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Tibio-femoral joint contact in healthy and osteoarthritic knees during quasi-static squat: A bi-planar X-ray analysis

A. Zeighami [a,*], R. Dumas [b], M. Kanhonou [a], N. Hagemeister [a], F. Lavoie [c], J.A. de Guise [a], R. Aissaoui [a]

[a] Laboratoire de Recherche en Imagerie et Orthopédie (LIO), École de Technologie Supérieure (ÉTS), Centre de Recherche du CHUM, Montréal, Québec, Canada
[b] Univ Lyon, Université Claude Bernard Lyon 1, IFSTTAR, UMR_T9406, LBMC, F69622 Lyon, France
[c] Department of Orthopedic Surgery, Centre Hospitalier de l'Université de Montréal (CHUM), Montréal, Québec, Canada

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ABSTRACT

The aim of this study was to quantify the tibio-femoral contact point (CP) locations in healthy and osteoarthritic (OA) subjects during a weight-bearing squat using stand-alone biplanar X-ray images.

Ten healthy and 9 severe OA subjects performed quasi-static squats. Bi-planar X-ray images were recorded at 0°, 15°, 30°, 45°, and 70° of knee flexion. A reconstruction/registration process was used to create 3D models of tibia, fibula, and femur from bi-planar X-rays and to measure their positions at each posture. A weighted centroid of proximity algorithm was used to calculate the tibio-femoral CP locations. The accuracy of the reconstruction/registration process in measuring the quasi-static kinematics and the contact parameters was evaluated in a validation study.

The quasi-static kinematics data revealed that in OA knees, adduction angles were greater ($p < 0.01$), and the femur was located more medially relative to the tibia ($p < 0.01$). Similarly, the average CP locations on the medial and lateral tibial plateaus of the OA patients were shifted (6.5 ± 0.7 mm; $p < 0.01$) and (9.6 ± 3.1 mm; $p < 0.01$) medially compared to the healthy group. From 0° to 70° flexion, CPs moved 8.1 ± 5.3 mm and 8.9 ± 5.3 mm posteriorly on the medial and lateral plateaus of healthy knees; while in OA joints CPs moved 10.1 ± 8.4 mm and 3.6 ± 2.8 mm posteriorly. The average minimum tibio-femoral bone-to-bone distances of the OA joints were lower in both compartments ($p < 0.01$).

The CPs in the OA joints were located more medially and displayed a higher ratio of medial to lateral posterior translations compared to healthy joints.

1. Introduction

An estimation of the *in vivo* 3D kinematics, the contact point (CP) locations, and the minimum distance between articular surfaces of knee joints can provide information that is useful in understanding osteoarthritis (OA) initiation and progression. Andriacchi et al., (2004) hypothesized that shifts in load-bearing CP locations towards less frequently loaded regions (i.e., far from the plateau center lines) initiate the cartilage degeneration process. However, the direction of the shift was not indicated in their proposed framework. A few literature studies have addressed CP locations in pathological knees. Experimental locations of CPs in anterior cruciate ligament (ACL)-reconstructed (Hoshino and Tashman, 2012), ACL-deficient (Dennis et al., 2005), and OA knees (Fiacchi et al., 2014; Hamai et al., 2009; Li et al., 2015) have been investigated using 3D-to-2D registration techniques during different activities such as kneeling, squatting, stair climbing, chair rising, and lunge, but still little is known about the quantitative differences in CP locations between OA and healthy subject during functional activities.

In 3D-to-2D registration techniques, bones are reconstructed from MRIs (Koo et al., 2011; Qi et al., 2013) or CT-scans (Farrokhi et al., 2016; Fiacchi et al., 2014; Hamai et al., 2009) and are then rigidly transformed to match X-ray or fluoroscopic images captured during movements. In MRI-derived models, cartilage overlap was used to identify CP locations, whereas in the CT-scan-derived

* Correspondence to: Imaging and Orthopaedics Research Laboratory (LIO), École de Technologie Supérieure, The CHUM Research Centre, Viger tower, 900 St-Denis, Room R11.322, Montréal, QC, Canada H2X0A9.

E-mail addresses: zeighamiali87@gmail.com, ali.zeighami.1@ens.etsmtl.ca (A. Zeighami), raphael.dumas@ifsttar.fr (R. Dumas), michele.kanhonou@gmail.com (M. Kanhonou), Nicola.Hagemeister@etsmtl.ca (N. Hagemeister), fredericlavoiemd@gmail.com (F. Lavoie), jacques.deguise@etsmtl.ca (J.A. de Guise), Rachid.Aissaoui@etsmtl.ca (R. Aissaoui).

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models, due to the absence the of cartilage layer in the reconstructions, the bone-to-bone closest point or a weighted center of tibio-femoral proximity has been used to determine the location of CPs.

Hamai et al. (2009) and Fiacchi et al. (2014) investigated the tibio-femoral anterior/posterior CP locations of OA subjects. However, they did not quantify the possible medial/lateral shifts in the CP locations. Li et al. (2015) reported that in OA knees the center of the medial and lateral CPs was located at the medial side of the tibia by 3.7% plateau width during a lunge activity. OA CPs were located medial to the both medial and lateral plateau centerlines throughout the lunge. After a posterior cruciate-retaining total knee arthroplasty, CPs had shifted laterally and had a reduced range of motion. In a recent study by Farrokhi et al. (2016), the excursion of CPs during a downhill gait task was found to be altered in the unstable OA group compared to healthy controls. The CP locations in the two groups during flexion were not reported in their study. Although previous works increase our knowledge of contact in OA, none of these studies compared the regions of contact in OA with healthy subjects, and a clear description of alterations in CP locations in OA is still lacking. Case-control studies comparing tibio-femoral CP locations between OA and healthy subjects are required before drawing any conclusion on altered tibio-femoral contact in OA.

The objective of the present study was to compare tibio-femoral CP locations of healthy and OA subjects during a load-bearing squat. We used a reconstruction/registration process based on stand-alone bi-planar X-ray images to quantify the contact parameters of OA and healthy joints. We hypothesized that the CPs in OA subjects would shift medially on both tibial plateaus with respect to the healthy controls.

2. Methodology

2.1. Study subjects

Nineteen subjects volunteered to participate in this study. They included 10 healthy subjects (4 women, 6 men, 5 right sides, 5 left sides, age 55 ± 17 years, weight 69 ± 20 kg, height 1.67 ± 0.17 m, body mass index (BMI) 24.67 ± 5.33 kg/m^2) and 9 medial compartment OA subjects (2 men, 7 women, 7 right sides, 2 left sides, age 61 ± 9 years, weight 89 ± 15 kg, height 1.63 ± 0.12 m, BMI 33.35 ± 7.23 kg/m^2). The OA subjects were classified as grade 4 using the Kellgren–Lawrence grading scale. The subjects did not have any self-reported meniscus or ligament injuries. The following procedures were in accordance with the ethics committees of the Centre de recherche, centre hospitalier de l'Université de Montréal (CRCHUM) and École de technologie supérieure de Montréal (ÉTS) as well as the Helsinki Declaration of 1975, as revised in 2000.

2.2. Bi-planar X-ray images

The EOS™ (EOS Imaging, Paris, France) bi-planar, low-radiation dose system recorded 5 pairs of orthogonal X-ray images of the lower limb at 0°, 15°, 30°, 45°, and 70° of knee flexion. The subjects performed controlled quasi-static squats assisted by a positioning jig (Clément et al., 2014) (Fig. 1(a)). Two digital X-ray images of the whole lower limb were captured simultaneously at each position.

2.3. Reconstruction/registration

The first pair of X-ray images in a standing posture was processed using IdefX software (LIO, Montreal, Quebec, Canada) to reconstruct the 3D personalized models of the tibia, femur, and fibula. This was performed starting with a generic 3D model of each segment. Each generic 3D model was then deformed and reconstructed via an as-rigid-as-possible approach based on the moving least squares optimization method until its projected contours on 2 radiographic planes matched the boundaries of the bones on biplanar X-rays (Cresson et al., 2010). The average reconstruction error of the bones using this technique was found to be 1 mm (STD = 0.9 mm) (Cresson et al., 2010).

To find the configuration in the other squat positions, the reconstructed bones were transformed rigidly until their silhouettes superimposed the acquired bi-planar X-ray images of each position (Fig. 1(b)). Translations and rotations were calculated based on an iterative closest point algorithm (Kanhonou et al., 2014).

Through a fine-tuning process in each of the 5 squat positions, the reconstructions and registrations were further modified to take into account the features in the X-ray images that are not visible in other views. The final fit was decided by the operator based on the best possible visual matching of segmentations with background X-ray images in all 5 positions. The whole process took up to 90 min for each subject.

2.4. Quasi-static kinematic measurements

Orthogonal local coordinate systems were constructed on tibia/fibula and femur according to the anatomical definitions given in previous studies (Südhoff, 2007) (Fig. 2). Flexion/extension, adduction/abduction, and internal/external rotations were measured according to the coordinate system proposed by Grood and Suntay (1983). Linear displacements were represented by the movement of the origin of the femoral coordinate system with respect to the origin of the tibial

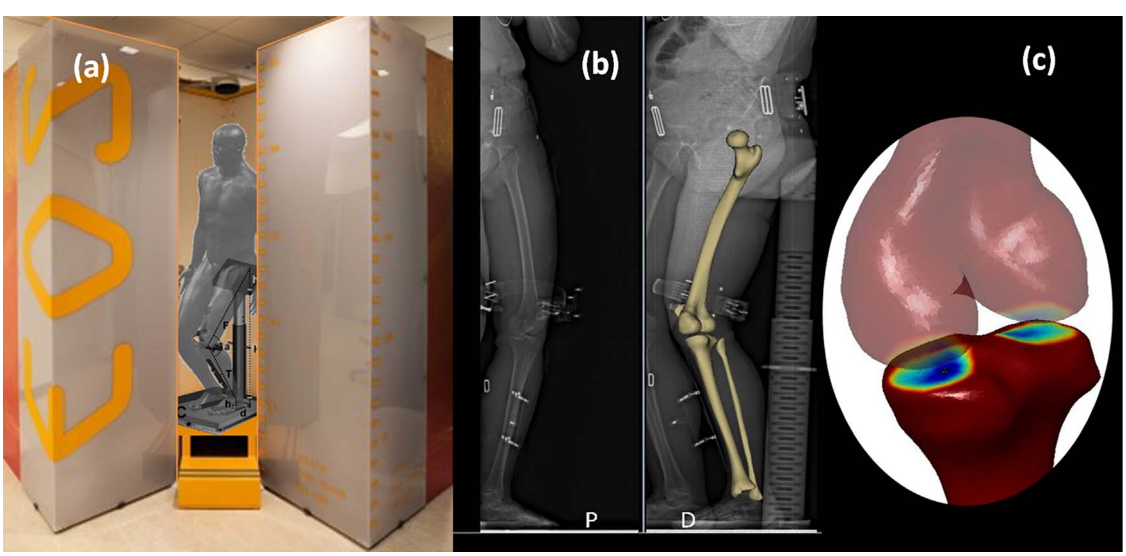

Fig. 1. (a) Subjects performed a quasi-static squat assisted by a positioning jig standardized to put the knee in desired flexion angles. 5 pairs of orthogonal X-ray images of the lower limb at 0°, 15°, 30°, 45°, and 70° of knee flexion were recorded. (b) Bones were reconstructed from bi-planar X-ray images, and registered to each of the 5 squat positions the subjects adopt in the EOS system cabinet. (c) 2 Pairs of points on the medial and lateral sides of the tibia and femur represented CPs and minimum tibio-femoral bone-to-bone distances.

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