Clinical Biomechanics 29 (2014) 629–635

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Altered tibiofemoral joint contact mechanics and kinematics in patients with knee osteoarthritis and episodic complaints of joint instability

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ARTICLE INFO

Article history:
Received 11 December 2013
Accepted 22 April 2014

Keywords:
Contact mechanics
Instability
Kinematics
Gait

ABSTRACT

Background: To evaluate knee joint contact mechanics and kinematics during the loading response phase of downhill gait in knee osteoarthritis patients with self-reported instability.
Methods: Forty-three subjects, 11 with medial compartment knee osteoarthritis and self-reported instability (unstable), 7 with medial compartment knee osteoarthritis but no reports of instability (stable), and 25 without knee osteoarthritis or instability (control) underwent Dynamic Stereo X-ray analysis during a downhill gait task on a treadmill.
Findings: The medial compartment contact point excursions were longer in the unstable group compared to the stable ($P = 0.046$) and the control groups ($P = 0.016$). The peak medial compartment contact point velocity was also greater for the unstable group compared to the stable ($P = 0.047$) and control groups ($P = 0.022$). Additionally, the unstable group demonstrated a coupled movement pattern of knee extension and external rotation after heel contact which was different than the coupled motion of knee flexion and internal rotation demonstrated by stable and control groups.
Interpretation: Our findings suggest that knee joint contact mechanics and kinematics are altered during the loading response phase of downhill gait in knee osteoarthritis patients with self-reported instability. The observed longer medial compartment contact point excursions and higher velocities represent objective signs of mechanical instability that may place the arthritic knee joint at increased risk for disease progression. Further research is indicated to explore the clinical relevance of altered contact mechanics and kinematics during other common daily activities and to assess the efficacy of rehabilitation programs to improve altered joint biomechanics in knee osteoarthritis patients with self-reported instability.

1. Introduction

Prevalence of episodic knee instability, described as subjective sensation of buckling, shifting, or giving way of the knee joint, is estimated to be as high as 63–80% in patients with knee osteoarthritis (OA) (Fitzgerald et al., 2004; Knoop et al., 2012; Ramsey et al., 2007). Findings from population-based studies further suggest that knee instability is significantly associated with self-reported and performance-based functional deficits in patients with knee OA (Felson et al., 2007; van der Esch et al., 2012). To this end, Fitzgerald and colleagues reported that up to 44% of knee OA patients participating in an observational study complained of instability affecting their ability to function (Fitzgerald et al., 2004). Felson and colleagues also reported that up to 47% of the Framingham Osteoarthritis study participants who experienced knee instability over the previous 3 months were limited in the kind of work they could do (Felson et al., 2007). These findings suggest that self-reported instability is an important and relevant independent variable related to function in patients with knee OA.

To date, little work has been done to evaluate the potential alterations in dynamic knee joint function in knee OA patients with self-reported instability. Previous reports indicate that knee OA patients with self-reported instability demonstrate decreased knee flexion excursions during level and downhill gait compared to volunteers without

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http://dx.doi.org/10.1016/j.clinbiomech.2014.04.014
0268-0033/

knee OA or self-report of instability (Farrokhi et al., 2012; Schmitt and Rudolph, 2007). However, since reduced knee flexion excursions have also been reported for knee OA patients without self-reported instability (Briem and Snyder-Mackler, 2009; Childs et al., 2004), the exact contribution of either knee OA or self-reported instability to the observed alterations in gait kinematics cannot be clearly elucidated from these studies and warrants further investigation. It also stands to reason that the subjective sensation of instability reported by patients with knee OA may be the result of excessive movements of the joint contact surfaces detected by proprioceptive joint receptors (Sharma, 1999). However, no previous attempts have been made to evaluate knee joint contact mechanics during a dynamic activity in this patient population.

Current literature is also void of objective measures of functional instability in patients with knee OA. If an objective measure of instability could be identified, mechanism-based interventions to address functional instability in patients with knee OA could be devised and implemented. Van der Esch and colleagues recently hypothesized that increased knee varus/valgus motion during gait may be a potential objective sign of joint instability in patients with knee OA as healthy knees move through minimal amounts of frontal-plane motion (van der Esch et al., 2008). However, their findings suggested that knee varus/valgus motion during gait is not related to biomechanical variables responsible for joint stability such as muscle strength, joint proprioception, laxity or skeletal alignment, and therefore cannot be used as a valid measure of joint instability. This conclusion should be interpreted with caution; however, as major skin-related movement artifacts associated with the video-based optoelectronic gait analysis approach used in this study may have limited accurate quantification of knee varus/valgus motion during gait (Benoit et al., 2006; Leardini et al., 2005). Additionally, only static correlates of joint instability were evaluated which may provide an incomplete picture of how varus/valgus motion may relate to dynamic joint instability. Therefore, additional studies to identify objective signs of knee joint instability in patients with knee OA are needed.

The aim of current study was to evaluate kinematics and contact mechanics of the knee joint during the loading response phase of downhill gait in knee OA patients with self-reported instability compared to knee OA patients without instability and a control group without knee OA or instability. We hypothesized that self-reported instability in patients with knee OA will be associated with biomechanical evidence of joint instability consisting of excessive and higher velocity joint contact excursions and knee rotations.

2. Methods

2.1. Participants

All subjects provided signed informed consent approved by the University of Pittsburgh's institutional review board. Participants in the study were stratified into one of following three groups: 1) an "unstable" group of knee OA patients with self-reported instability; 2) a "stable" group of knee OA patients without instability; and 3) a "control" group of volunteers without knee OA or self-reported instability. Participants were included in the stable and unstable groups if they: 1) met the American College of Rheumatology classification criteria for knee OA (Altman et al., 1986), and 2) demonstrated primary medial compartment knee OA of grade II or greater according to the Kellgren and Lawrence (KL) radiographic severity rating scale (Kellgren and Lawrence, 1957). Knee OA patients with coexisting lateral compartment disease with KL grades less than the involved medial compartment and patients with bilateral knee OA were deemed eligible for the study and were included in the analysis. Participants in the unstable group also had to have a self-reported knee instability rating of $\leq$3 on the knee stability scale indicating that the patient perceived the symptom of instability to be affecting their ability to perform activities of daily living (Fitzgerald et al., 2004). To be included in the control group, participants had to have no history of knee pain and a KL radiographic grade of $\leq$1.

Participants were excluded if they had a past history of traumatic knee injury, total joint arthroplasty, cardiovascular disease, or neurological disorders that affected lower extremity function. To ensure safe participation in the study, individual patients were also excluded if they required the use of an assistive device for ambulation, reported a history of two or more falls within the previous year, or if they reported lack of confidence in ambulating a distance of 30.5 m (100 ft) without an assistive device.

2.2. Testing procedures

Dynamic Stereo X-ray (DSX) methods were used to quantify 3D joint kinematics and tibiofemoral contact mechanics from biplane radiographic images acquired during the loading response phase of downhill gait. Loading response was selected as a critical time period associated with high demands on the knee joint and reports of dynamic alignment change in patients with knee OA (Astephen and Deluzio, 2005; Schipplein and Andriacchi, 1991). Participants were positioned on a treadmill within the biplane X-ray system so that the knee of interest would remain in the system's 3D imaging volume throughout the loading response phase of gait. For participants with knee OA, the knee in which they reported symptoms or episodes of instability was designated as the test knee. In cases where both knees experienced symptoms, the more problematic knee was designated as the test knee. For control participants, the knee from the dominant lower limb was designated as the test knee.

The biplane X-ray system contained two X-ray gantries that were configured with their beam paths intersecting at 60° in a plane parallel to the floor. Each gantry contained a 100 kW pulsed X-ray generator (CPX 3100CV; EMD Technologies, Quebec, Canada), a 40 cm image intensifier (Thales, Neuilly-sur-Seine, France), and a high-speed 4 megapixel digital video camera (Phantom v10, Vision Research, Wayne, New Jersey, USA). The X-ray generators were customized to provide short-duration pulses at very high repetition rates. For the current study, radiographs were generated with a 1 ms pulse width at 100 Hz, with a maximum radiographic protocol of 90 kVp/200 mA and a 1 s collection time (100 ms total X-ray exposure) per trial.

Participants' knees were imaged during a moderately declined gait condition (7% grade, 0.75 m/s) on an instrumented treadmill (Bertec Corp., Columbus, OH, USA) due to the frequent patient reports of knee instability during this task. To this end, previous reports indicate that downhill gait is more demanding on the knee joint as it leads to significant increases in knee flexion angle, vertical ground reaction force and knee joint moments compared to level gait (Kuster et al., 1995; Lay et al., 2006; McIntosh et al., 2006; Redfern, 1997). Data was collected for 3 individual downhill gait trials and averaged for statistical analysis. For each trial, the X-ray system was triggered manually prior to heel contact to record a 200 ms time period. The loading response phase was then defined as the first 20% of the stance phase of gait after heel contact determined from the vertical ground reaction force profile (Perry and Burnfield, 2010). For safety, participants were attached to an overhead harness system during all gait trials.

2.3. Quantification of knee joint kinematics

All participants also underwent computed tomography (CT) imaging of their knee using a GE LightSpeed CT Scanner (LightSpeed Pro 16, GE Medical Systems, Fairfield, Connecticut, USA). The CT field of view was approximately 28 × 28 cm, slice thickness ranged from 0.6 to 1.25 mm, and in-plane resolution was approximately 0.55 mm per pixel. The CT images were reconstructed to create 3D bone models of the distal femur and proximal tibia (Tashman and Anderst, 2003). The tibia and femur were manually segmented and feature-based interpolation was performed to create 3D bone models using MIMICS (Materialise Inc., Ann Arbor, Michigan, USA). A model-based tracking algorithm was