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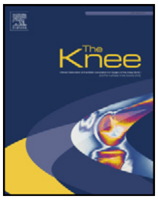

Knee joint contact mechanics during downhill gait and its relationship with varus/valgus motion and muscle strength in patients with knee osteoarthritis☆

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ABSTRACT

Objective: The objective of this exploratory study was to evaluate tibiofemoral joint contact point excursions and velocities during downhill gait and assess the relationship between tibiofemoral joint contact mechanics with frontal-plane knee joint motion and lower extremity muscle weakness in patients with knee osteoarthritis (OA).
Methods: Dynamic stereo X-ray was used to quantify tibiofemoral joint contact mechanics and frontal-plane motion during the loading response phase of downhill gait in 11 patients with knee OA and 11 control volunteers. Quantitative testing of the quadriceps and the hip abductor muscles was also performed.
Results: Patients with knee OA demonstrated larger medial/lateral joint contact point excursions ($p < 0.02$) and greater heel-strike joint contact point velocities ($p < 0.05$) for the medial and lateral compartments compared to the control group. The peak medial/lateral joint contact point velocity of the medial compartment was also greater for patients with knee OA compared to their control counterparts ($p = 0.02$). Additionally, patients with knee OA demonstrated significantly increased frontal-plane varus motion excursions ($p < 0.01$) and greater quadriceps and hip abductor muscle weakness ($p = 0.03$). In general, increased joint contact point excursions and velocities in patients with knee OA were linearly associated with greater frontal-plane varus motion excursions ($p < 0.04$) but not with quadriceps or hip abductor strength.
Conclusion: Altered contact mechanics in patients with knee OA may be related to compromised frontal-plane joint stability but not with deficits in muscle strength.

1. Introduction

An accumulating body of scientific evidence suggests that altered gait mechanics may play a role in onset and progression of knee osteoarthritis (OA) [1,2]. To this end, Andriacchi and colleagues [1] have previously proposed that the mechanical breakdown of the articular cartilage may be the result of abnormal motions that shift the joint contact point to infrequently loaded areas of the knee joint. Shifts in the areas of load-bearing to regions in the cartilage that have not adapted to the high customary loads of daily activities can cause surface-zone fibrillations and loss of articular cartilage surface lubrication which can lead to increased friction and large tangential shear stresses [3]. In response to the elevated shear stress, chondrocyte production of catabolic mediators is upregulated, leading to greater matrix damage and a progressive cascade of cartilage loss [4,5]. Once the OA sequence has begun, the articulating surfaces respond negatively to the cyclical ambulatory compressive loads and shear stresses which lead to further cartilage degradation and disease progression [3]. To date, evidence in support of altered knee joint contact patterns during gait in patients with knee OA remains scant due to the technical challenges associated with direct evaluation of in-vivo knee contact mechanics.

Altered patterns of knee joint contact during gait in patients with knee OA could theoretically occur due to age-associated changes in the musculoskeletal system such as deficits in lower extremity muscle strength and/or presence of joint instability. Muscles of the lower extremity have been indicated to play a critical role in the preservation of normal knee joint function by providing dynamic knee joint stability and shock absorption, while maintaining safe transfer of forces across the joint [6,7]. As such, weakness of the quadriceps muscle has long

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been considered as a strong risk factor for onset [8–10] and progression [11] of knee OA. More recently, increasing research evidence indicate that the commonly observed impairments of the hip abductor musculature can also contribute to the pathomechanics of knee OA [12–15] and a greater likelihood of disease progression [16]. However, reports from randomized clinical trials of quadriceps and hip abductor muscle strengthening suggest that despite improvements in pain and function, stronger quadriceps or hip abductor muscles do not reduce the ambulatory compressive loads often associated with the pathomechanics of knee OA [13,17–20]. Therefore, the mechanism(s) by which stronger muscles contribute to the reported clinical improvements in pain and function after muscle strengthening remains unclear.

A potential hypothesis related to the role of stronger muscles in providing clinical benefits for patients with knee OA may be through providing increased dynamic knee joint stability to compensate for the previously reported increases in knee joint laxity in arthritic knees [21,22]. In support of this notion, recent evidence suggests that lower extremity muscle weakness may be associated with self-reports of knee joint instability in patients with knee OA [23,24]. Knee joint instability can be mechanically defined as increased total motion or high velocity displacements and rotations of the tibia with respect to the femur in arthritic compared to healthy knees and has been linked to altered gait mechanics in patients with knee OA [21]. Given that healthy knees move through minimal amounts of frontal-plane knee joint motion during weightbearing [25,26], increased varus/valgus motion of the knee joint during gait has been suggested as a potential sign of compromised knee joint stability [27]. Increased varus/valgus motion could contribute to the etiology of knee OA by shifting the location and movements of the tibiofemoral joint contact points, thus altering the patterns of knee joint loading. To date, evidence in support of the associations between increased varus/valgus knee joint motion and altered joint contact patterns in patients with knee OA remains limited.

The primary purpose of this study was to evaluate the differences in tibiofemoral joint contact point excursions and velocities between patients with knee OA compared to a control group of older adults without knee OA during the loading response phase of downhill gait. Downhill gait was selected as a frequently reported problematic task in patients with knee OA that challenges both knee stability and lower extremity muscle strength. Additionally, the secondary aim of this study was to assess the linear association between knee joint contact point excursions and velocities with frontal-plane varus/valgus knee joint motion excursions and quadriceps and hip abductor muscle strength in patients with knee OA. It was hypothesized that compared to the control group, patients with knee OA would demonstrate evidence of greater and more abrupt tibiofemoral joint contact point motion during the loading response phase of downhill gait that are associated with increased varus/valgus motion excursions and quadriceps and hip abductor muscle weakness.

2. Materials and methods

2.1. Subjects

Eleven patients with symptomatic, medial compartment knee OA participated in this study. All knee OA patients met the American College of Rheumatology classification criteria for knee OA [28] and demonstrated primary medial compartment radiographic knee OA of at least grade II or higher according to the Kellgren and Lawrence radiographic severity rating scale [29]. A control group of 11 older adults without radiographic evidence of knee OA was recruited to undergo identical testing to the knee OA group. Participants were excluded, regardless of group designation, if they had a past history of traumatic knee injury or knee surgery, lower extremity total joint arthroplasty or if they required use of an assistive device or a rest period to walk a distance of 30.5 m (100 ft). All participants were informed as to the nature of the study and signed an informed consent form approved by the Institutional Review Board of the University of Pittsburgh.

2.2. Dynamic Stereo X-ray testing procedures

Dynamic Stereo X-ray (DSX) methods were used to quantify 3-dimensional (3D) tibiofemoral joint kinematics from biplane radiographic images. 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 four 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 one millisecond pulse width at 100 Hz, with a maximum radiographic protocol of 90 kVp/200 mA and a one second collection time (100 ms total X-ray exposure) per trial.

Participants' knees were imaged during a downhill gait condition (seven percent grade, 0.75 m/s) on an instrumented treadmill (Bertec Corp., Columbus, OH, USA). The decision to use a downhill gait condition was made based on our previous clinical experience with patients with knee OA who reported frequent difficulty and pain while walking downhill. To this end, downhill walking has been suggested to be more demanding on the knee joint compared to level gait, as it leads to significant increases in knee flexion angle, vertical ground reaction force and knee joint moments [30–33]. Given that downhill walking also challenges knee joint stability and lower extremity muscle strength [31,34], it represents a reasonable model for assessing knee joint biomechanics during high-demanding daily tasks such as going up or down stairs [35]. Additionally, a relatively slow gait velocity of 0.75 m/s was chosen for our experimental set-up based on the result of our pilot testing demonstrating that most patients with knee OA were unable to walk downhill at higher speeds.

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. 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 [36,37]. For participants with knee OA, the knee in which they reported symptoms or the most painful knee in bilateral cases was designated as the test knee. For control participants, the knee from the dominant lower limb was designated as the test knee. For each subject, data was collected for three individual 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 [38].

2.3. Quantification of knee joint motion

All participants also underwent computed tomography (CT) imaging of the tibiofemoral joint of interest. 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. Single slices through the center of the femoral head and tibial plafond were acquired during the same scan to determine the mechanical axis of the lower extremity. The tibia and femur were manually segmented from the CT images and custom software was used to perform feature-based interpolation to create 3D bone models [39]. A model-based tracking algorithm was then employed to determine 3D joint motion by matching the radiographic images with projections through the 3D volumetric bone models [40].