Medical Engineering and Physics 000 (2017) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

In vivo tibiofemoral skeletal kinematics and cartilage contact arthrokinematics during decline walking after isolated meniscectomy

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ARTICLE INFO

Article history:
Received 18 October 2016
Revised 16 October 2017
Accepted 29 October 2017
Available online xxx

Keywords:
In vivo
Tibiofemoral kinematics
Cartilage contact
Meniscectomy
Dynamic stereo-radiography

ABSTRACT

We investigated the effects of isolated meniscectomy on tibiofemoral skeletal kinematics and cartilage contact arthrokinematics *in vivo*. We recruited nine patients who had undergone isolated medial or lateral meniscectomy, and used a dynamic stereo-radiography (DSX) system to image the patients' knee motion during decline walking. A volumetric model-based tracking process determined 3D tibiofemoral kinematics from the recorded DSX images. Cartilage contact arthrokinematics was derived from the intersection between tibial and femoral cartilage models co-registered to the bones. The kinematics and arthrokinematics were analyzed for early stance and loading response phase (30% of a gait cycle), comparing the affected and intact knees. Results showed that four patients with medial meniscectomy had significantly greater contact centroid excursions in the meniscectomized medial compartments while five patients with lateral meniscectomy had significantly greater cartilage contact area and lateral shift of contact centroid path in the meniscectomized lateral compartments, comparing to those of the same compartments in the contralateral intact knees. No consistent difference however was identified in the skeletal kinematics. The current study demonstrated that cartilage-based intra-articular arthrokinematics is more sensitive and insightful than the skeletal kinematics in assessing the meniscectomy effects.

1. Introduction

Meniscectomy—the surgical removal of a portion or the entirety of an injured meniscus—is one of the most frequently performed orthopedic procedures [1]. It is known, however, to have deleterious consequences such as degenerative joint changes and accelerated onset of osteoarthritis (OA) [2,3]. Accurate assessment of the effects of meniscectomy on joint motion and contact congruity is an initial but critical step in understanding how patho-mechanics instigates the development of OA [4]. Data resulting from such assessment would also serve as baselines for evaluating the efficacy of alternative repair strategies and post-meniscectomy interventions such as meniscus transplantation [5].

The effects of meniscectomy on tibiofemoral joint function or mechanics have been examined by in vitro cadaveric studies and in vivo motion analysis studies [5–8]. With an in vitro experimental model, Spang et al. [5] discovered that total medial meniscectomy increased anterior cruciate ligament (ACL) strain and anterior tibial translation. The latter effect on anterior tibial translation was contrary to the conclusion from an earlier in vitro study [6]. This disparity, as well as the methodological inconsistency speculated to have caused it, reflects the limitations of in vitro studies: testing conditions, including combinations of kinematics and loading, and types of simulated meniscectomy, cannot be made physiological variable. It is a formidable challenge for cadaveric studies to replicate the complex combination of and interplay between the gravitational, inertial and active muscular forces. Sturnieks et al. [7] performed the first *in vivo* gait analysis of pain-free meniscectomy patients and reported reduced range of motion and lower peak moments in the sagittal plane on the operated limb comparing to the nonoperated limb. Netravali et al. [8] conducted *in vivo* biomechanical study of patients with partial medial meniscectomy and identified significant kinematic and kinetic differences between the meniscectomized and contralateral intact knees. The

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https://doi.org/10.1016/j.medengphy.2017.10.014
1350-4533/

Please cite this article as: L. Zheng et al., In vivo tibiofemoral skeletal kinematics and cartilage contact arthrokinematics during decline walking after isolated meniscectomy, Medical Engineering and Physics (2017), https://doi.org/10.1016/j.medengphy.2017.10.014

Table 1
Arthroscopic assessment of the meniscal condition for the patients with medial or lateral meniscectomy.

(a) Four patients with medial meniscectomy

	Injured knee	Description of injured meniscus
S2	Left	66% of posterior horn, 0% mid portion and 66% anterior horn remaining.
S3	Right	66% of posterior horn, 0% mid portion and 100% anterior horn remaining.
S5	Right	66% of anterior horn, 33% of mid portion and 100% of posterior horn remaining.
S6	Right	lost most of the posterior and medial portion of the medial meniscus with only 20% of rim remaining, 66% of anterior horn remaining

(b) Five patients with lateral meniscectomy

	Injured knee	Description of injured meniscus
S1	Left	33% of posterior horn, less than 33% of mid body, 50% of anterior horn remaining.
S4	Left	33% in all posterior, mid, and anterior regions remaining; early arthritis of left knee; grade 3 change in weight-bearing area of posterior horn.
S7	Right	0% of posterior horn, 33% (or less) of mid portion, and 100% of anterior horn remaining.
S8	Right	balanced and stable rim with 50% of meniscus remaining.
S9	Left	total lateral meniscectomy.

study employed surface-based measurement of tibiofemoral kinematics and a point cluster method [9,10] to mitigate skin motion artifacts that otherwise could be substantial enough to obscure the effect or difference of interest [11,12]. However, no study has yet to attain measures that delineate intra-articular cartilage contact or interactions which are more pertinent to the fundamental patho-mechanics of meniscectomy. Previous studies that investigated the knee cartilage contact have typically involved magnetic resonance imaging (MRI) and most of studies were for in vitro conditions or in vivo low-speed movements [13–17]. A newly validated approach at our center combining accurate bone kinematics data from biplane radiography with cartilage models from MRI is ready for noninvasively assessing *in vivo* cartilage contact during functional activities—the accuracy of cartilage contact estimation has been comprehensively validated in vitro against a laser scanning gold standard under multiple body weight loading and over a range of knee flexion angles (with root mean square errors in contact area averaged 8.4% and 4.4% of the medial and lateral compartmental areas, respectively) [18]. One challenge associated with experimental study of the biomechanical effects of meniscectomy is the variability of meniscectomy presented. The difficulty of accurately estimating and resecting the desired percentage of the meniscus intra-operatively, even with a meniscal measuring device, has been reported [19]. This, in addition to the natural variability of the types of meniscus injury that necessitate the meniscectomy, makes it particularly challenging to achieve a study cohort with well controlled clinical or surgical variables. On the other hand, coping with rather than controlling the variability may afford a valuable opportunity to elicit insight into what is common or remains invariant across patients or cohorts.

In this study, we investigated three-dimensional (3D) *in vivo* tibiofemoral skeletal kinematics and arthrokinematics (cartilage contact kinematics) of meniscectomized knees using a state-of-art dynamic stereo-radiographic (DSX) imaging system in our facility, where the similar approach has been validated [18]. We sought to take advantage of the system's sub-millimeter accuracy in translation and sub-degree accuracy in rotation [20] in detecting the following hypothesized effects of meniscectomy: (1) altered three-dimensional tibiofemoral kinematics, (2) increased cartilage contact area and deformation, and (3) altered tibiofemoral cartilage contact locations and trajectories.

2. Materials and methods

We recruited nine patients (six females and three males)—age: 25 ± 11 (18–53) years old [average ± standard deviation (range)]; weight: 80.2 ± 22.0 (46.2–112.0) kg; height: 177.8 ± 9.1 (162.0–187.0) cm; BMI: 25.0 ± 5.2 (17.6–33.0), who had undergone unilateral subtotal or total meniscectomy (four medial and five lateral meniscectomy; Table 1) to participate in this study. These patients were identified from candidates who were scheduled for meniscal allograft transplantation surgery. The condition of patients' meniscectomized meniscus (such as the location and portion of removed tissue) was arthroscopically examined and documented (Table 1) by the operating surgeon (CHD), and further confirmed by processed MRI data (pixel size = 0.365×0.365 mm^2, slice thickness = 0.7 mm, pixel resolution = 384×384 pixels, field of view = 14.0 cm, number of slices = 160). The participants had no other knee injuries (such as deficient anterior or/and posterior cruciate ligaments), total joint arthroplasty, cardiovascular disease or neurological disorders that affected lower extremity function. Pregnancy tests were performed prior to the experiment to exclude pregnant participants. This study was approved by the University of Pittsburgh Institutional Review Board (IRB) and informed consent was obtained from all participants.

During the experiment, the participants performed decline-walking trials (15° tilted with respect to the ground) on a dual-belt instrumented treadmill at 1.0 m/s (Fig. 1). The DSX system imaged both knees in motion (1-s duration including heel strike) at a frame rate of 100 Hz (X-ray parameters: 80 KV, 125 mA, 1 ms pulse width). The ground reaction forces (GRFs) were measured at 1000 Hz by two force plates (Bertec Corporation, Columbus, OH) embedded in the treadmill. CT scans (slice spacing: 0.625 mm; in-plane resolution: 0.3125 mm) of both knees were also collected prior to the DSX testing. The 3D femoral and tibial bone models were reconstructed from the CT images using a combination of commercial software (Mimics, Materialise, Leuven, Belgium) and manual segmentation.

A volumetric model-based tracking process determined 3D tibiofemoral kinematics using recorded DSX images and CT-acquired bone models [20]. All collected frames (100 frames per second) were processed in the tracking process. A 10 Hz low-pass filter (8th-order Butterworth) was employed to reduce noise from the 3D tracking results before calculating the kinematics. The six-degree-of-freedom (6-DOF) tibiofemoral kinematics including anterior-posterior (AP), proximal-distal (PD) and lateral-medial (LM) translations and internal-external rotation, abduction-adduction and flexion-extension were expressed in the tibial and femoral anatomical coordinate systems defined based on CT-acquired bone models [21]. The translations were expressed in the tibial anatomical coordinate system, while the rotations of the tibia relative to the femur were defined with respect to the femoral anatomical coordinate system. A gait cycle was defined to begin at heel strike and end at the same heel hitting the ground again, consistently identifiable from the vertical GRF profile.

Please cite this article as: L. Zheng et al., In vivo tibiofemoral skeletal kinematics and cartilage contact arthrokinematics during decline walking after isolated meniscectomy, Medical Engineering and Physics (2017), https://doi.org/10.1016/j.medengphy.2017.10.014