Combined MR and Weight-Bearing CT Imaging for In Vivo Knee Joint Assessment in Functional Poses

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INTRODUCTION: Patients who suffer an anterior cruciate ligament (ACL) injury are at high risk of developing post-traumatic osteoarthritis (PTOA). ACL reconstruction (ACLR) can successfully alleviate pain and improve joint instability and function, but PTOA risk following ACLR remains high. Altered knee joint biomechanics likely influences PTOA risk. However, in vivo assessment of knee joint biomechanics is challenging because it requires characterization of both soft and hard tissues as well as their interactions under functional loads. Until recently, in vivo knee joint imaging has been limited to the measurement of 2D joint space width (JSW) from weight-bearing radiographs or characterization of soft tissue degeneration from MRI acquired in a supine pose. The introduction of 3D extremity weight-bearing CT (WBCT) has provided new opportunities to characterize the hard tissue (bones) of a knee joint under weight-bearing conditions at a low radiation dose. The objective of this study is to demonstrate the feasibility of an in vivo assessment for both soft and hard tissues of a knee joint in functional poses by combining images from supine MRI and extended and flexed WBCT.

METHODS: A patient was recruited for this pilot study [IRB22-164] from an ongoing, multicenter cohort study [IRB19-573]. In vivo knee imaging was performed on the contralateral knee 10 years following ACLR using MRI (3T, Siemens Prisma) in supine and WBCT (Carestream OnSight 3D Extremity) in two weight-bearing (extended and flexed) poses. MRI protocols included high-resolution 3D DESS (0.36mm x 0.36mm, 0.7mm slice thickness) and SPACE (0.5mm x 0.5mm, 0.7mm slice thickness) sequences. The WBCT protocol used a high-resolution, isotropic (90kVp, 5mAs, 0.26mm x 0.26mm, 0.26mm slice thickness) acquisition. For MRI, bones (femur bone: FB, patella bone: PB, and tibia bone: TB), cartilages (femoral cartilage: FC, patella cartilage: PC, and tibial cartilage: TC), and meniscus (lateral meniscus: LM and medial meniscus: MM) were segmented using in-house developed, machine learning-based algorithms [1]. For WBCT imaging, bones were segmented using a threshold-based algorithm. Local coordinate systems (LCS) were defined for the FB, PB, and TB using an automated algorithm based on bone surfaces [2]. Bone-to-bone registrations were performed to register soft tissue masks (FC, PC, TC, LM, and MM) segmented from MRI to two, weight-bearing (extended and flexed) poses relative to each bone from WBCT. To assess the knee joint relationship among non-weight bearing (MR_{SUP}) and weight-bearing ($WBCT_{EXT}$ and $WBCT_{FLX}$) poses, the volumes of MR_{SUP} and $WBCT_{FLX}$ were registered to the TB of $WBCT_{EXT}$ (**Figure 1**). All bone, cartilage, and meniscus masks registered were converted into the stereolithography surface mesh models. The surface mesh models were used to calculate the Euclidean distance from the center of each of the triangle mesh faces to the opposing surface mesh model based on the normal vectors. JSW is calculated between the bones and mapped to each bone surface. Cartilage-to-cartilage (C2C) distance is calculated between the cartilages and mapped to each cartilage surface. Cartilage-to-meniscus (C2M) distance is calculated between the femoral cartilage (FC) to the meniscus (LM and MM). Lastly, the knee joint relationship is calculated as the distance vectors and rotations in 3D between the origins of the local coordinate systems (LCS_{FB} and LCS_{PB}) with respect to the tibial bone coordinate system (LCS_{TB}).

RESULTS: The results of the knee joint relationship are summarized in **Table 1**. Flexed pose resulted in large positional and rotational changes of the FB and the PB, compared to the other poses. Notably, flexion of the femur bone was achieved to 31.8° relative to the tibia bone. The results of 3D distance mapping for JSW, C2C, and C2M are shown in **Figure 1**. The results of the JSW map (FB to TB) showed more medially located weight distribution at extended and shifted posteriorly at flexed pose. Similar patterns were shown in C2C (FC to TC) and C2M (FC to LM/MM) mapping. The locations of the JSW (FB to PB) and C2C mapping (FC to PC) were changed among the supine, extended, and flexed poses.

DISCUSSION: These results demonstrate the feasibility and importance of in vivo assessment of a knee joint in functional poses in terms of joint relationship and distance mapping between the bones, cartilage-to-cartilage, and cartilage-to-meniscus, especially in weight-bearing, extended and flexed poses. Most MRI and CT imaging are clinically performed in supine pose; however, when a knee joint is imaged under the weight-bearing (extended and flexed) loading condition, the relationships between the associated structures allow for functional assessment of the knee joint because it represents the complex interaction between the joint loading, bone/cartilage/meniscus geometry, and muscle contraction. More patients are being recruited.

SIGNIFICANCE/CLINICAL RELEVANCE: For the first time, we have presented a method allowing in vivo assessment of a knee joint for both soft and hard tissues in weight-bearing, functional poses by combining MRI and WBCT imaging. Future applications of our method in patient cohorts with OA/PTOA or with a high risk of OA/PTOA would improve our understanding on the development or progression of OA/PTOA.

REFERENCES: [1] Gaj, et al., Magn Reson Med, 2020. [2] Peters et al., ORS, 2023.

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Table 1. Results of the knee joint relationship between bone to bone at different functional poses.

Bone to Bone	Poses	Positions [mm]				Rotations [deg]		
		Lat (+)	Ant (+)	Pro (+)	3D	IR (+)	FLX (+)	VAL (+)
FB to TB	Supine	-1.0	2.1	35.1	35.2	-12.2	4.0	-0.3
	Extended	-2.9	2.4	33.3	33.5	-5.3	-4.2	-0.5
	Flexed	-1.6	-9.2	34.6	35.8	-30.5	31.8	-6.9
TB to PB	Supine	4.7	43.5	43.3	61.5	-2.8	-0.8	1.1
	Extended	2.6	47.5	32.8	57.8	-3.7	-10.9	1.8
	Flexed	6.2	28.8	48.4	56.7	-5.4	9.3	0.9
FB to PB	Supine	5.6	41.3	8.2	42.5	9.4	-4.8	1.5
	Extended	5.5	45.1	-0.5	45.5	1.6	-6.8	2.2
	Flexed	7.9	38.0	13.8	41.2	25.1	-22.5	7.8

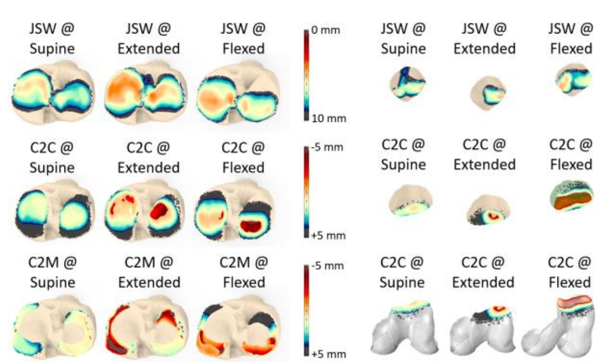

Figure 1. The results of the 3D distance mapping for JSW, C2C, and C2M.