [8]. To the best of our knowledge, the only study describing

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☆ Level of evidence: Controlled laboratory study using a repeated measure design, Level IIa.

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the six kinematical parameters of the ACLD knees is the work of Defrate et al. [11], in which the joint's motion was measured during quasi-static lunge.

Considering the complicated interactions between the kinematics and loading conditions of the knee joint, studying the detailed six degrees of freedom kinematics of the ACLD knees, during different physiological activities and muscle contraction patterns, can improve our understanding of the joint's altered biomechanics due to ACL deficiency. This is particularly important if one considers the fact that an increased hamstring activity has been reported in ACLD patients that can help to stiffen and stabilize the injured knee [12,13]. There are also reports that the simultaneous contraction of the quadriceps and hamstrings decreases the ACL strain, and subsequently the anterior tibial translation [14–18]. However, this is not yet a well tested fact, and some investigations [19–21] have suggested that the kinematical effect of the hamstrings activation is not sufficient to compensate for the loss of the ACL and reduce the anterior tibial translation significantly.

The aim of the present study was to investigate the effect of the simultaneous contraction of the quadriceps and hamstrings during a common rehabilitation exercise, i.e., isometric leg press, on the kinematics of ACLD knees. It was hypothesized that the co-activation of the muscles can compensate for the loss of the ACL and reduce the altered kinematics of the injured knees. The six degrees of freedom kinematics of the ACLD and healthy knees, during supine passive flexion and isometric leg press, was measured using standard closed MR images analyzed by an accurate and robust registration technique. The results were employed to provide a better understanding of the stabilizing effect of muscles co-activation in ACLD knees, and to determine the extent of the normal kinematics restoration obtained during isometric leg press exercise for such knees.

2. Method

Twenty-five male volunteers, including 11 normal and 14 unilateral ACLD subjects, participated in this study. The number of samples was determined by priori sample-size power analysis ($\beta = 0.20$, and $\alpha = 0.5$) based on the preliminary results of a pilot study. The normal (control) and ACLD (experiment) groups were matched for sex (all male), age (27.9 (±5.0 SD) vs 29.4 (±7.1 SD) years, respectively), height (177 (±5 SD) vs 176 (±6 SD) cm, respectively), and weight (73.5 (±5.0 SD) vs 78.9 (±7.8 SD) kg, respectively).

The normal subjects were university students and had no history of injury or structural abnormality in either knee, and exhibited no signs of knee instability during manual examination. The ACLD patients were selected from the list of two clinical centers during a period of one year prior to the experiments of this study. All of the patients had a unilateral ACL injury at least six months before the tests. ACL injury was documented via MRI and clinical examination, i.e., positive Lachman, pivot shift and anterior drawer tests, performed by an expert orthopedic surgeon. Furthermore, all patients exhibited at least one episode of knee joint instability, i.e., “giving way” in the last six months prior to test. Subjects were excluded if they had present pain, more than a trace effusion, and knee joint movement restriction, as well as any contraindications to MRI, or height over 186 cm (to permit sufficient knee flexion in the MRI tunnel). Prior to testing, all participants read and signed an informed consent form approved by the university's Human Investigations Committee.

The subjects lay supine in a 1.5 T MRI system (GE Healthcare, UK) to obtain the three dimensional configuration of the knee joint at four different flexion angles, i.e., 0° (full extension) , 15°, 30° and 45°. A testing apparatus, made of MRI compatible material, was used to position the subject's leg on a triangular jig, adjusted to provide the desired flexion angles accurately (Fig. 1). Elastic straps were used to fix the thigh and foot in neutral position and avoid medial/lateral movements. For the passive knee flexion experiments, the subjects' legs were positioned at rest on the triangular jig with no muscular effort. In the leg press experiments, the subjects performed isometric leg press against the foot pedal of the apparatus, equipped with a load cell (DACELL Co, Ltd. South Korea) at 30° and 45° knee flexion. They were asked to control their muscular effort, using the visual feedback from the load cell, to keep the pressing force constant on 250 N, approximately. This force was the highest possible force that the subjects could apply without tremor for the duration of the test.

A total of 37 knees of 25 individuals, including a randomly selected knee of each normal subject and both knees of 12 ACLD subjects, were examined. High resolution $256*256$ matrix T1 parasagittal slices with 2 mm thickness no space were acquired using fast spin echo sequences. For the leg press experiments, the slice thickness was increased to 4 mm to avoid prolonged imaging periods, which could cause unwanted limb movements and disturb the image quality, due to the muscular fatigue.

We used a novel variational approach, within the framework of the phase field approximation of the Mumford–Shah's functional [22], for joint segmentation–rigid registration of the MR images. The performance of this approach was examined in a previous study [22], in a comprehensive set of synthetic, phantom and clinical experiments, and it was shown that it provided a sub-pixel, robust algorithm for edge extraction, as well as edge based rigid registration.

At first, course three dimensional surface models of the proximal tibia and distal femur were constructed for each knee configuration by means of appropriate deformable models. Then considering the femoral and tibial models of the knee, while resting at full extension as reference, the discontinuity set between them and those of the target models, due to a rigid spatial transformation, were extracted by matching 800 to 1200 surface points. The target models included the femoral and tibial models of the knee passive flexion experiments at 15°, 30° and 45°, as well as those of the leg press experiments at 30° and 45° knee flexion.

Transformation matrixes, representing the rotations and translations of the target models from the reference, were recorded for both the tibia and femur. Then multiplying the inverse transformation matrix

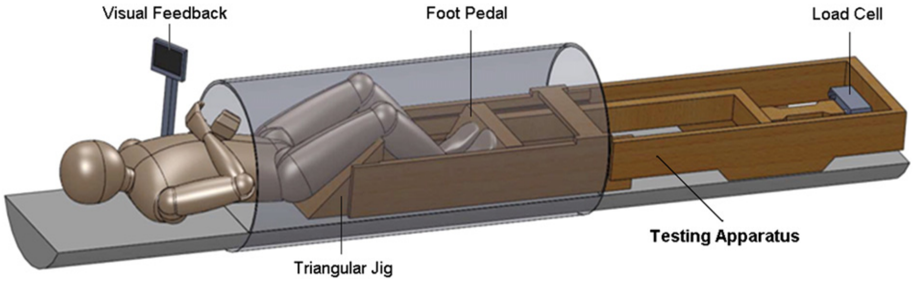

Fig. 1. A schematic illustration of the experimental setup. The subjects lay supine in the MRI system with their legs on the triangular jig to provide the desired flexion angle between zero and 45°. During leg press experiments, the subjects performed isometric leg-press against the foot pedal, with a constant pressing force controlled via the visual feedback from the load cell.