MORPHOLOGY AND THICKNESS IN TIBIAL AND FEMORAL CARTILAGE AT THE KNEE IS INFLUENCED BY THE MECHANICS OF WALKING

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INTRODUCTION

Progressive osteoarthritis (OA) of the knee is typically characterized by radiographic measures of joint space narrowing [1]; as newer treatment modalities become available it is important to have new and accurate methods of measuring cartilage thickness. The purpose of this study was to develop methods for determining cartilage thickness, to test normal cartilage for regional variations in thickness, and to relate thickness variations to the mechanics of gait..

METHODS

Three dimensional computer cartilage models were generated to measure the average thicknesses of functional regions on femoral and tibial cartilages. The data was obtained from 11 normal subjects after IRB approval and informed consent (36.2 +/- 11.1 yrs, 1.74 +/-0.03m, 83.0 +/- 10.2 kg). Standard gait analysis was performed on six subjects. The 3D models with thickness color maps are made from knee MR images by the following processes:
(1) MR image acquisition (2) Femur and tibia segmentation from the MR images (3) 3D volume building from the segmented images (4) Thickness color map calculation of the 3D volume (5) Average thickness calculation of each functional region.

MR image acquisition

MR Images were acquired using a 3D spoiled gradient-echo sequence in the sagittal plane. The image specifications of these images are SPGR, 3DFT, fat-saturated, TR=60msec, TE=5msec, flip angle 40°, 1 excitation (NEX), matrix 256x160 elements, rectangular FOV 16x12 cm, slice thickness 1.0 mm, 128 slices.

Femur and Tibia segmentation

The B-spline snake method was used [2,4] with manual initialization to exactly detect the cartilage boundary on each MR image. The segmentation using B-spline Snakes is not fully automatic; rather it requires manual correction as MR images do not always have consistent brightness. This interactive tool allowed feature segmentation in short times with reliable results.

3D volume building from the segmented images

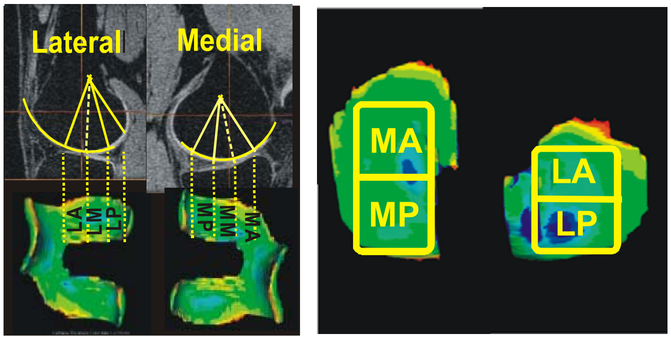
When the segmentation process was completed for all MR images, a 3D model was created from the segmented images using the Marching Cubes algorithm which is a surface rendering algorithm. The Marching Cubes algorithm divides the space which contains a stack of segmented images into regular cubical cells and calculates scalar values at each grid point to create surface patches of each cell. The 3D surface models were then made by connecting these surface patches. The Laplacian smoothing algorithm was used to regularize the surface points.

Thickness color map calculation of the 3D volume

For each point on the surface, normal vectors were calculated and a line was generated using the normal vector and the location of the point. The 3D surface model was regularly triangulated in the process of the Marching Cubes and the Laplacian smoothing algorithms; thus, we could locate the intersection between the line and a triangle on the surface, resulting in a color coded thickness map of the surface.

Average thickness calculation of each functional region

In this study, we divided the femoral cartilage into six regions and the tibial cartilage into four regions to examine average thicknesses and find the cartilage thickness patterns of normal subjects. The regions of interest on the femoral condyles are divided on the basis of the load bearing areas of the knee during locomotion. The greatest and most frequent loads during locomotion take place between 0 and 40 degrees of flexion. This regional division for the lateral and medial condyles is graphically depicted in Figure 1. The knee scanned at full extension was used to define the neutral position by a line drawn from the center of an arc fit through the distal femoral condyles to a central contact location (Dashed lines Figure 1(a)). This neutral position is taken as a reference line, and then three new lines are drawn, at -30, 30, and 60 degrees from the neutral position about the center of the arc through the distal condyles. The regions of interest on the tibia were divided into two regions in each compartment. Lines were constructed to define regions as illustrated in Figure 1(b). The boundaries were constructed by placing a best fit rectangle within 80% of the projected boundaries to the tibial cartilage.



(a) (b)

Figure 1. Regions of Femoral and Tibial Cartilage

Standard gait analysis test

Six of the subjects were tested during level walking at normal, slow and fast speeds. Typically, this protocol produced gait measurements over a range of walking speeds. External knee adduction moment data was acquired using a three-dimensional opto-electronic system and a previously described 6-marker link model of the lower extremity [5].

RESULTS

Average thicknesses of each region were obtained and are shown in Table 1 and Table 2. In the femur, both middle regions on the lateral and medial condyle are thickest and showed a significant difference. Both anterior regions were thinnest and they had similar values. In the tibia, the posterior region in the lateral compartment was the thickest and the lateral compartment was significantly thicker than the medial compartment.

	Lateral	Medial
Anterior	1.75 (0.35)	1.89 (0.23)
Middle*	**2.70 (0.55)**	**2.17 (0.33)**
Posterior	2.39 (0.40)	2.14 (0.42)

Table 1. Average Femoral Cartilage Thickness (mm) : Mean (SD)

	Lateral	Medial
Anterior	2.80 (0.39)	2.24 (0.36)
Posterior*	3.30 (0.48)	2.40 (0.42)

Table 2. Average Tibial Cartilage Thickness (mm) : Mean (SD)

The results of gait analysis for six subjects are shown in Figure 2. The lateral to medial thickness ratio for anterior, middle and posterior regions are calculated and compared with knee adduction moment. The results demonstrate a potential adaptive increase in medial compartment cartilage thickness relative to the lateral compartment with increasing adduction moment. The posterior region and middle region had relatively strong correlations given the small sample size.

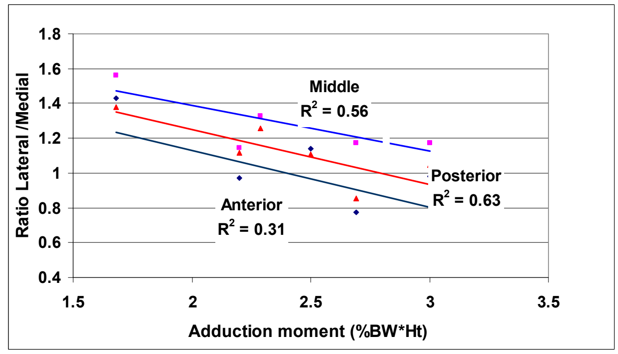


Figure 2. Lateral to Medial Femoral Cartilage Thickness Ratio and Knee Adduction Moment.

DISCUSSION

This study showed significant regional variations in normal cartilage thickness. In agreement with previous studies [3], cartilage was found to be generally thicker on the lateral side than the medial. Further the middle region which bears most of the loads was found to be thicker than anterior and posterior regions in femoral cartilage. For the six subjects whose adduction moments were obtained, we found that the subjects with higher force on medial side have thicker medial cartilage, almost equal to the thickness of the lateral cartilage.

The interpretation of the finding that the cartilage is thicker in the lateral compartment can be explained by anatomical differences in the curvatures between the articulating surfaces in the lateral and medial compartments affecting larger contact stress in the lateral compartment. Finally, the results of this study suggest that normal cartilage responds differently to load than cartilage with osteoarthritis. Cartilage thinning with advancing disease state has been related to increased load in patients with knee osteoarthritis. However, this study shows that normal cartilage tends to thicken with increased load.

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