

Three-Dimensional MRI-Based Statistical Shape Model of the Knee in Patients with ACL Injuries

Valentina Pedoia¹, Drew Lansdown², Paul Jung¹, C. Benjamin Ma², and Xiaojuan Li¹

¹Department of Radiology and Biomedical Imaging, UCSF, San Francisco, California, United States, ²Department of Orthopedic Surgery, UCSF, San Francisco, California, United States

INTRODUCTION: Statistical Shape Modeling (SSM) is a promising mathematical tool that has the ability to characterize complex shapes in a brief but comprehensive feature vector using Principal Component Analysis (PCA) to reduce the dimensionality of the data. The potential of SSM, coupled with the three-dimensional nature of MR imaging has generated interest in the application to knee osteoarthritis.¹ Anterior cruciate ligament (ACL) injuries are known risk factors for the development of post-traumatic osteoarthritis, with early degenerative changes evident within the first year after injury.² The aim of this work is to apply SSM to MRI in order to analyze the shape of the tibia and femur in patients with ACL injuries to examine for shape differences between control and injured groups as well as determine longitudinal changes in the injured knee following ACL reconstruction.

METHODS: Bi-lateral knees were scanned using a 3 Tesla MRI scanner (GE Healthcare) with an 8-channel phased array knee coil (Invivo) for 10 patients (age = 33.1 ± 4.79, 5 female) with ACL injuries prior to surgical reconstruction, and at 6 and 12 months after surgical reconstruction. Five control patients (age = 31.6 ± 4.04, 1 female) with no history of knee injuries underwent MR imaging at a baseline point and a second scan 12 months later. In total the dataset is composed of 80 knees. The imaging protocol included sagittal T2 fast spin-echo (FSE) images with TR/TE = 4000/49.3ms, slice thickness of 1.5 mm, spacing of 1.5 mm, field of view of 16 cm, 512 x 512 matrix size and echo train length 9. The edge of the tibia and femur are detected semi-automatically in FSE images, a three-dimensional triangulated mesh of the bone is extracted using the Marching Cube algorithm, and a Laplacian smoothing is applied to the mesh, all using in-house developed software. The Statistical Shape Model is extracted individually for the tibia and femur to be invariant to the relative position of the joint. All surfaces of the tibia and femur are rigidly registered so only distinct shape features remain in the model. Landmark identification is performed using a vertex-to-vertex correspondence algorithm that implies the direct matching of the curvature features defined on the surface and regularized by using the spectral coordinates.³ A total of 8,120 and 11,222 landmarks are identified for the tibia and the femur respectively. Before the extraction of the SSM, a preliminary analysis for only control knees is conducted on the landmark matching to assess the reliability of the method. The mean of the distance of the landmarks between the baseline and 12-month follow up is computed for the left and right knees of every case to ensure longitudinal repeatability. This data is compared with the matched landmark distances for each subject's right and left knee (bilateral intra-subject variability) as well as within all subjects (inter-subject variability). PCA is computed on the matched 3D coordinates of the landmarks. PCA provides an orthonormal basis, therefore each mode describes a different aspect of the bone shape. The information in the various bases are uncorrelated and independent. The first ten modes, which represent more than 90% of the entire variability, were analyzed at baseline, and compared between control, ACL-injured and contralateral knees. The longitudinal shape changes of ACL-injured knees were evaluated by calculating the difference in mode values between baseline, 6 month follow-up and 12 month follow-up and by comparing to the changes in the control knees. Paired t-tests were used to compare ACL-injured vs. contralateral knees, and unpaired t-tests were used to compare ACL-injured vs control knees and contralateral vs control knees. Statistical significance was determined at an alpha of 0.05.

RESULTS: *Algorithm Reliability* The mean ± standard deviation (std) of longitudinal distances between matched landmarks at baseline and 12-month follow up for all controls are 1.27 ± 0.14 mm for the tibia and 1.53 ± 0.5 mm for the femur. The bilateral intra-subject distances are 1.47 ± 0.22 mm and 1.56 ± 0.27 mm, and the inter-subject distances are 2.47 ± 0.35 mm and 2.71 ± 0.47 mm.

Cross-Sectional Shape Differences At baseline, significant differences were found in mode 2 and mode 6 for the femur, and in mode 2 and mode 3 for the tibia, between ACL-injured knees and control knees as well as between contralateral knees and control knees (Table 1). No significant differences between the injured and contralateral knees were found. Additionally, the bilateral shape differences detected for injured and contralateral knees are similar to the magnitude of differences observed between the left and right knees in the control group.

Longitudinal Shape Changes Significantly larger longitudinal changes from baseline to 12-months are found in the ACL-injured knees compared to the control group in mode 1, mode 6, and mode 8 in the tibia (Table 2). No significant longitudinal difference was observed between control knees and contralateral knees.

Table 1 Statistics for the modes with significant differences at baseline between control knees and injured knees and between control knees and contra lateral (significant difference in bold)

Modes		Control		Injured		Contralateral	
		mean	std	mean	std	mean	std
FEMUR	2	-55.8	34.7	33.2	90.1	-14.4	84.8
	6	33.6	36.1	26.8	50.4	-17.5	36.1
TIBIA	2	-33.5	45.8	31.0	80.9	-14.9	83.9
	3	44.2	66.2	-23.3	73.2	-23.3	30.5

Table 2 Statistics for the modes with significant longitudinal changes in injured knees (significant difference in bold)

Modes		Control Bas. >12 mth.		Baseline -> 6-months		Baseline -> 12-months		6-months -> 12-months							
		mean	std	Injured		Contralateral		Injured		Contralateral					
				mean	std	mean	std	mean	std	mean	std				
TIBIA	1	-2.9	19.1	17.1	13.3	10.8	23.8	6.4	18.1	17.4	28.9	-10.6	18.8	6.6	28.3
	6	6.8	29.1	-0.8	33.1	-9.1	27.8	-32.7	37.7	-11.2	34.0	-31.9	33.3	-2.1	48.3
	8	2.7	17.9	-20.1	29.5	-5.7	23.6	-17.9	26.0	14.9	38.9	2.2	20.2	20.6	46.3

a single mode. This method allows for the identification of the specific shape feature that is described in each mode. Interestingly, when applying this methodology to patients with ACL injuries, we have observed that the femur mode 2 (Figure 1a) represents the intercondylar notch width, a marker previously observed as a risk factor for ACL injury.⁴ The tibia mode 6 represents the lateral tibial plateau elevation, and an increase of this elevation has been described on radiographs of knees with osteoarthritis.⁵ Future work will involve further analysis of all significant modes to investigate the possible clinical implications of the shape changes as both risk factors for injury and as a marker for the progression of degenerative changes.

CONCLUSION: We have presented a novel 3D MRI-based method to analyze the knee bone shape and for the first time applied the technique to knees with ACL-injuries. Our experiments show that there are significant shape differences between the ACL-injury knees and control knees at baseline, suggesting a common shape feature that may predispose these knees to injury. Moreover, significant differences are detected in longitudinal shape changes in the tibia between injured knees and control knees. Some of these observed changes in shape align with previously observed changes in post-traumatic OA, while others merit further investigation. Bone shape quantification has the potential to identify specific risk factors for injuries and to describe novel imaging markers for the development of post-traumatic OA after an acute injury.

REFERENCES: [1] Tuhina N. et al. Arthritis Rheum. 2013; 65(8), 2048–2058. [2] Li X et al. Radiology. 2011;258(2):505-5. [3] Lombaert H. et al. IEEE PAMI. 2013 Sep; 35(9):2143-60. [4] Smith HC et al. Sports Health. 2012 Jan; 4(1):69-78. [5] Haverkamp DJ et al. Arthritis Rheum. 2011 Nov; 63(11) :3401-7.

DISCUSSION: The initial experiment shows the reliability of the landmark matching algorithm. The mean displacement has a comparable value with the MRI slice thickness both for tibia and femur and the value is much smaller than the inter-subject variability, indicating good reliability of the algorithm. The second and third experiments demonstrate the application of the proposed method. Due to the orthogonal nature of the SSM basis description, we can compute both the analysis and synthesis equations and return to the space domain after the perturbation of

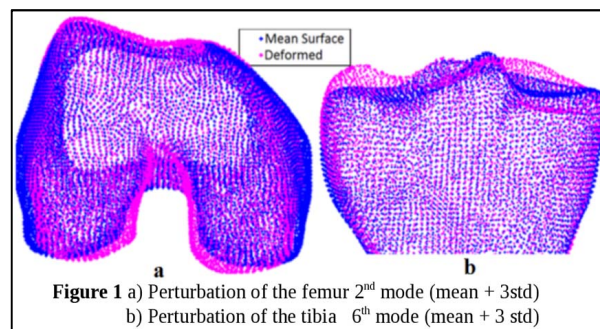


Figure 1 a) Perturbation of the femur 2nd mode (mean + 3std)
b) Perturbation of the tibia 6th mode (mean + 3std)