Validation of Pediatric Tibiofemoral and Patellofemoral Kinematics Using Subject-Specific Finite Element Models

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INTRODUCTION: Over the past three decades, numerous finite element (FE) models of the knee have been developed. These models aimed to predict three-dimensional kinematics of tibiofemoral (TFJ) and patellofemoral (PFJ) joints in cadavers as well as healthy and pathologic individuals [1]. Despite widespread use, there is a dearth of FE models developed for the pediatric knee, which is problematic given the increasing number of orthopedic interventions among youth. Indeed, a validated FE model of the pediatric knee would enable a mechanistic investigation of the influences of knee anatomy on function in pathological conditions. Furthermore, a validated FE model would enable examination of how model modifications (e.g., removal of constraints) can replicate unstable joint motion observed in pediatric cases such as those caused by anterior cruciate ligament injuries. Therefore, the aim of this study was to develop subject-specific FE models of the knee from eight healthy pediatric participants to validate FE-driven kinematics of both TFJ and PFJ by comparing them to matched patient-specific in-vivo kinematics obtained from magnetic resonance imaging (MRI).

METHODS: This study used an atlas-based technique [1] to develop patient-specific FE models of eight healthy pediatric knees (i.e., TD1-TD8), with each knee based on the participant's MRI. This cohort was comprised of four males and four females, with an average age of 14.0±2.6 years, mass of 51.1±10.5 kg, and height of 1.64±0.11 m. To validate the FE models, passive simulations were conducted using Abaqus/Standard soils consolidation solver, separately for each participant. Inputs to the models consisted of TFJ flexion angles of 0° to 25° and a superior/inferior displacement of 3 mm to establish initial contact between model components. The remaining model degrees of freedom (DoF) were free to move in response to applied constraints. In validation simulations, the femur had 4 active DoF, consisting of 2 translations (anteroposterior and mediolateral) and 2 rotations (abduction/adduction and internal/external), whereas patella had 6 active DoF, consisting of 3 translations (anteroposterior, mediolateral, and proximal-distal) and 3 rotations (abduction/adduction, internal/external, and flexion/extension), while the tibia was fixed. Root mean square error (RMSE) was computed for each participant between their knee (TFJ and PFJ) kinematics predicted by the FE model and those measured directly from MRI for flexion angles of 0°, 7°, 15°, and 25°[2].

RESULTS SECTION: The FE models well-replicated MRI-based measurements [1] of both TFJ and PFJ joint kinematics. The RMSE between model prediction and MRI-based measurements for all DoF at TFJ and PFJ, except for internal/external rotation, were generally acceptable across (n=8) participants. Modelled TFJ had an average RMSE<2.8 mm for anteroposterior and mediolateral translations and <1.6° for all rotations, indicating generally good agreement with MRI-based measures (Table 1). The exception was TFJ internal/external rotation (Figure. 1), which had substantial average RMSE (~38°), indicating divergence with MRI-based measurements. When compared with MRI-based measurements of PFJ kinematics, FE model predictions had average RMSE for rotations <4.5° and translations <6.9 mm. In addition, compared with prior reports in the literature [3], passive TFJ and PFJ kinematics predicted by the FE models showed strong correlations with knee kinematics measured during experiments conducted on cadaveric specimens for most DoF (Table 1).

DISCUSSION: We used atlas-based approach to develop subject-specific FE models of the knee joint in eight typically developing pediatric individuals. Validation simulations showed FE models well-predicted both TFJ and PFJ kinematics compared to corresponding measurements of the same pediatric individuals made using MRI and those from the literature[2,3]. In the case of large error reported for TFJ internal/external rotation, this is explained by differences in the coordinate system used for the direct measurement of the knee kinematics in the MRI which is biased towards external rotation due to the definition of the tibial frontal plane using the trans-malleolar line. In the context of the reported errors, development, and validation of FE models of the pediatric knee which mimic in-vivo biomechanics may have significant clinical implications in the future.

SIGNIFICANCE/CLINICAL RELEVANCE: These now validated models hold promise as effective tools for population-based clinical studies, parametric analyses, and enhancing our understanding of various pediatric knee injury mechanisms. They also support intervention design and prediction of surgical outcomes in pediatric populations.

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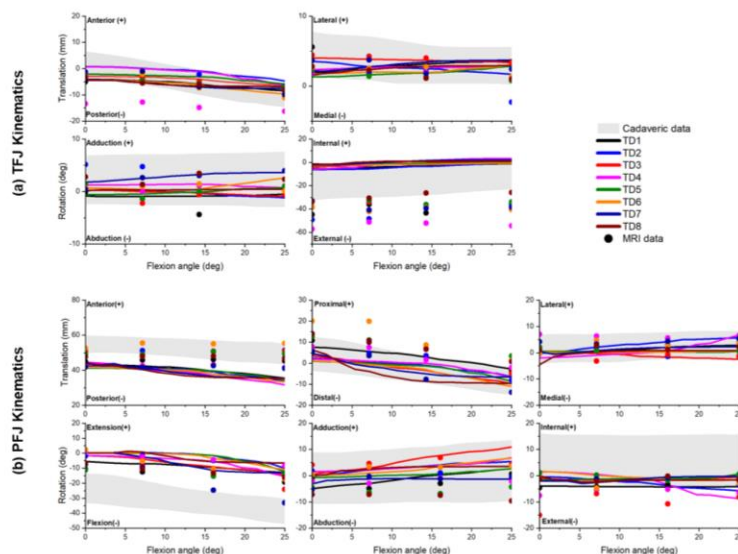
Figure 1. Comparison of kinematics from (a) tibiofemoral joint (TFJ) and (b) patellofemoral joint (PFJ) as simulated by the FE models (colored lines), MRI-based measurements (dots) [2], and published values from measurements [3] taken from cadaveric specimens (grey) across a range of TFJ flexion angles.

Table 1: Root mean square error and Pearson's correlation coefficients (ρ), along with their average and standard deviation [2,3]

RMSE between model and MRI-based measurements of joint kinematics					
	Rotation (°)			Translation (mm)		
Joint	F/E	A/A	I/E	A/P	P/D	M/L
TFJ	-	1.63 (0.95)	38.27 (6.23)	2.82 (3.80)	-	1.31 (0.55)
PFJ	7.12 (3.14)	3.21 (1.47)	3.13 (2.89)	9.85 (3.89)	8.29 (4.6)	2.80 (1.55)

Pearson's correlation coefficients between model and cadaver-based measurements					
TFJ	-	0.41 (0.13)	0.93 (0.073)	0.96 (0.02)	-	-0.67 (0.58)
PFJ	0.96 (0.03)	0.89 (0.16)	0.62 (0.41)	0.96 (0.02)	0.95 (0.03)	0.86 (0.13)

F/E – flexion and extension; A/A – adduction and abduction; I/E – internal and external rotation; A/P – anteroposterior; P/D – proximodistal; M/L – mediolateral; TFJ – tibiofemoral joint; PFJ – patellofemoral joint; RMSE – root mean square error.