Comparing Methods for Combining Bone Shape Models in the Tibiofemoral Joint with Knee Osteoarthritis

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INTRODUCTION: Bone shape has been shown to be associated with knee osteoarthritis (KOA) onset and to be predictive of OA development following traumatic knee injury [1,2]. Nearly all shape models (SMs) of the knee joint are created using individual bone surfaces or sets of surfaces arranged by anatomical location [2,3]. While these SMs using sets of combined surfaces naturally represent the correlations in shapes between individual bones they also contain inter-bone orientation and translation variance and inter-subject positioning variance which may overshadow local shape changes. The purpose of this study was to investigate an alternative method of creating combined bone SMs and to compare this novel method with individual bone SMs and combined surface SMs in terms of compactness, surface reconstruction error, and separability in KOA.

METHODS: Segmentations of the tibia and femur from 275 subjects, 55 from each Kellgren-Lawrence (KL) grade, were obtained from the publicly available OAI ZIB dataset, reconstructed using a marching cubes algorithm, and smoothed using improved Laplacian smoothing [4-5]. The subject set was then split into a training and test set of sizes 220 and 55 respectively, with the test set consisting of 11 randomly selected subjects from each KL grade. Three shape models were created, by (I) performing PCA on the tibia and femur surfaces separately, (II) by carrying out a secondary PCA on combined scores generated by the individual surfaces in (I), and (III) by running PCA on the combined tibia and femur surfaces [6]. Generalized Procrustes analysis (GPA) was performed as appropriate for each method to remove size and orientation variance between subjects [7]. The number of principal components (PCs) was truncated based on a 95% variance cutoff for each method, and PC scores were collected for all subjects in the test set. These scores were then used to reconstruct the tibia and femur surfaces in the test set, and the root mean squared errors (RMSEs) were calculated between the reconstructions and original surfaces to evaluate generalizability. Next, the PC scores were separated by KL grade and used to calculate an "OA-score" by projecting the PC scores onto a unit vector pointing from the KL0 group to the KL4 group and dividing by the standard deviation of the KL0 group. The separability of the OA-scores across KL grades, for each model, was quantified by summing the Fréchet distance (FD) between adjacent KL groups, assuming normally distributed OA-scores [8].

RESULTS: The individual femur and tibia models contained 59 (14,847-dimensional) and 54 (9,387-dimensional) PCs, had average RMSEs of 0.49 mm and 0.43 mm, and FDs of 3.02 and 3.03 respectively. The combined score model contained an additional 113 (113-dimensional) PCs resulting in an average RMSE of 0.60 mm and a FD of 3.07, while the combined surface model consisted of 75 (24,234-dimensional) components with an average RMSE of 0.68 mm and FD of 3.01. For the combined surface model, the first two PCs corresponded with flexion-extension (Figure 1) and axial rotation (Figure 2) of the knee joint while those for the individual surface models and combined score models related to the dilation of the femoral condyles and widening of the trochlear groove and widening of the medial tibial plateau and changes in tibial slope (Figure 3).

DISCUSSION: Despite the additional PCA projection of the combined score method, its average RMSE was lower than that of the combined surface method. The combined score method was also more compact than the combined surface methods, requiring nearly 420,000 less shape component values and was more separable than both the individual bone method and the combined surface method. While the individual bone SM method was even more compact and produced the lowest average RMSEs, this method cannot retain the correlations between bones within a subject and would require additional post-processing to model them. The significant size reduction of the combined score method, better characterization of shape variance, and better reconstruction accuracy makes it the superior combined model compared to the combined surface method. Compared to the model with separate bones, the combined score model had slightly higher FD (better OA separability), suggesting that by identifying potential concurrent shape changes between femur and tibia, the combined model may better characterize bone shape changes associated with OA.

SIGNIFICANCE: Improved characterization of the tibiofemoral joint bone shape in KOA could lead to improved diagnostics for the disease

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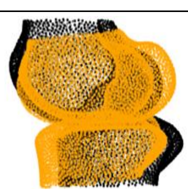

Figure 1. Black and orange figures show +3 std and -3 std, respectively, from the mean along the first principal component of the combined surface model, corresponding primarily to knee flexion-extension.

Figure 2. Same as Figure 1 but with the second principal component (bones shown separately for clarity), corresponding primarily to knee rotation.

Figure 3. Same as Figure 1 but for combined score model (bones shown separately for clarity). The first PC corresponds primarily to femur and tibia shape changes.