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Gait adaptation in chronic anterior cruciate ligament-deficient patients: Pivot-shift avoidance gait

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ABSTRACT

Background: A variety of biomechanical adaptations of the knee during gait have been reported in ACL-deficient patients to cope with anteroposterior knee instability. However, strategies to prevent rotatory knee instability are less recognized. We hypothesized that ACL-deficient patients would make distinctive gait changes to prevent anterolateral rotatory knee instability. Specifically, we hypothesized that during the terminal stance phase of the gait cycle, ACL-deficient patients would reduce the internal rotation knee joint moment and exhibit a higher knee flexion angle. We call this altered gait a *pivot-shift avoidance gait.* We also hypothesized that patients would not be able to adapt their knee biomechanics as efficiently at a fast gait speed.
Methods: Twenty-nine patients with chronic ACL deficiency and 15 healthy volunteers took part in a treadmill gait analysis. The terminal stance phase was analyzed under both comfortable and fast gait speed conditions.
Findings: At both gait speeds, ACL-deficient patients significantly reduced the internal rotation knee joint moment and showed larger knee flexion angles during the terminal stance phase of the gait cycle than did the control group. However, the difference in the minimum knee flexion angle between groups under the fast gait speed condition was not statistically significant.
Interpretation: ACL-deficient patients adopted the proposed pivot-shift avoidance gait, possibly to prevent anterolateral rotatory knee instability. The patients were not able to adapt their knee biomechanics as effectively during fast-paced walking. This study reinforces the pertinence of gait analysis in ACL-deficient knees to acquire more information about the function of the knee joint.

1. Introduction

The anterior cruciate ligament (ACL) is involved in 20% of all sports-related knee injuries (Majewski et al., 2006), which corresponds to approximately 80000 ACL injuries per year in the United States alone (Griffin et al., 2000). It is well documented that this injury leads to knee joint instability and functional impairment (Daniel et al., 1994). More specifically, ACL deficiency leads to anteroposterior laxity and anterolateral rotatory instability (Almekinders et al., 2004; Daniel et al., 1994; Galway and MacIntosh, 1980; Okazaki et al., 2007). For clinical assessment, the *Lachman* test and the *lateral pivot-shift* tests are recognized to adequately assess the laxity and the rotatory instability of the knee, respectively (Lane et al., 2008).

Gait analysis can provide valuable information in assessing the functional impairments associated with ACL injury (Wexler et al., 1998). Gait analysis is a dynamic evaluation that complements an orthopedic physical examination by quantifying the subtle mechanical changes that result from adaptive strategies. Biomechanical evaluation of the knee motion also provides precise information for comparison between ACL-intact and ACL-deficient knees when assessing knee stability (Lam et al., 2009).

Although walking is an activity generally not strenuous enough to provoke giving way episodes, quantifying knee biomechanics during walking gait can provide a better understanding of the behavior of the joint in compensating for the injury. Since episodes of instability following an ACL injury are mostly reported when the knee is in slight flexion position, numerous studies have examined biomechanical adaptations during the loading phase (between 0% and 10% of the gait cycle) and the midstance phase (between 10% and 30% of the gait cycle). By investigating knee joint moments, which can provide an estimation of the forces occurring at the knee joint, previous studies showed that ACL-deficient patients modify their gait patterns to limit the forces that could lead to anteroposterior joint instability

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(Berchuck et al., 1990; Patel et al., 1997; Wexler et al., 1998). After assessing sagittal plane knee joint moments, a gait strategy named the "quadriceps avoidance gait" was proposed (Berchuck et al., 1990). This strategy is characterized by an important reduction or absence of external knee flexor joint moment during the midstance phase of the gait cycle. Theoretically, this reduces the anterior force applied to the tibia by the eccentric contraction of the quadriceps (net extensor force) at low knee flexion angles that could lead to anterior displacement of the tibia in relation to the femur. Therefore, during the midstance phase, patients avoid placing their knee in a position where dynamic stabilizers are in poor position to provide support. Also, one could imagine, from a clinical point of view, that by adopting a quadriceps avoidance gait, patients avoid a condition during walking that mimics the Lachman manual test maneuver (a knee flexed between 0° and 30° submitted to an anterior force applied to the tibia (Magee, 1997)). More recent studies have proposed that this reduction in the external flexor moment could instead be explained by increased hamstring activity, demonstrating the lack of consensus regarding gait adaptation in the ACL-deficient population (Beard et al., 1996; Hart et al., 2010; Rudolph et al., 2001).

Studies examining biomechanical compensations during the terminal stance phase of the gait cycle (between 30% and 50% of the gait cycle) in the ACL-deficient population are scarce. This subphase of the gait cycle takes place during single-limb support, when the primary role of the knee is to allow stable weight bearing (Perry, 1992). Additionally, it has been shown that the intact ACL is significantly loaded during level walking and that the largest strain on the ligament occurs near full knee extension (Zhang et al., 2001). In fact, during the terminal stance phase, the knee is close to full extension and is submitted to an internal tibial rotation moment (Andriacchi and Dyrby, 2005). The screw-home mechanism usually allows the joint to remain stable in an extended position; however, ACL-deficient knees have been shown to lose their screw-home mechanism (Andriacchi and Dyrby, 2005; Ellison, 1980). Furthermore, it is well established that ACL deficiency leads to anterolateral rotatory knee instability near extension. Considering these factors, it is relevant to assess how patients alter their knee biomechanics to stabilize their joints during the terminal stance phase.

In the clinical setting, the lateral pivot-shift test provides an adequate assessment of anterolateral rotatory knee instability. The first part of this manual test consists of applying an internal tibial torque with the knee in full extension, in order to anteromedially sublux the lateral tibial plateau. The clinician then flexes the patient's knee while applying a valgus stress until the tibia reduces to between 20° and 40° of flexion (Lane et al., 2008).

From a clinical point of view, during the terminal stance phase, the knee is in a position that mimics the first part of the lateral pivot-shift test (a knee positioned near full extension and submitted to an internal tibial torque). Therefore, investigating knee internal rotation joint moments and knee flexion–extension kinematics during the terminal stance phase of the gait cycle in patients with ACL deficiency could provide valuable information about the adaptive strategies used to stabilize the knee. We hypothesized that ACL-deficient patients would avoid placing their knees in a position that could potentially lead to anterolateral rotatory knee instability during terminal stance by adopting what we propose to call a *pivot-shift avoidance gait*. ACL-deficient patients achieve this proposed gait strategy by (1) significantly reducing the internal rotation knee joint moment and (2) exhibiting a higher knee flexion angle during the terminal stance phase of the gait cycle. These biomechanical compensations allow patients to avoid a condition mimicking the first part of the lateral pivot-shift maneuver. Since reports of joint instability are more common during more demanding physical activities, we also hypothesized that ACL-deficient patients would not be able to adapt their knee biomechanical patterns as effectively at a fast gait speed as they would at a comfortable gait speed.

2. Methods

2.1. Subjects

Twenty-nine patients, all recruited from a waiting list for ACL reconstructive surgery, took part in the study to form the ACL-deficient (ACLD) group. Each patient presented with an ACL tear with positive Lachman and pivot-shift tests, confirmed by an experienced orthopedic surgeon. Patients with any history of fractures, previous surgery to the lower extremities, neurological pathologies or any other musculoskeletal pathology of the lower limbs (i.e. other ligament injuries or posterolateral corner injuries) were excluded. The ACLD group was composed of 21 males and 8 females. Only the patients' injured legs – 14 right and 15 left – were evaluated. The mean time that had elapsed between the injury and the biomechanical evaluation was 22 months, ranging from 5 to 78 months. Episodes of instability in the ACLD group were assessed using the instability subscore of the Lysholm Knee Scale. The mean score for the ACLD group was 15 over 25, corresponding to "gives way frequently during athletic events or other severe exertion". In recognition that the contralateral leg may also develop biomechanical adaptations to an ACL injury (Berchuck et al., 1990), a control group was evaluated to compare results. Fifteen physically active, healthy participants (13 males and 2 females) with no history of musculoskeletal pathology formed the control group, in which 11 right and 4 left legs were assessed. All subjects gave their written consent prior to participation in the study, the design of which was previously approved by the institution's ethics committees.

2.2. Apparatus

Kinematic data were recorded using a six-camera VICON motion analysis system (VICON 460, Oxford Metrics, Oxford, UK). The system captured the 3D displacements of four rigid bodies, each composed of four reflective markers, at a frequency of 120 Hz. These rigid bodies were used to follow the 3D movements of the lower limb segments (foot, shank, thigh and pelvis). A knee marker attachment system designed to reduce skin motion artifacts (Sati et al., 1996; Sudhoff et al., 2007) facilitated the fixation of two rigid bodies over the femur and the tibia, respectively. The other two rigid bodies were positioned as follows: one secured over the midfoot and the other over the sacrum using a sacro-illiac belt (Fig. 1). This acquisition setup methodology has shown high intra- and inter-observer reliability for recording 3D knee kinematics (Labbe et al., 2008). To avoid the effect of footwear on lower limb biomechanics, all subjects wore the same neutral sandals (Portofino, Spain). Kinetic data were collected using an instrumented treadmill (ADAL3DM-F-COP-Mz, Medical Development, France). Two side-by-side belts with imbedded independent Kistler force plates allowed for simultaneous measurement of 3D ground reaction forces and the center of pressure under each foot at a frequency of 120 Hz.

2.3. Gait analysis protocol

The gait analysis protocol consisted of treadmill walking at a self-selected comfortable speed and at a fast gait speed (20% faster than the comfortable speed). Through assessment of spatiotemporal parameters, ground reaction forces and 3D lower limb joint kinematics and moments, treadmill walking has been shown to be qualitatively and quantitatively similar to normal overground gait (Riley et al., 2007). Furthermore, a treadmill provides the ability to adequately control gait speed throughout data acquisition and to record a larger number of gait cycles. All subjects completed a 10-min treadmill walking familiarization period for identification of their comfortable gait speed and to ensure reproducible knee kinematics and spatiotemporal parameters (Van de Putte et al., 2006). Thereafter,