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Knee mechanics during landing in anterior cruciate ligament patients: A longitudinal study from pre- to 12 months post-reconstruction

Kai Daniel Oberländer [a,b,*], Gert-Peter Brüggemann [a,e], Jürgen Höher [c], Kiros Karamanidis [a,d]

[a] Institute of Biomechanics and Orthopaedics, German Sport University Cologne, Germany
[b] Institute of Movement and Sport Gerontology, German Sport University Cologne, Germany
[c] Clinic for Sports Traumatology at Cologne Merheim Medical Center, University of Witten-Herdecke, Germany
[d] Department of Mathematics and Technology, University of Applied Sciences Koblenz, RheinAhrCampus Remagen, Germany
[e] Cologne Center for Musculoskeletal Biomechanics, Medical Faculty, University of Cologne, Germany

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ABSTRACT

Background: Patients with a history of anterior cruciate ligament rupture are at elevated risk of developing knee osteoarthritis. Altered knee kinematics and kinetics during functional activities have been viewed as risk factors for cartilage breakdown and, therefore, one of the primary goals of anterior cruciate ligament reconstruction is to restore knee joint function.
Methods: Patients' ($n = 18$) knee mechanics while performing a single leg hop for distance were calculated for both legs using a soft-tissue artifact optimized rigid lower-body model at the pre-reconstruction state and six and twelve months after anterior cruciate ligament reconstruction.
Findings: Independent of the analyzed time point the involved leg showed a lower external flexion and adduction moment at the knee, and an increased anterior translation and external rotational offset of the shank with respect to the thigh compared to the uninvolved leg. There were no differences for any of the analyzed knee kinematic and kinetic parameters within the control subject group.
Interpretation: The identified kinematic changes can cause a shift in the normal load-bearing regions of the knee and may support the view that the risk of developing knee osteoarthritis in an anterior cruciate ligament ruptured joint while performing activities involving frequent landing and stopping actions is less likely to be associated with the knee adduction moment and is rather due to kinematic changes. Anterior cruciate ligament reconstruction surgery failed to restore normal knee kinematics during landing, potentially explaining the persistent risk for the development of knee osteoarthritis in patients who have returned to sports following reconstruction surgery.

1. Introduction

Individuals who have suffered a complete rupture of the anterior cruciate ligament (ACL) have a higher rate of cartilage thinning (Frobell, 2011) and a considerably elevated risk of developing knee osteoarthritis (OA) (Lohmander et al., 2004; Roos, 2005). Even where an ACL reconstruction procedure has been carried out, cartilage loss is often still persistent (Asano et al., 2004; Lohmander et al., 2004). Therefore, long-term knee function after ACL rupture remains a concern, and such ruptures may have a devastating effect on the quality of life.

Using different methods to capture motion, most studies agree that tibiofemoral motion is altered after ACL rupture (Gao and Zheng, 2010; Papannagari et al., 2006; Scanlan et al., 2010). The changes in knee kinematics after ACL rupture are viewed as a possible mechanical factor in the initiation of knee OA (Andriacchi and Mündermann, 2006; Andriacchi et al., 2004). In particular, the observed offsets in transversal rotation and anteroposterior translation of the tibia with respect to the femur in ACL-deficient patients during functional movement have been suggested as playing a key role in the pathomechanics of knee OA after ACL rupture, because they shift the ambulatory loading applied to cartilage (Andriacchi and Mündermann, 2006; Andriacchi et al., 2004; Roos et al., 2011). One of the primary goals of ACL reconstruction is, therefore, to reduce or eliminate such changes in tibiofemoral kinematics (Beynnon et al., 2005). Although treatment using modern reconstructive surgery is arguably successful in restoring knee function after ACL rupture (Loh et al., 2003; Woo et al., 2002), the incidence of knee OA in individuals who have undergone reconstructive surgery is often comparable to the incidence of knee OA among those who have not (Asano et al., 2004; Lohmander et al., 2004). Therefore long-term knee joint function remains a concern.

It is widely accepted that patients with a history of ACL rupture modify the joint moments of their involved leg in the sagittal plane while performing functional activities such as walking and landing (i.e. ACL-deficient patients decrease the contribution of the knee

* Corresponding author at: Institute of Biomechanics and Orthopaedics, German Sport University Cologne, Am Sportpark Müngersdorf 6, 50933 Cologne, Germany.
E-mail address: oberlaender@bme-tech.com (K.D. Oberländer).

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extensors by shifting the demand to the ankle plantarflexors and hip extensors: Oberländer et al., 2012; Rudolph et al., 2001), with the potential aim of adjusting task demand to the reduced knee extensor muscle capacities (Oberländer et al., 2013). However, altering the joint moments in one plane can affect the joint moments in other planes because lower extremity muscle activity influences the direction of the ground reaction force (GRF) vector (Pandy and Andriacchi, 2010). Regarding this issue, Jenkyn et al. (2008) reported that the frontal knee joint moment can be reduced while walking by altering locomotion strategy and transforming the external knee adduction moment to the sagittal plane, thereby increasing the external knee flexion moment. The external knee adduction moment is a surrogate measure of the mechanical load distribution at the tibiofemoral joint (a higher external knee adduction moment indicates a higher medial compartment mechanical loading; Schipplein and Andriacchi, 1991) and is generally accepted as a relevant component of the initiation and progression of knee OA (Amin et al., 2004). It seems possible, therefore, that patients with a history of ACL rupture adjust task demand at their involved knee to their reduced knee extensor muscle capacities by using an altered joint kinetic strategy that allows them to reduce the external knee flexion moment by means of joint moment redistribution in the sagittal plane (from the knee to the ankle joint) and knee joint moment transformation (from the sagittal to the frontal plane). The consequence of this altered joint kinetic strategy will be a higher magnitude of external knee adduction moment, increasing the risk of developing knee OA in patients with a history of ACL rupture. However, most studies analyzing ambulatory joint mechanics in patients with a history of ACL rupture focus on sagittal plane kinetics and, therefore, it remains unclear whether, besides the kinematic changes, higher mechanical loading in terms of knee adduction moment is a potential mechanical risk factor initiating degenerative knee joint changes in such patients. To our knowledge, there are only a few studies that have analyzed external knee adduction moment during functional activities in patients with ACL rupture; however, the findings are contradictory by showing an increased or decreased external knee adduction moment in ACL ruptured patients or no difference between legs (Butler et al., 2009; Hall et al., 2012; Hooper et al., 2002; Webster and Feller, 2011; Webster et al., 2012).

The above studies all examined cyclic motor tasks such as walking and running where knee joint kinetics in the patient's involved leg is influenced by the action of the ipsilateral limb. For example, Karamanidis and Arampatzis (2011) recently reported that older adults modify their gait strategy, controlling descent of stairs by using the musculature of the trailing leg more than that of the leading leg. This altered gait strategy between legs resulted in an increased external knee adduction moment in the trailing leg. In the current work, we decided to examine knee joint mechanics during landing after a single-leg hop test (SLHT) and analyze ambulatory joint mechanics separately for each leg. Landing and stopping actions are involved in a number of different sports (e.g. basketball, soccer, rugby), require greater lower extremity joint moments than those required during walking and running and might, therefore, be characterized as high-risk motor tasks for the onset and progression of knee OA in physically active patients with a history of ACL rupture if these patients return to sports.

The aim of this study was, therefore, to examine both the motion of the shank in relation to the thigh (i.e. transversal rotation, anteroposterior translation) and the external knee adduction moment during landing, assuming both to be mechanical components of the development of knee OA (Andriacchi et al., 2004; Roos et al., 2011), and the sagittal plane joint moments at the knee and ankle. By using a SLHT performed with the involved and uninvolved leg in a group of physically active male patients with a history of ACL rupture, a longitudinal design (pre-reconstruction and six and twelve months post ACL reconstruction state) was realized. Furthermore, we analyzed a matched healthy control group to identify normal joint kinematic and kinetic asymmetries between legs. It was hypothesized that ACL reconstruction fails to fully restore anteroposterior translation and transversal rotational profiles at the involved knee to limits similar to the patients' uninvolved knee during landing after an SLHT; however, in comparison to their ACL-deficient state, ACL reconstruction will partly restore patients' altered knee kinematics at the involved knee. Additionally, it was suggested that, independent of the analyzed time point (pre-reconstruction and six and twelve months after reconstruction surgery), patients with a history of ACL rupture will reduce the magnitude of their external knee flexion moment during landing by increasing the external ankle dorsiflexion moment (joint moment redistribution in the sagittal plane) and the external adduction moment at the knee (joint moment transformation from the sagittal to the frontal plane). It is important to note that the above described research questions have not been answered by our previous studies (Oberländer et al., 2012, 2013); more precisely the current study continues on from the research that the authors have produced in recent years. These additional findings might be important for the development of more effective treatments for knee OA in patients with a history of ACL rupture participating in sport activities involving frequent landing and stopping actions.

2. Methods

2.1. Subjects

Eighteen male unilateral ACL-deficient patients (age: 26 (6) yrs. mean and SD; height: 1.80 (0.08) m; body mass: 84.9 (12.4) kg) and twelve healthy, age matched, male controls (no ACL-injury or other knee joint disease, no neuromuscular impairments; age: 25 (2) yrs.) with similar anthropometric characteristics (height: 1.83 (0.08) m; body mass: 78 (7.2) kg) participated in the study. Inclusion criteria for the ACL-deficient patients were a complete unilateral rupture of the ACL with no other ligament injury, no clearly identifiable meniscii or articular cartilage damage at the knee (all documented during ACL reconstruction surgery), no history of other musculoskeletal injuries and the absence of clinical knee axis misalignment. Participants were assessed for inclusion by a specialist medical practitioner using magnetic resonance imaging, as well as the surgeon performing their reconstruction, who assessed whether the patient met the criteria during the surgery. A further inclusion criterion for the patients was no knee joint pain while performing athletic activities (e.g. running, jumping).

All subjects were active in sporting activities that involve high lower-extremity joint loading (soccer, basketball, rugby or skiing). All patients underwent ACL reconstruction at the Department for Orthopedics and Sports Traumatology (Cologne, Germany), performed by the same orthopedic surgeon (JH) using a quadrupled semitendinosus and gracilis tendon graft harvested from the involved limb. All patients returned to their usual sports activities between four and five months after surgery. Ethics approval was obtained from the local institution and all participants provided written informed consent before enrollment.

2.2. Analysis of landing mechanics

A longitudinal design with three different time points (pre-reconstruction and six and twelve months post ACL reconstruction state) was used. Biomechanical testing of the patients in a pre ACL reconstruction state was accomplished three to six months after the ACL injury and approximately five days before surgery. Post-operative outcomes were biomechanically assessed at six and twelve months after ACL reconstruction. Control subjects were examined once to identify potential asymmetry between legs related to physiological side-to-side differences within an asymptomatic population.

The method used to analyze landing mechanics during the SLHT has previously been reported in detail (Oberländer et al., 2012). In brief, all subjects performed a modified SLHT for distance, keeping their hands