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Cartilage loss patterns within femorotibial contact regions during deep knee bend ☆

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ABSTRACT

Osteoarthritis (OA) can alter knee kinematics and stresses. The relationship between cartilage loss in OA and kinematics is unclear, with existing work focusing on static wear and morphology. In this work, femorotibial cartilage maps were coupled with kinematics to investigate the relationship between kinematics and cartilage loss, allowing for more precise treatment and intervention. Cartilage thickness maps were created from healthy and OA subgroups (varus, valgus, and neutral) and mapped to a statistical bone atlas. Video fluoroscopy determined contact regions from 0° to 120° flexion. Varus and valgus subgroups displayed different wear patterns across the range of flexion, with varus knees showing more loss in early flexion and valgus in deeper flexion. For the femur, varus knees had more wear in the medial compartment than neutral or valgus and most wear at both 0° and 20° flexion. In the lateral femoral compartment, the valgus subgroup showed significantly more wear from 20° to 60° flexion as compared to other angles, though varus knees displayed highest magnitude of wear. For the tibia, most medial wear occurred at 0–40° flexion and most lateral occurred after 60° flexion. Knowing more about cartilage changes in OA knees provides insight as to expected wear or stresses on implanted components after arthroplasty. Combining cartilage loss patterns with kinematics allows for pre-surgical intervention and treatments tailored to the patient's alignment and kinematics. Reported wear patterns may also serve as a gauge for post-operative loading to be considered when placing implant components.

1. Introduction

Osteoarthritis (OA) of the knee brings about many changes in the affected joint, ranging from fluctuations in cartilage distribution, development of osteophytes, or subchondral edemas (Moskowitz et al., 2007). Ultimately, these changes are brought about by, and can lead to, abnormal kinematic motion. These kinematic changes alter the distribution of stresses on the articulating surface, often leading to suboptimal loading (Andriacchi et al., 2009). As the knee moves through the various degrees of flexion, the femorotibial contact regions progress from the central compartments of the femur surface to a posterior position (Komistek et al., 2003). It is likely that this contact pattern, and deviations from the described pattern, can give insight into degenerative changes in OA knees. Additionally, these contact regions, and cartilage loss within them, may give insight into expected implant wear patterns, specifically in TKA-utilizing procedures claiming restoration of natural kinematics.

In healthy subjects, the cartilage is thicker in regions that undergo the majority of stresses during normal gait (Koo et al., 2011). Furthermore, Li et al. (2005) showed that the cartilage-to-cartilage contact regions were associated with the thickest cartilage. Eckstein et al. (2008) and Wirth et al. (2009) further studied cartilage loss in the femorotibial joint in OA subjects by segmenting the cartilage plates and assigning regions for statistical analysis. The regions on the articulating surfaces, defined for the femur and the tibia, were located relative to manually selected landmarks as described in Eckstein et al. (2006a, 2006b). The findings by Wirth suggest that centrally located compartments of both joints undergo the majority of cartilage wear. While providing an excellent overview of cartilage loss, there are some shortcomings in the works of Wirth and Eckstein, such as poor resolution and reduced study reproducibility due to manually defined landmarks. One proposed method of high-resolution cartilage quantification across a population is through the use of statistical shape models (SSM), as first described by Cootes et al. (1995).

SSM for shape analysis is fairly common, as the 3D–3D landmark matching allows analogous morphological regions to be compared directly. Mahfouz (2012) have used high resolution SSM of the bony

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anatomy to perform morphological analyses across gender and ethnicities (Mahfouz et al., 2007). SSM of the bone can be used to drive the morphological cartilage analyses, not unlike Fripp et al. (2005), who used SSM for cartilage segmentation but not for degenerative morphology and Williams et al. (2010), who used a form of SSM for morphological analysis – but without a kinematic link. Kinematics were indirectly related to degenerative changes by Wirth et al. (2010) by spatially linking cartilage loss using angular femoral subregions.

In this work, a novel application of SSM is proposed for the purpose of cartilage thickness quantification of the femorotibial joint in healthy and pathological subjects from the Osteoarthritis Initiative, which is available for public access at http://www.oai.ucsf.edu/. The pathological dataset is combined with a kinematic contact analysis of healthy knees, using single plane X-ray video fluoroscopy (Komistek et al., 2003; Mahfouz et al., 2003, Leszko et al., 2011) with surface models having SSM point correspondence. While the motion data and cartilage data were derived from different subjects, the statistical atlas provides a framework for coupling the datasets. By integrating the cartilage model with kinematics *via* SSM correspondence, a link between cartilage wear and flexion angle can be established. This methodology can be applied to existing patient databases to provide high-resolution cartilage maps for degenerative subjects with point-to-point correspondence of cartilage loss for varying knee alignments. This framework for coupling *in vivo* cartilage loss with kinematic contact regions will allow for pre-surgical intervention and patient-specific treatment. It is expected that wear patterns will vary throughout the range of flexion and differ between joint space patterns.

2. Methods

2.1. Bone atlas

In order that we may model the cartilage layer across a population at sufficiently good spatial resolution, a statistical bone atlas is used to define point correspondence and anchor the cartilage layer to the bone. The atlas was created as outlined in previous works by Mahfouz et al. (2006). All data for the atlases were from healthy specimens segmented from CT with resolution of $0.625 \times 0.625 \times 0.625$ mm. For this work, separate atlases for the distal femoral component and proximal tibia component were used. The surface models for the femoral component contained $N = 4120$ vertices and the tibia contained $N = 4182$ vertices. The atlases were further split by gender, so that four atlases were used in total. The male femoral atlas was created from 199 healthy femurs, the female femoral atlas from 112 samples, the male tibia atlas from 89 samples, and female tibia atlas from 151 samples. Both male and female statistical atlases were created with identical point correspondence for each anatomy. Point correspondence, a non-trivial problem, was determined as outlined in Mahfouz et al. (2007) using a combination of registration and warping techniques. Given atlas correspondence, we seek to model cartilage relative to the bone surface as a list of bone vertices (the bone–cartilage interface [BCI]), mean cartilage thickness at each BCI vertex, and standard deviation of the thickness at each BCI vertex.

2.2. Cartilage dataset

Data for cartilage modeling was segmented from magnetic resonance imaging (MRI) datasets. All MRI data used in the preparation of this article were obtained from

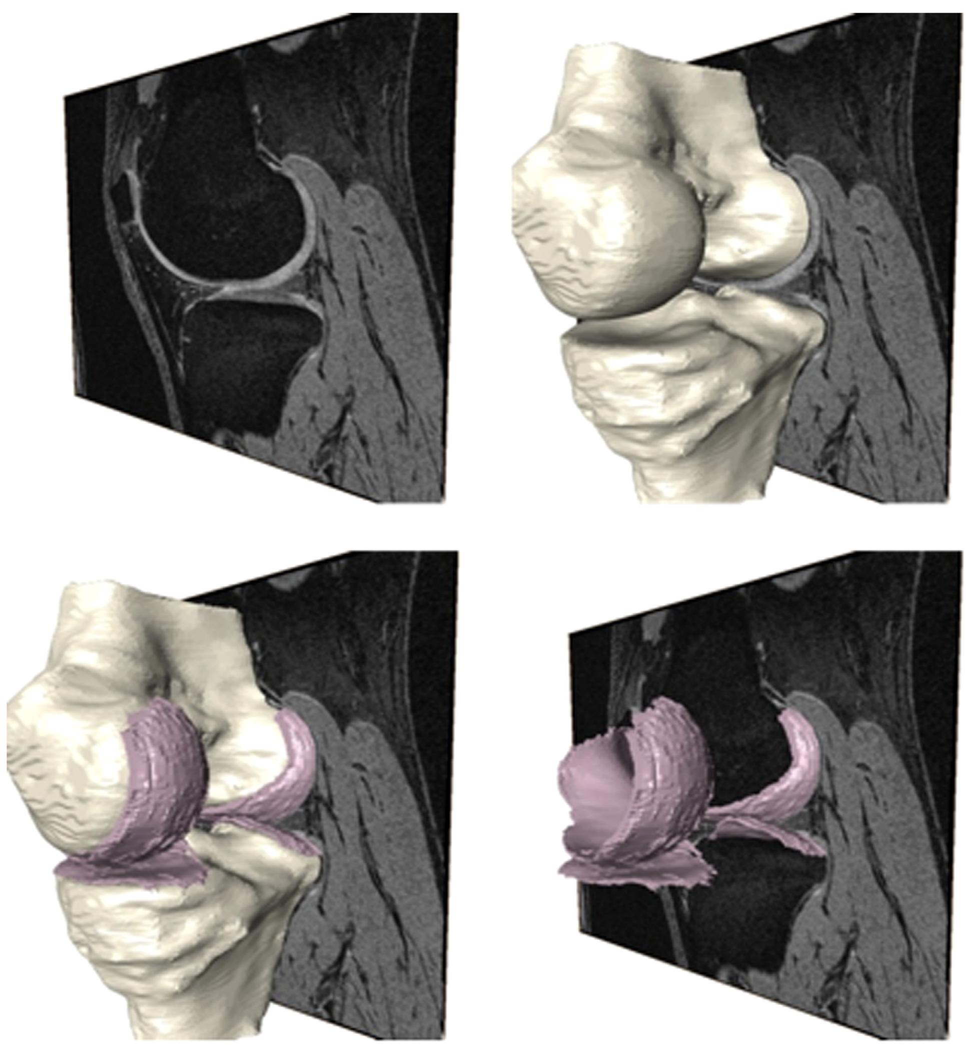

Fig. 1. Sample MRI image set (top left), bone segmentation (top right), cartilage segmentation (bottom right) and complete specimen (bottom left).