Analysis of the Relationship Between 3D Knee Bone Shape and the Progression of T1ρ and T2 6 month and 1 year after ACL Reconstruction

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INTRODUCTION: Anterior cruciate ligament (ACL) tear is one of the most common ligament injury of the knee joint and it has been shown to be risk factor for the development of early post-traumatic osteoarthritis (OA)[1,2]. Previous studies demonstrated that $T_{1\rho}$ and T_2 MRI quantification can be used to detect cartilage damage and early degeneration after ACL injury and reconstruction[3,4]. Recently, bone shape features have been proposed as potential markers for predicting hip and knee OA progression[5,6]. However, the potential role of the tibia and femur shape in post-traumatic OA development after ACL injury is unknown. It has been shown that multiple geometric measurements used for the description of a complex shape are often highly correlated and a comprehensive approach to modeling the shape can be more effective[5]. Statistical Shape Modeling (SSM) is a state-of-the-art method for bone shape features extraction[7]. The potential of SSM, coupled with the three-dimensional nature of MR imaging allows for the analysis of the complex shape avoiding the choosing of specific geometrical indices. In the present study, SSM is applied to explore the relationship between knee bone shape and the progression of cartilage $T_{1\rho}$ and T_2 1 year after ACL reconstruction.

METHODS: *Subjects:* Bilateral knees were scanned using a 3 Tesla MRI scanner (GE Healthcare, Milwaukee, WI, USA) with an 8-channel phased array knee coil (Invivo, Orlando, FL, USA) for thirty-six patients with ACL injuries prior to surgical reconstruction and 6 month and 1 year after reconstruction (age = 28.56 ± 7.46 years, BMI = 23.69± 2.75 kg/m^2, 15 female). *MRI Protocol*: The imaging protocol included: (1) sagittal T2 fast spin-echo (FSE) images with TR/TE = 4000/49.3 ms, 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; (2) high-resolution 3D FSE (CUBE) (TR/TE = 1500/26.69 ms, field of view of 16 cm matrix 384 x 384 matrix size, slice thickness 0.5 mm, echo train length 32; (3) $T_{1\rho}$ and T_2 mapping: $T_{1\rho}$ time of spin-lock (TSL)= 0/10/40/80 ms, spin-lock frequency = 500 Hz slice thickness 4 mm, field of view 14 cm, 256 × 128 matrix size, T2 preparation TE= 0/12.87/25.69/51.39 ms_

Image Post Processing: The post processing pipeline included 2 main steps: $T_{1\rho}$ and T_2 quantification and SSM extraction. *$T_{1\rho}$ and T_2 Quantification*: Sagittal CUBE images were rigidly registered on the $T_{1\rho}$ and used for the cartilage segmentation. Six compartments were identified: medial femoral condyle (MFC), medial tibia (MT), lateral femoral condyle (LFC) and lateral tibia (LT) trochlea (TRO) and patella (PAT).. $T_{1\rho}$ and T_2 relaxation times were determined with a pixel-by-pixel, two-parameter exponential fit. The mean $T_{1\rho}$ and T_2 values of each ROIs were computed. The process is applied both on the baseline, 6 month and 1 year acquisitions, and the progression between the baseline $T_{1\rho}/T_2$ in each of the other time points is computed as: $T_{1\rho\_1year}$ - $T_{1\rho\ \_baseline}$ and $T_{1\rho\_6month}$ - $T_{1\rho\ \_baseline}$. *SSM extraction:* The tibia and femur at baseline are segmented semi-automatically on the FSE image. The Statistical Shape Model is extracted individually on the segmentation of tibia and femur to be invariant to the relative position of the joint. Landmarks are defined in a fully automatic fashion with a vertex-to-vertex correspondence algorithm based on the local curvature features. Principal component analysis (PCA) of the covariance matrix of the landmark 3D coordinates is used to extract a brief signature of the shape. The first 20 femur and tibia modes which represent more than 90% of the entire variability, were analyzed. *Statistical Analysis:* Single Pearson correlations between each modes of baseline bone shape and the progression of $T_{1\rho}/T_2$ at 6 month and 1 year was computed. The level of significance was fixed at alpha < 0.01.

RESULTS: Tab.1 shows the results obtained analyzing the $T_{1\rho}$/T2 progression in the cartilage compartments. Four specific modes showed significant correlations: Tibia 2nd, Tibia 16th, Femur 17th and Femur 20th. In the statistical shape model each mode describes a different aspect of the bone shape and it can be modeled separately. The physical meaning of each mode was investigated by changing the value of the significant modes from the mean to the mean ± 3 standard deviations (SD) and observing the displacement of the landmarks. Three-dimensional colored meshes are constructed according to the anterior-posterior, medial-lateral, and superior-inferior voxel displacement between the average surface and the surfaces obtained after changing the values of a specific mode (Fig. 1). Modification in the value of Tibia 2 lead to the change of the relative elevation of medial and lateral tibiae plateau. Low value of Tibia 2 is correlated to a high progression of T2 in the MT and it corresponds to a higher medial side.. No significant correlations were found for this mode and the progression of $T_{1\rho}$. Modification in the values of Tibia 16th lead to a change of the medial tibiae slope; low value of the mode (steeper medial tibia) are related to a higher progression of $T_{1\rho}$.Femur 17th is related to the deepness and medial lateral width of the anterior central area of the femoral condyle. Larger and deeper condyle are correlated to higher progression of T2 in the lateral tibia at 6 month. Similar shape feature is described in the mode Femur 20th but the deformation interests just the lateral side and deeper trochlea is modeled by low values of the modes.

Global Compartmens	T1rho		T2	
	Progression at 1 Year	Progression at 6 months	Progression at 1 Year	Progression at 6 months
MFC	**Tibia16: P = 0.002 R = -0.51'**	NS	NS	NS
MT	NS	NS	**Tibia 2 :P = 0.0017 R = -0.52'**	NS
LT	**Femur 20: P = 0.006 R = -0.46'**	**Femur 20: P = 0.0016 R = 0.52'** Tibia 10: P = 0.0058 R = -0.46'	NS	**Femur 17: P = 0.0072 R = 0.45'**
TR0	NS	NS	Tibia 7: P = 0.0056 R = -0.46'	**Femur 20: P = 0.0062 R = -0.46'**

Table 1: correlations between the knee bone shape and T1rho/T2 progression 6 months and 1 year after ACL reconstruction in the cartilage global compartments

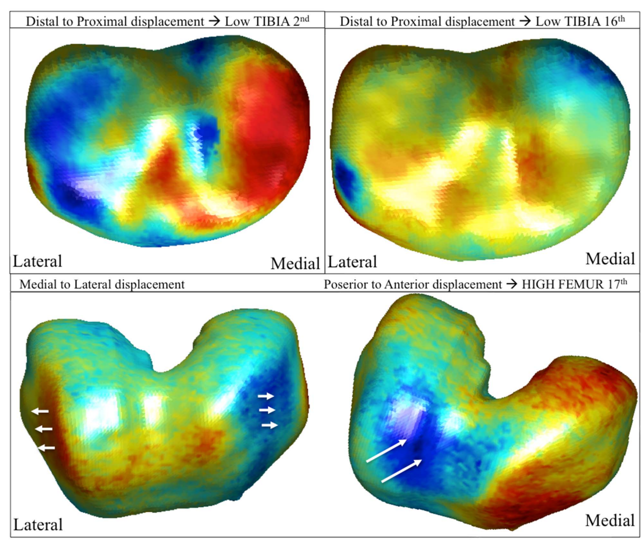

Figure1: 3D representation of the vertices displacement modeling the main bone shape features that can predict $T_{1\rho}$ and T2 progression.
Posterior to Anterior: positive values (red) displacement towards anterior direction, negative values (blue) displacement towards posterior direction. Medial to lateral: positive values (red) displacement towards lateral direction, negative values (blue) dispzlacement towards medial direction. Distal to proximal: positive values (red) displacement towards proximal direction, negative values (blue) displacement towards distal direction.

DISCUSSION and CONCLUSION: The results of this study suggest that specific aspects of the bone shape may predict the progression of $T_{1\rho}$ and T2 6 month and 1 year after ACL reconstruction. Our results suggest that $T_{1\rho}$ and T2 are influenced by different aspects of the knee bone shape. However the steep of the medial tibiae plateau is correlated with both $T_{1\rho}$ and T2. Understanding the interrelationship between the knee shape in the ACL reconstructed knee and signs of early cartilage changes may help with better understanding post-traumatic OA development in ACL reconstructed knees and ultimately help with improving patient management.

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