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Dzialo, Christine Mary; Pedersen, Peter Heide; Jensen, Kenneth Krogh ; de Zee, Mark; Andersen, Michael Skipper

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C M Dzialo[1,2]*, P H Pedersen[3], K K Jensen[4], M de Zee[5], M S Andersen[2]

[1] *AnyBody Technology, A/S Niels Jernes Vej 10, DK 9220 Aalborg, Denmark*

[1]*Department of Materials and Production, Aalborg University, Fibigerstræde 16, DK-9220 Aalborg, Denmark*

[2]*Department of Orthopedic Surgery, Aalborg University Hospital, Hobrovej 18-22, DK-9000 Aalborg, Denmark*

[3]*Department of Radiology, Aalborg University Hospital, Hobrovej 18-22, DK-9000 Aalborg, Denmark*

[4]*Department of Health Science and Technology, Sport Sciences, Aalborg University, Fredrik Bajers Vej 7D, DK-9220 Aalborg*

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*Corresponding author:

Christine Dzialo

Department of Materials and Production, Aalborg University, Fibigerstræde 16, DK-9220 Aalborg, Denmark

Tel. +45 42 48 98 90

E-mail: christinedzialo@gmail.com or cmd@anybodytech.com

Abstract

The main objectives of this study were to expand the moving-axis joint model concept to the patellofemoral joint and evaluate the patellar motion against experimental patellofemoral kinematics. The experimental data was obtained through 2D-to-3D bone reconstruction of EOS images and segmented MRI data utilizing an iterative closest point optimization technique. Six knee model variations were developed using the AnyBody Modeling System and subject-specific bone geometries. These models consisted of various combinations of tibiofemoral (hinge, moving-axis, and interpolated) and patellofemoral (hinge and moving-axis) joint types. The newly introduced interpolated tibiofemoral joint is calibrated from the five EOS quasi-static lunge positions. The patellofemoral axis of the hinge model was defined by performing surface fits to the patellofemoral contact area; and the moving-axis model was defined based upon the position of the patellofemoral joint at 0° and 90° tibiofemoral-flexion. In between these angles, the patellofemoral axis moved linearly as a function of tibiofemoral-flexion, while outside these angles, the axis remained fixed. When using a moving-axis tibiofemoral joint, a hinge patellofemoral joint offers (-5.12 ± 1.23 mm, 5.81 ± 0.97 mm, 14.98 ± 2.30°, -4.35 ± 1.95°) mean differences (compared to EOS) while a moving-axis patellofemoral model provides (-2.69 ± 1.04 mm, 1.13 ± 0.80 mm, 12.63 ± 2.03°, 1.74 ± 1.46°) in terms of lateral-shift, superior translation, patellofemoral-flexion, and patellar-rotation respectively. Furthermore, the model predictive capabilities increased as a direct result of adding more calibrated positions to the tibiofemoral model (hinge-1, moving-axis-2, and interpolated-5). Overall, a novel subject-specific moving-axis patellofemoral model has been established; that produces realistic patellar motion and is computationally fast enough for clinical applications.

1. Introduction

The patellofemoral (PF) joint contains the body's largest sesamoid bone, the patella, nestled in the femoral trochlear groove. The patella acts as a lever arm to translate force from the quadriceps muscle across the tibiofemoral (TF) joint, while also serving as a bony shield to protect the tibiofemoral joint [1]. Dysfunction and mal-tracking often arise when the homeostasis of a joint is compromised [2–5], for example: increased patellar tilt [6,7], a more laterally positioned tibial tuberosity [8], abnormal "screw-home" rotation of the tibiofemoral joint [9], and hip muscle weakness [10] especially in the female population [11] may lead to anterior knee pain during activities of daily living. In addition, correlations exist between the patellofemoral morphology and resulting kinematics [7,12] so it is important that subject-specific morphology is captured when constructing musculoskeletal joint models.

Musculoskeletal modeling is a non-invasive computational tool used to better understand what occurs in the body internally as a result of external loads and movements. The patellofemoral joint is often excluded from pure kinematic models [13]; however when it is included, it is frequently modeled as a 1 degree-of-freedom hinge joint with an additional rigid patella tendon [14–22] which may not provide realistic joint kinematics. In hopes of achieving more realistic joint kinematics, researchers have included a 6 degrees-of-freedom patellofemoral joint utilizing multi-body contact models [17,23–31]. The main advantage of these models is that they can capture contact and ligaments forces; however, they may be too computationally slow for clinical applications.

The main objective of this study, therefore, was to establish a more computationally fast patellofemoral model capable of predicting subject-specific patellar motion when using motion capture input, while also avoiding error from skin artifact movement, for future use in the clinical setting. This model applies the concepts established in the moving-axis tibiofemoral joint model [32] to the patellofemoral joint. In a moving-axis joint applied to the knee (patellofemoral or tibiofemoral), the articulation is model such that the joint axis moves linearly back and forth between two known positions, as a function of tibiofemoral flexion. The proposed model was evaluated against the patellar positions extracted from a series of bi-planar EOS x-rays, which has an accurancy of 0.95 ± 0.55 mm [32].

2. Methods

Data Collection

Preexisting imaging data [33], approved by the Scientific Ethical Committee for the Region of Nordjylland, was utilized in this study. This dataset consisted of lower limb Magnetic Resonance Image (MRI) acquisitions (T1W-LAVA-XV-IDEAL COR, 1.6 mm slice thickness, 0 mm gap thickness) of ten healthy male subjects (age 33 ± 10 years, body mass 79 ± 11 kg, height 1.82 ± 0.07 m) and five low dose radiation orthogonal x-rays (EOS^{TM}) of the loaded knee joint at roughly 0°, 20°, 45°, 60°, and 90° tibiofemoral-flexion during a quasi-static lunge.

Patella segmentation and registration

Bone surface geometries and contours of the patella were manually segmented from the lower limb MRIs and biplane EOS images respectively, using Mimics Research 19.0 (Materialise, Leuven, Belgium). Custom MATLAB (The Mathworks Inc., Natick, MA, USA) code was used to manually transform the 3D bone geometry and its' projected contours to roughly match the segmented biplanar contours. Then, an iterative closest point approach was employed to minimize the least-square difference between the contour sets. EOS reconstructions of the 3D patella positions and orientations for each set of EOS images were then read into the AnyBody Modeling System (AMS v 7.1, AnyBody Technology A/S, Denmark) to calculate translations and rotations of the patellofemoral joint.

Joint coordinate system (CS) and kinematic measures

For EOS data and all models, the patella anatomical CS origin was defined at the center of the outermost superior, inferior, medial, and lateral points. Each of these points were determined by first manually selecting the general location in 3-Matic Research 11.0 (Materialise, Leuven, Belgium), exporting this surface as a STL, and then taking an average of the STL cluster in MATLAB. The orientation was determined by (1) creating a temporary flexion axis running between the medial-lateral points, (2) defining the long axis (directed superiorly) between the superior-inferior points, (3) the anterior-posterior axis was defined as the cross product between (1) and (2), and finally the real medial-lateral axis was defined as the cross product between (2) and (3) [34–37]. We defined the patellofemoral joint in terms of a femoral and patella fixed-body axis with a perpendicular floating axis (Figure 1), adapted from the ISB standards of the tibiofemoral joint [35,38,39]. The femoral anatomical axis was defined with the y-axis running from the center point between the two epicondyles to the hip joint center. The z-axis was defined orthogonal to the y-axis and pointing towards the lateral epicondyle. Finally, the x-axis is defined as the cross product between the y-axis and z-axis pointing anteriorly [33,40–43]. The tibiofemoral joint was defined using ISB standards [38] and is discussed in detail in Dzialo et al. (2018).

Knee Model Development

Six knee models were created using combinations of tibiofemoral and patellofemoral joint types (Supplementary Table 1). These joint types include: two previously established tibiofemoral joint models (hinge and moving-axis) [33], one new tibiofemoral joint (Interpolation-INT), and two new patellofemoral joints (hinge and moving-axis). In each knee model, the patellar tendon is defined as a non-deformable element, connecting the patella to the tibia tuberosity.

<u>Hinge</u>: The tibiofemoral hinge joint axis was defined as a line running from the medial to lateral femoral epicondyles from the EOS_0 reconstruction pose [33]. To determine the patellofemoral hinge joint axis, we first applied a least-squares cylindrical fitting function using MATLAB to the medial and lateral surfaces of the femoral trochlear groove [44,45] to find the respective centers. The patellofemoral hinge joint axis was then defined by a line connecting these centers (Figure 2.a).

<u>Moving-Axis (MA)</u>: The tibiofemoral MA joint model was taken directly from Dzialo et al. (2018). The patellofemoral MA model was calibrated from the position and orientation of the patellofemoral joint in the 0° and 90° EOS reconstructions. We fit four cylinders to femoral trochlear groove surface

selections (Figure 2.b-c), which were based on selections made by Bowes et al. 2015 [44,45] and discussed in the Hinge section above, based on where the patella contacts the femur when the tibiofemoral joint is in full extension (EOS-0), and in roughly 90° flexion (EOS-90). The facet centers from medial and lateral cylinder fits in extension (EFC) and flexion (FFC) were connected to define two axes (Figure 2.b-c). During hyperextension of the tibiofemoral joint, we assumed that the patellofemoral joint rotates about the EFC axis. For TF-flexion angles greater than the EOS 90° reconstruction, rotation occurs about the FFC axis. We assumed angles within these limits will move linearly as a function of TF-flexion between the patellofemoral EFC to FFC axes.

Interpolation (INT): Due to the correlation between patellofemoral and tibiofemoral joint kinematics during weighted knee flexion, and the fact that the patellofemoral moving-axis is expressed as a function of the tibiofemoral flexion angle, the error present in the tibiofemoral joint may influence the model's predictability of the patellofemoral kinematics. This is especially the case in terms of PF-flexion, tilt, anterior-posterior (AP), and medial-lateral (ML) translations [46]. The Interpolation tibiofemoral model was simulated by applying a piecewise linear function, between the exact measured points from the tibiofemoral EOS reconstructions. With this, the only model error left would be within the patellofemoral model when comparing against the EOS experimental data.

Model Evaluation and Statistics

Patellofemoral kinematics were extracted from each EOS reconstruction (0°, 20°, 45°, 60°, and 90°). Corresponding model prediction results for each of the six model types were extracted at these TF-flexion angles. The 0° and 90° EOS reconstructions were not considered in the evaluation because they were used for model calibrations, eliminating any model predictive capabilities. The root mean square error (RMSE), mean differences with corresponding standard errors, Pearson's correlation coefficient (R), coefficient of determination (R^2), and adjusted R^2 were calculated for each of the six model predictions against the EOS experimental measures for each patellofemoral measure using SPSS version 25.0 (SPSS, Chicago, IL, USA). The absolute values of R were then categorized as weak, moderate, strong, or excellent prediction for $R \leq 0.35$, $0.35 < R \leq 0.67$, $0.67 < R \leq 0.90$, and

0.90 < R, accordingly[47]. The data was tested for normality using Shapiro-Wilk tests. Eighteen one-way repeated measures ANOVAs (6 clinical measures at 3 lunge angles) were run with the necessary Greenhouse-Geisser corrections. Due to the multiple comparisons and a small sample size, post-hoc tests using Bonferroni adjustments ($\alpha = 0.05/18=0.002778$) were performed.

3. Results

Experimental and model subject means of each patellofemoral kinematic measure are depicted in Figure 3, with standard deviations recorded in Supplementary Tables 2-8. Tables 1 and 2 display that the lowest RMSE and mean differences for medial-lateral shift, superior-inferior translation, flexion-extension, and patellar-rotation were achieved when utilizing a MA-PF joint, often decreasing with added known tibiofemoral positions (MA, INT). However, utilizing a MA-PF with any tibiofemoral joint type will result in underestimated tilt and AP translations. Additionally, the superior-Inferior (SI) translation for high TF-flexion (60°) significantly overestimated the experimental data using a Hinge-PF for all tibiofemoral models. Although the AP and tilt remain best predicted by a Hinge-PF with MA-TF, the Int-TF with MA-PF decreases the mean differences in all measures besides SI. The commonly used hinge model presented the most significantly different patellofemoral measures when compared to the experimental EOS data especially in deep TF-flexion.

Overall, when using a MA-PF joint, the model predictive capabilities (R^2, R^2, and R^2_{adj}) increase for ML, AP, SI, and patellar-rotation measures (Table 3); and furthermore, increase when modeling the tibiofemoral with known positions (MA and INT models). Additionally, these measure all have strong to excellent prediction capabilities. However, a MA-PF joint does not necessarily improve the PF-flexion and tilt predictions, which both range in predictive capabilities from moderate to weak. PF-flexion if best captured when modeling the tibiofemoral joint with known positions (MA and INT). In general, the ML-shift, patellar-rotation and tilt are not well predicted by the models, with adjusted R^2 values ranging from 0.06 to 0.38 (Table 3).

4. Discussion

This study presents a novel way of modeling the patellofemoral joint, utilizing MRI and EOS technology, and evaluates various models against in vivo kinematics extracted from consecutive quasi-static lunge positions. The moving-axis model is derived from subject-specific bone morphology and alignment. Being calibrated using two knee flexion positions (0° and 90°), the model captures the true tibiofemoral and patellofemoral kinematics at these poses and estimates what occurs in-between. Our results show that when changing a Hinge-PF to MA-PF joint provides more realistic patellar motion in terms of ML-shift, SI-translation, and patellar-rotation, when compared to experimental EOS. We found that AP translations are underestimated when using a MA-PF joint. This could partially be explained by the strong correlation between posterior patellar translation and posterior femoral translation [46] and the fact that our previously established tibiofemoral moving-axis and hinge models resulted in significantly underestimated AP translations for all lunge conditions [49].

Kinematics of the patella during dynamic weight-bearing [50] and unloaded [51,52] activities may not be accurately predicted or represented from a passive supine position. Although bone geometries were from lower limb MRI, the initial model positions were set to the EOS-0 configuration (weight-bearing) to avoid these shortcomings. Patellofemoral kinematics can vary drastically between subjects and throughout the knee flexion cycle. If future aims include determining optimal patient treatments and or investigating injury progression it is important to consider subject-specific models that capture more than just one time point based off anatomical landmarks selections.

Applying a moving-axis model to the patellofemoral joint has its limitations. Patella instability normally occurs between 0° and 30° flexion. At this point, the patella may not be fully engaged with the trochlear groove, and or beyond this flexion may not track in smooth patella motion [10,53]. There is a chance that the patella was not sitting correctly in the trochlear groove during the EOS-0 scan. In these cases, a piecewise linear relationship may not result in correct patellar motion. Furthermore, the question of whether a linear relationship is appropriate for the MA-PF model is important to note; perhaps a polynomial relationship would fit better, but this would require fitting the model to more than two positions, like the INT-TF joint. In the future, evaluating other moving-axis relationships against dynamic in vivo data, at more extreme ROM, may provide a more comprehensive validation.

Additionally, other computationally fast joint models should be considered such as a functional patellofemoral hinge axis. Although a functional PF hinge axis may have given better results than our cylinder fit hinge axis, we choose this for two main reasons: (1) it is know that for the tibiofemoral joint the cylinder fit hinge axis is a better anatomical surrogate compared to a trans-epicondylar hinge axis [54], we made the assumption that this would also hold true for the patellofemoral joint. (2) A functional patellofemoral hinge axis would require two poses of the patella relative to the femur, and many users may not have access to this kind data. While creating a hinge joint by fitting cylinders to scalable cadaver geometric data, similar to methods conducted in the Twente Lower Extremity Model [21], may be a more manageable option.

In conclusion, we have successfully applied the concept of a moving-axis model to the patellofemoral joint. The results show that a piecewise linear model can provide more accurate estimates of what is going on in the patellofemoral joint between two active TF-flexion positions when compared to the commonly used hinge joint. Most patellofemoral kinematics are best captured by using MA-PF with an INT-TF joint, followed by a MA-TF and then Hinge-TF with MA-PF. In order to bring musculoskeletal modeling of the patellofemoral joint to the clinical setting, the model needs capture more realistic joint kinematics (compared to the hinge) and be computationally fast (compared to the existing multi-body contact models). While applying a moving-axis joint partially accomplishes this, more investigation is needed to determine the best joint model for the clinical applications.

Conflict of Interest

Mark de Zee is co-founder of the company AnyBody Technology A/S, owning the AnyBody Modeling System, which was used for the simulations. Mark de Zee is a minority shareholder on the company. Christine Dzialo, is now an Anybody Technology employee. However, during her participation in this project she was a PhD student under the supervision of Assoc. Prof. Michael Skipper Andersen and had nothing to do with Anybody Technology apart from using their software.

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Ethical approval

This study was approved by the Scientific Ethical Committee for the Region of Nordjylland and informed consent was obtained prior to data collection.

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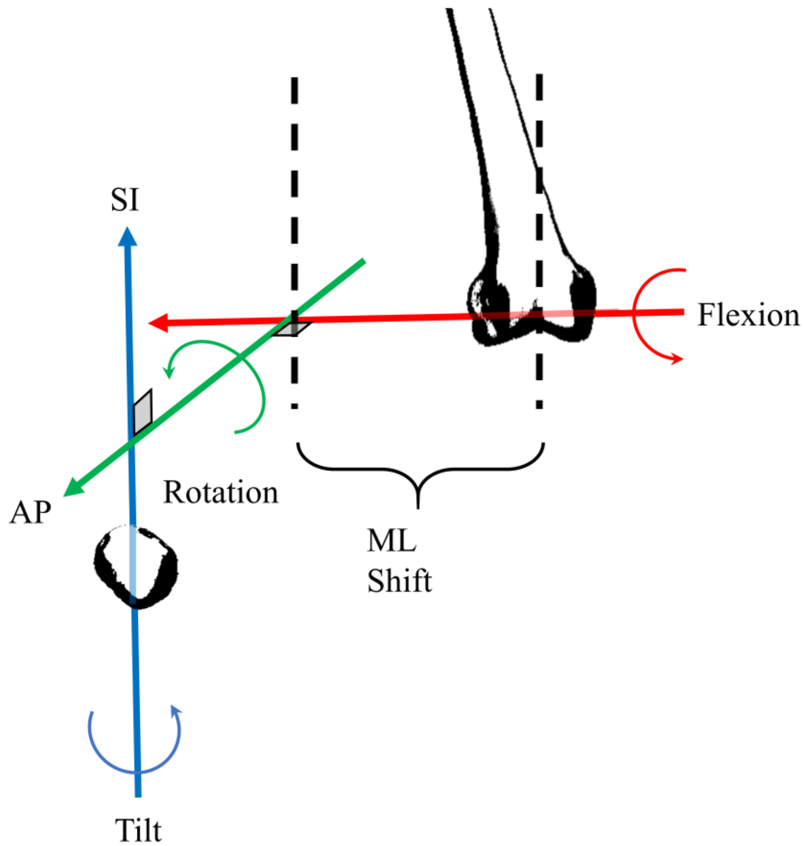
SI
Flexion
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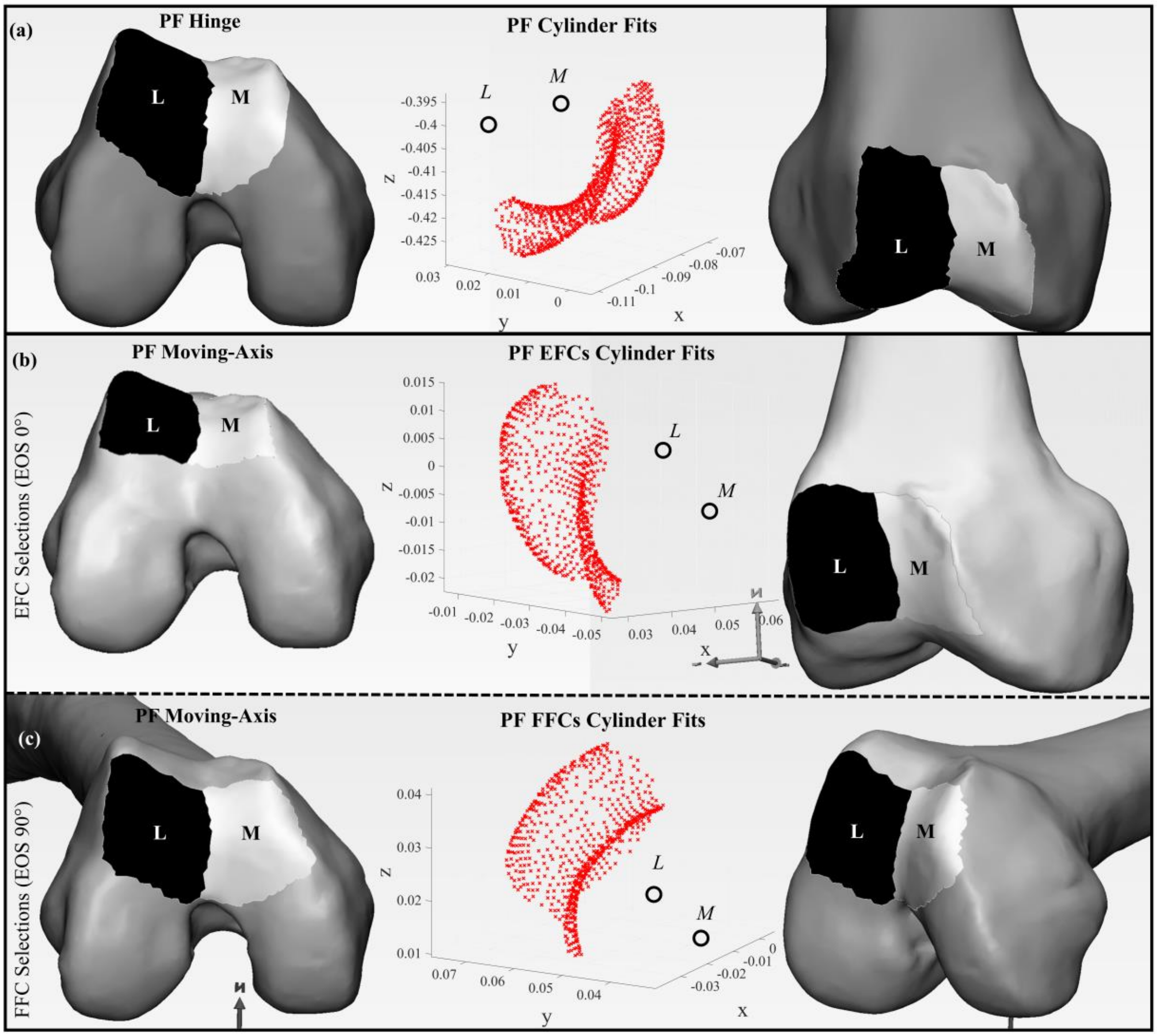
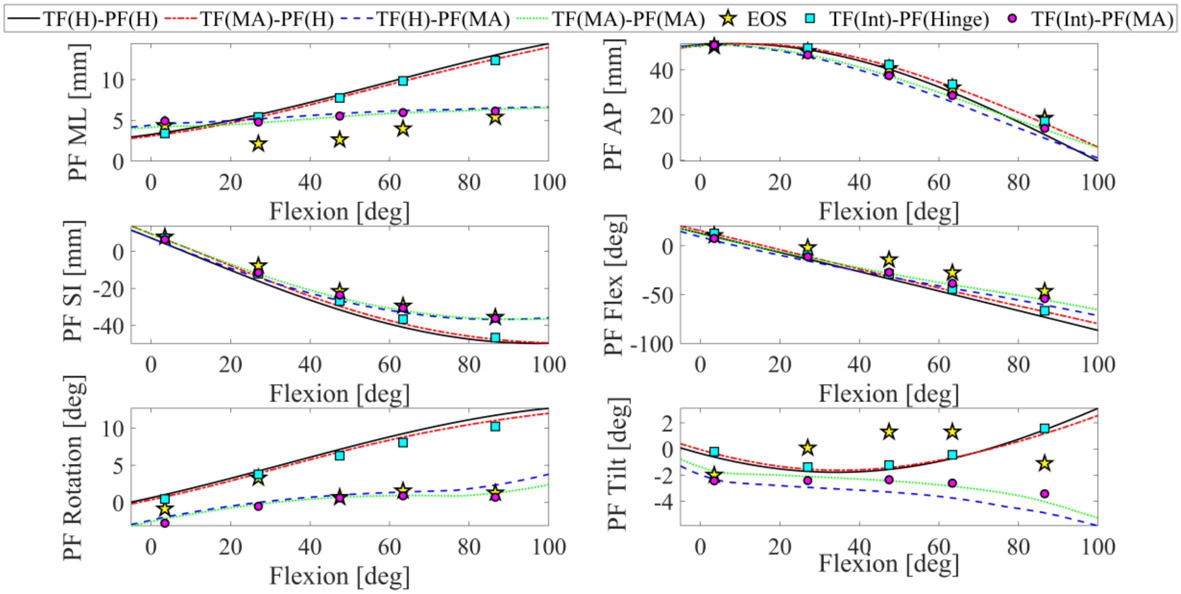

(a)
PF Hinge
L
M
PF Cylinder Fits
L
M
(b)
PF Moving-Axis
EFC Selections (EOS 0°)
PF EFCs Cylinder Fits
(c)
PF Moving-Axis
FFC Selections (EOS 90°)
PF FFCs Cylinder Fits



TF(H)-PF(H)
TF(MA)-PF(H)
TF(H)-PF(MA)
TF(MA)-PF(MA)
EOS
TF(Int)-PF(Hinge)
TF(Int)-PF(MA)
PF ML [mm]
PF AP [mm]
PF SI [mm]
PF Flex [deg]
PF Rotation [deg]
PF Tilt [deg]
Flexion [deg]

Figure Legends

Figure 1—Description of patellar motion: **Medial-lateral shift** corresponds to the distance the patella origin moves along the fixed femoral axis (red), **Flexion** is defined as how much the patella rotates about the fixed femoral axis (red), **Anterior-posterior translation** corresponds to the distance the patella origin moves along the floating axis (green), **Rotation** is the amount the patella rotates about the floating axis (green**), Superior-inferior translation** corresponds to the distance traveled by the patella along the fixed patellar axis (blue), and **Tilt** is defined as the amount the patella rotates about the fixed patellar axis (blue). Image depicts directions of positive translations and rotations for right knee.

Figure 2—Patellofemoral contact surface selections and corresponding analytical surface fits on (a) EOS_0 Femur for hinge joint definition (b) EOS_0 Femur for extension facet center definition (c) and EOS_90 femur for flexion facet center definition. (b-c) are combined to define the moving-axis patellofemoral joint.

Figure 3—Subject mean data (n=10) of patellofemoral kinematic measures for the six model types and EOS data**.** *Standard deviations are listed in a Supplementary Tables 1-7 to avoid clutter and make for a clear image.*

Tables

Table 1—Root mean square error between experimental data (EOS) and various knee models for quasi-static lunge conditions **with respect to femur reference frame** for each clinical measure level for the given lunge conditions.

	Translations (*mm*)			Rotations (°)		
	ML	**AP**	**SI**	**Flexion**	**Rotation**	**Tilt**
			EOS - Hinge TF & PF			
20° Flexion	4.54 ± 2.76	1.58 ± 1.33	7.44 ± 4.70	11.88 ± 7.55	4.26 ± 2.83	4.26 ± 5.57
45° Flexion	6.13 ± 3.43	3.99 ± 2.40	6.72 ± 3.76	19.81 ± 6.35	6.96 ± 3.21	6.21 ± 4.20
60° Flexion	6.70 ± 3.53	3.85 ± 2.80	9.30 ± 3.41	22.39 ± 7.38	8.75 ± 5.75	5.95 ± 4.08
Average	**5.79 ± 1.88**	**3.14 ± 1.31**	**7.82 ± 2.30**	**18.03 ± 4.11**	**6.66 ± 2.39**	**5.47 ± 2.69**
			EOS - Hinge TF : Moving-Axis PF			
20° Flexion	3.77 ± 2.39	3.75 ± 1.67	5.50 ± 4.37	13.27 ± 10.66	5.45 ± 5.13	6.34 ± 6.13
45° Flexion	3.91 ± 3.33	7.03 ± 1.89	2.80 ± 1.92	16.73 ± 7.42	3.94 ± 2.68	7.08 ± 7.27
60° Flexion	2.65 ± 2.74	6.74 ± 2.76	1.81 ± 1.53	15.39 ± 7.54	4.03 ± 3.94	6.42 ± 6.07
Average	**3.45 ± 1.64**	**5.84 ± 1.25**	**3.37 ± 1.67**	**15.13 ± 5.01**	**4.47 ± 2.33**	**6.61 ± 3.76**
			EOS - Moving-Axis TF: Hinge PF			
20° Flexion	4.32 ± 2.70	1.75 ± 1.07	5.29 ± 3.24	9.46 ± 6.41	4.16 ± 2.95	4.41 ± 5.47
45° Flexion	5.91 ± 3.34	2.52 ± 1.39	4.66 ± 2.84	16.61 ± 7.17	6.86 ± 3.01	5.78 ± 4.01
60° Flexion	6.47 ± 3.41	1.91 ± 1.35	7.46 ± 3.15	18.88 ± 8.23	8.72 ± 5.73	5.83 ± 3.99
Average	**5.57 ± 1.83**	**2.06 ± 0.74**	**5.81 ± 1.78**	**14.98 ± 4.22**	**6.58 ± 2.37**	**5.34 ± 2.62**
			EOS - Moving-Axis: TF & PF			
20° Flexion	3.47 ± 2.38	3.13 ± 1.90	4.03 ± 2.71	10.46 ± 8.00	5.54 ± 5.68	5.94 ± 5.71
45° Flexion	3.64 ± 3.27	5.54 ± 1.44	1.82 ± 1.27	13.12 ± 6.00	4.17 ± 3.05	6.61 ± 6.45
60° Flexion	2.36 ± 2.67	4.61 ± 1.99	1.23 ± 0.94	11.65 ± 4.50	3.94 ± 4.71	5.84 ± 5.28
Average	**3.16 ± 1.61**	**4.43 ± 1.03**	**2.36 ± 1.05**	**11.75 ± 3.66**	**4.55 ± 2.66**	**6.13 ± 3.37**
			EOS - Interpolated TF : Hinge PF			
20° Flexion	3.95 ± 2.51	2.00 ± 1.89	4.28 ± 2.48	7.79 ± 6.30	4.11 ± 3.27	4.59 ± 5.68
45° Flexion	5.63 ± 3.06	1.82 ± 1.96	5.24 ± 2.57	14.49 ± 7.42	7.01 ± 3.10	5.53 ± 4.33
60° Flexion	6.25 ± 3.29	2.01 ± 2.02	7.19 ± 3.21	16.75 ± 8.20	8.82 ± 5.59	5.73 ± 4.28
Average	**5.28 ± 1.72**	**1.94 ± 1.13**	**5.57 ± 1.60**	**13.01 ± 4.24**	**6.65 ± 2.39**	**5.28 ± 2.78**
			EOS - Interpolated TF : Moving-Axis PF			
20° Flexion	3.29 ± 2.29	1.48 ± 1.41	3.83 ± 2.77	9.90 ± 8.11	5.38 ± 5.75	5.92 ± 5.29
45° Flexion	3.49 ± 3.19	3.10 ± 1.74	2.41 ± 1.92	12.86 ± 6.22	4.65 ± 2.92	6.59 ± 6.29
60° Flexion	2.35 ± 2.57	3.42 ± 2.23	1.52 ± 1.17	10.90 ± 4.90	4.08 ± 4.78	5.57 ± 5.10
Average	**3.04 ± 1.56**	**2.67 ± 1.05**	**2.59 ± 1.19**	**11.22 ± 3.78**	**4.70 ± 2.68**	**6.03 ± 3.22**

Table 2—Mean differences ± standard error between experimental data (EOS) and various knee models for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure. Symbol denotes that the clinical measure was statistically significantly different, appropriate Bonferroni adjustments were made for multiple comparisons, at *(α=0.05/18=0.002778) level for the given lunge condition.

	Translations (*mm*)			Rotations (°)		
	ML	**AP**	**SI**	**Flexion**	**Rotation**	**Tilt**
			EOS - Hinge TF & PF			
20° Flexion	-3.95 ± 1.15	1.04 ± 0.58	7.44 ± 1.49	11.88 ± 2.39	-1.02 ± 1.64	1.35 ± 2.22
45° Flexion	-5.81 ± 1.26	3.86 ± 0.83	6.72 ± 1.19	19.81 ± 2.01*	-6.07 ± 1.53	2.01 ± 2.37
60° Flexion	-6.46 ± 1.26	3.35 ± 1.09	9.3 ± 1.08*	22.39 ± 2.33*	-7.03 ± 2.51	1.55 ± 2.31
Average	**-5.41 ± 1.22**	**2.75 ± 0.83**	**7.82 ± 1.25**	**18.03 ± 2.24**	**-4.71 ± 1.89**	**1.64 ± 2.3**
			EOS - Hinge TF : Moving-Axis PF			
20° Flexion	-3.29 ± 0.97	3.75 ± 0.53*	5.16 ± 1.52	13.01 ± 3.48	3.71 ± 2.10	3.47 ± 2.62
45° Flexion	-3.36 ± 1.25	7.03 ± 0.60*	1.35 ± 1.02	16.73 ± 2.35*	0.03 ± 1.56	4.74 ± 2.89
60° Flexion	-2.36 ± 0.95	6.74 ± 0.87*	1.40 ± 0.62	15.39 ± 2.39*	0.32 ± 1.83	5.17 ± 2.30
Average	**-3.01 ± 1.06**	**5.84 ± 0.67**	**2.63 ± 1.05**	**15.05 ± 2.74**	**1.35 ± 1.83**	**4.46 ± 2.61**
			EOS - Moving-Axis TF: Hinge PF			
20° Flexion	-3.70 ± 1.13	0.59 ± 0.65	5.29 ± 1.03	9.46 ± 2.03	-0.75 ± 1.65	1.14 ± 2.24
45° Flexion	-5.51 ± 1.27	2.2 ± 0.60	4.66 ± 0.90	16.61 ± 2.27*	-5.7 ± 1.59	1.91 ± 2.22
60° Flexion	-6.14 ± 1.27	0.84 ± 0.71	7.46 ± 10.00*	18.88 ± 2.60*	-6.61 ± 2.62	1.48 ± 2.26
Average	**-5.12 ± 1.23**	**1.21 ± 0.65**	**5.81 ± 0.97**	**14.98 ± 2.30**	**-4.35 ± 1.95**	**1.51 ± 2.24**

EOS - Moving-Axis: TF & PF						
20° Flexion	-2.91 ± 0.98	3.13 ± 0.60	3.26 ± 1.17	13.12 ± 2.77	3.97 ± 2.21	2.71 ± 2.52
45° Flexion	-3.05 ± 1.23	5.54 ± 0.45*	-0.16 ± 0.73	13.12 ± 1.90*	0.43 ± 1.69	3.99 ± 2.69
60° Flexion	-2.09 ± 0.92	4.61 ± 0.63*	0.28 ± 0.50	11.65 ± 1.42*	0.84 ± 0.50	4.41 ± 2.10
Average	**-2.69 ± 1.04**	**4.43 ± 0.56**	**1.13 ± 0.80**	**12.63 ± 2.03**	**1.74 ± 1.46**	**3.7 ± 2.44**
EOS - Interpolated TF : Hinge PF						
20° Flexion	-3.29 ± 1.08	-1.5 ± 0.74	4.28 ± 0.79	7.52 ± 2.11	-0.49 ± 1.71	1.46 ± 2.31
45° Flexion	-5.13 ± 1.24	-1.72 ± 0.65	5.24 ± 0.81*	14.49 ± 2.35	-5.59 ± 1.72	2.54 ± 2.13
60° Flexion	-5.88 ± 1.26	-1.56 ± 0.77	7.19 ± 1.02*	16.75 ± 2.59*	-6.48 ± 2.67	1.76 ± 2.26
Average	-4.76 ± 1.19	-1.59 ± 0.72	5.57 ± 0.87	12.92 ± 2.35	-4.19 ± 2.03	1.92 ± 2.24
EOS - Interpolated TF : Moving-Axis PF						
20° Flexion	-2.67 ± 0.96	1.48 ± 0.45	3.68 ± 0.94	9.24 ± 2.83	3.82 ± 2.22	2.5 ± 2.45
45° Flexion	-2.9 ± 1.2	3.1 ± 0.55	1.98 ± 0.76	12.86 ± 1.97*	0.08 ± 1.8	3.66 ± 2.7
60° Flexion	-1.98 ± 0.91	3.42 ± 0.71	1.04 ± 0.52	10.9 ± 1.55*	0.67 ± 2.02	3.93 ± 2.08
Average	-2.52 ± 1.03	2.67 ± 0.57	2.23 ± 0.74	11 ± 2.11	1.52 ± 2.01	3.36 ± 2.41

Table 3—Model predictive capabilities: Pearson's Correlation Coefficient, coefficient of determination (R^2) and adjusted R^2 values calculated from model and experimental data (EOS) for quasi-static lunge angles (20°, 45°, 60°). R categorized as a weak (W) $r \leq 0.35$, moderate (M) $0.35 < r \leq 0.67$, strong (S) $0.67 < r \leq 0.90$, or excellent (E) $0.90 < r$ prediction.

	Model Compared with EOS	*Translations*			*Rotations*		
		ML	**AP**	**SI**	**Flexion**	**Rotation**	**Tilt**
R	**Hinge: TF & PF**	0.30 (W)	0.96 (E)	0.95 (E)	0.91 (E)	0.39 (M)	0.39 (M)
	Hinge TF : MA PF	0.57 (M)	0.98 (E)	0.97 (E)	0.81 (S)	0.48 (M)	0.30 (W)
	MA TF : Hinge PF	0.31 (W)	0.98 (E)	0.97 (E)	0.92 (E)	0.39 (M)	0.42 (M)
	MA: TF & PF	0.59 (M)	0.99 (E)	0.98 (E)	0.89 (S)	0.48 (M)	0.34 (W)
	Int. TF : Hinge PF	0.62 (M)	0.99 (E)	0.98 (E)	0.88 (S)	0.47 (M)	0.36 (M)
	Int. TF : MA PF	0.36 (M)	0.98 (E)	0.98 (E)	0.92 (E)	0.41 (M)	0.42 (M)
R^2	**Hinge: TF & PF**	0.09	0.93	0.90	0.83	0.15	0.15
	Hinge TF : MA PF	0.32	0.95	0.93	0.66	0.23	0.09
	MA TF : Hinge PF	0.10	0.96	0.94	0.85	0.15	0.17
	MA: TF & PF	0.35	0.98	0.96	0.80	0.23	0.11
	Int. TF : Hinge PF	0.13	0.96	0.95	0.85	0.17	0.17
	Int. TF : MA PF	0.39	0.99	0.97	0.78	0.22	0.13
R^2_adj	**Hinge: TF & PF**	0.06	0.93	0.90	0.83	0.12	0.12
	Hinge TF : MA PF	0.30	0.95	0.93	0.65	0.20	0.06
	MA TF : Hinge PF	0.07	0.96	0.94	0.85	0.12	0.14
	MA: TF & PF	0.33	0.98	0.95	0.79	0.21	0.08
	Int. TF : Hinge PF	0.10	0.96	0.95	0.85	0.14	0.14
	Int. TF : MA PF	0.36	0.99	0.97	0.77	0.19	0.10

Supplementary Table 1—Six different knee joint models with various combinations of tibiofemoral (TF) and patellofemoral (PF) joint types. A hinge joint axis can either defined between two anatomical landmarks or based on an analytical cylinder fit of a contact surface. A moving-axis (MA) joint articulates linearly between two known axes with respect to tibiofemoral flexion, these axes are derived from two known flexion positions and joint contact surface fits. We included one additional tibiofemoral joint model, Interpolation (INT), to isolate the patellofemoral model error by simulating the tibiofemoral positions and orientations of the five EOS reconstructions.

Model abbreviation	Tibiofemoral joint	Patellofemoral joint
Hinge: TF-PF	Hinge	Hinge
Hinge TF : MA-PF	Hinge	Moving-Axis
MA-TF : Hinge-PF	Moving-Axis	Hinge
MA: TF-PF	Moving-Axis	Moving-Axis
INT-TF : Hinge-PF	EOS Interpolation	Hinge
INT-TF : MA-PF	EOS Interpolation	Moving-Axis

Supplementary Table 2—Kinematic measures ± standard deviation of the **EOS** in-vivo experimental data for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)			Rotations (°)		
	ML	**AP**	**SI**	**Flexion**	**Rotation**	**Tilt**
EOS_0	4.37 ± 6.25	50.45 ± 2.53	7.77 ± 11.34	10.61 ± 6.70	-0.85 ± 5.24	-2.00 ± 10.14
EOS_20	2.12 ± 3.57	48.19 ± 4.79	-7.76 ± 10.34	-1.86 ± 10.85	3.31 ± 4.77	0.08 ± 7.58
EOS_45	2.63 ± 2.53	40.64 ± 8.19	-21.58 ± 10.56	-14.23 ± 9.69	0.69 ± 5.80	1.31 ± 6.79
EOS_60	3.97 ± 2.47	32.13 ± 9.65	-29.48 ± 7.22	-27.61 ± 9.43	1.57 ± 6.79	1.31 ± 5.65
EOS_90	5.40 ± 2.37	18.66 ± 8.16	-35.58 ± 5.06	-46.59 ± 8.15	1.29 ± 5.74	-1.11 ± 5.52
Average (20-60)	**2.91 ± 2.86**	**40.32 ± 7.54**	**-19.61 ± 9.37**	**-14.57 ± 9.99**	**1.86 ± 5.79**	**0.90 ± 6.68**
Average (0-90)	**3.70 ± 3.44**	**38.01 ± 6.66**	**-17.33 ± 8.90**	**-15.94 ± 8.97**	**1.20 ± 5.67**	**-0.08 ± 7.14**
min	0.25 ± 2.92	18.66 ± 8.16	-35.58 ± 5.06	-46.59 ± 8.15	-2.83 ± 6.04	-7.20 ± 7.43
max	7.33 ± 4.19	50.63 ± 2.67	7.77 ± 11.34	11.09 ± 6.67	4.94 ± 4.58	5.65 ± 6.32
ROM	7.07 ± 3.27	31.98 ± 8.09	43.36 ± 8.20	57.68 ± 10.88	7.77 ± 5.03	12.85 ± 5.72

Supplementary Table 3—Kinematic measures ± standard deviation of the **Hinge: TF-PF model** output for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)			Translations (mm)		
	ML	**AP**	**SI**	**Flexion**	**Rotation**	**Tilt**
EOS_0	3.18 ± 3.96	58.65 ± 3.77	0.20 ± 9.58	9.62 ± 7.66	1.04 ± 7.94	-1.92 ± 5.28
EOS_20	6.08 ± 3.14	47.14 ± 5.30	-15.20 ± 7.28	-13.75 ± 9.25	4.32 ± 6.40	-1.27 ± 4.62
EOS_45	8.44 ± 2.77	36.78 ± 8.72	-28.30 ± 8.36	-34.04 ± 11.74	6.76 ± 5.99	-0.70 ± 5.91
EOS_60	10.43 ± 3.74	28.78 ± 9.43	-38.78 ± 6.57	-50.00 ± 13.79	8.60 ± 5.52	-0.24 ± 8.17
EOS_90	12.76 ± 3.80	17.47 ± 9.39	-54.51 ± 5.28	-73.05 ± 10.85	11.55 ± 4.87	0.69 ± 11.77
Average (20-60)	**8.31 ± 3.22**	**37.57 ± 7.81**	**-27.43 ± 7.40**	**-32.60 ± 11.59**	**6.56 ± 5.97**	**-0.74 ± 6.23**
Average (0-90)	**8.18 ± 3.48**	**37.76 ± 7.32**	**-27.32 ± 7.41**	**-32.24 ± 10.66**	**6.46 ± 6.14**	**-0.69 ± 7.15**
min	3.18 ± 3.96	17.47 ± 9.39	-54.51 ± 5.28	-73.05 ± 10.85	1.04 ± 7.94	-6.07 ± 5.89
max	12.76 ± 3.80	58.65 ± 3.77	0.20 ± 9.58	9.62 ± 7.66	11.55 ± 4.87	4.84 ± 8.32
ROM	9.59 ± 4.85	41.18 ± 9.71	54.71 ± 10.41	82.68 ± 13.26	10.51 ± 6.94	10.91 ± 8.94

Supplementary Table 4—Kinematic measures ± standard deviation of the **Hinge TF: MA-PF model** output for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)	Translations (mm)

	ML	AP	SI	Flexion	Rotation	Tilt
EOS_0	4.87 ± 5.96	56.47 ± 4.31	-1.06 ± 9.80	3.27 ± 10.31	-1.46 ± 8.45	-2.84 ± 9.01
EOS_20	5.42 ± 4.75	44.44 ± 6.03	-12.92 ± 7.43	-14.88 ± 7.67	-0.40 ± 6.98	-3.39 ± 7.61
EOS_45	5.99 ± 3.88	33.61 ± 8.69	-22.93 ± 8.79	-30.96 ± 7.23	0.66 ± 5.75	-3.43 ± 7.15
EOS_60	6.33 ± 3.34	25.38 ± 9.34	-30.88 ± 7.05	-43.01 ± 7.79	1.25 ± 4.91	-3.86 ± 7.10
EOS_90	6.47 ± 2.49	13.52 ± 8.60	-42.85 ± 4.92	-61.21 ± 8.45	2.37 ± 4.10	-3.61 ± 8.95
Average (20-60)	**5.91 ± 3.99**	**34.48 ± 8.02**	**-22.24 ± 7.76**	**-29.62 ± 7.57**	**0.50 ± 5.88**	**-3.56 ± 7.29**
Average (0-90)	**5.82 ± 4.08**	**34.68 ± 7.39**	**-22.13 ± 7.60**	**-29.36 ± 8.29**	**0.48 ± 6.04**	**-3.43 ± 7.96**
min	3.62 ± 3.91	13.52 ± 8.60	-42.85 ± 4.92	-61.21 ± 8.45	-2.28 ± 7.64	-7.65 ± 8.57
max	7.73 ± 4.30	56.47 ± 4.31	-1.06 ± 9.80	3.27 ± 10.31	3.19 ± 4.62	1.20 ± 6.69
ROM	4.10 ± 3.16	42.96 ± 8.94	41.80 ± 9.45	64.48 ± 13.76	5.47 ± 6.09	8.84 ± 6.62

Supplementary Table 5—Kinematic measures ± standard deviation of the **MA-TF: Hinge-PF model** output for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)			Translations (mm)		
	ML	AP	SI	Flexion	Rotation	Tilt
EOS_0	2.96 ± 3.90	58.01 ± 3.67	2.58 ± 9.74	11.55 ± 7.24	0.85 ± 7.78	-1.61 ± 5.61
EOS_20	5.82 ± 3.10	47.60 ± 5.48	-13.05 ± 8.00	-11.32 ± 9.96	4.05 ± 6.46	-1.06 ± 4.71
EOS_45	8.14 ± 2.85	38.44 ± 8.78	-26.25 ± 9.29	-30.85 ± 13.04	6.40 ± 6.30	-0.60 ± 5.85
EOS_60	10.11 ± 3.87	31.29 ± 10.11	-36.95 ± 7.36	-46.49 ± 15.63	8.18 ± 6.06	-0.17 ± 8.06
EOS_90	12.37 ± 4.03	21.33 ± 10.36	-52.82 ± 5.89	-68.76 ± 13.56	11.02 ± 5.69	0.63 ± 11.56
Average (20-60)	**8.02 ± 3.27**	**39.11 ± 8.13**	**-25.42 ± 8.22**	**-29.55 ± 12.88**	**6.21 ± 6.27**	**-0.61 ± 6.20**
Average (0-90)	**7.88 ± 3.55**	**39.33 ± 7.68**	**-25.30 ± 8.06**	**-29.17 ± 11.89**	**6.10 ± 6.46**	**-0.56 ± 7.16**
min	2.96 ± 3.90	21.33 ± 10.36	-52.82 ± 5.89	-68.76 ± 13.56	0.85 ± 7.78	-5.95 ± 5.75
max	12.37 ± 4.03	58.01 ± 3.67	2.58 ± 9.74	11.55 ± 7.24	11.02 ± 5.69	4.96 ± 8.28
ROM	9.41 ± 5.21	36.68 ± 10.59	55.40 ± 10.52	80.31 ± 15.42	10.17 ± 6.58	10.91 ± 9.21

Supplementary Table 6—Kinematic measures ± standard deviation of the **MA: TF-PF model** output for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)			Translations (mm)		
	ML	AP	SI	Flexion	Rotation	Tilt
EOS_0	4.47 ± 6.00	56.23 ± 3.94	1.28 ± 10.17	6.06 ± 8.77	-1.57 ± 8.73	-2.13 ± 8.84
EOS_20	5.04 ± 4.78	45.06 ± 6.30	-11.02 ± 8.23	-11.77 ± 7.60	-0.66 ± 7.53	-2.63 ± 7.21
EOS_45	5.68 ± 3.92	35.10 ± 9.21	-21.42 ± 9.72	-27.36 ± 8.27	0.27 ± 6.47	-2.68 ± 6.67
EOS_60	6.06 ± 3.41	27.52 ± 10.70	-29.77 ± 7.78	-39.27 ± 9.29	0.73 ± 5.76	-3.10 ± 6.43
EOS_90	6.22 ± 2.68	16.71 ± 10.55	-42.20 ± 5.26	-56.88 ± 9.61	1.70 ± 4.88	-2.80 ± 8.25
Average (20-60)	**5.59 ± 4.03**	**35.89 ± 8.73**	**-20.74 ± 8.57**	**-26.13 ± 8.39**	**0.11 ± 6.59**	**-2.80 ± 6.77**
Average (0-90)	**5.49 ± 4.16**	**36.12 ± 8.14**	**-20.62 ± 8.23**	**-25.84 ± 8.71**	**0.09 ± 6.68**	**-2.67 ± 7.48**
min	3.17 ± 3.95	16.71 ± 10.55	-42.20 ± 5.26	-56.88 ± 9.61	-2.36 ± 8.10	-6.95 ± 7.94
max	7.52 ± 4.34	56.23 ± 3.94	1.28 ± 10.17	6.06 ± 8.77	2.49 ± 5.24	2.02 ± 6.23
ROM	4.34 ± 3.35	39.52 ± 10.56	43.48 ± 8.91	62.94 ± 13.64	4.85 ± 5.23	8.97 ± 6.54

Supplementary Table 7—Kinematic measures ± standard deviation of the **INT-TF: Hinge-PF model** output for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)			Translations (mm)		
	ML	AP	SI	Flexion	Rotation	Tilt
EOS_0	3.39 ± 3.86	50.91 ± 3.34	7.15 ± 8.95	12.73 ± 7.01	0.47 ± 6.39	-0.21 ± 5.65
EOS_20	5.42 ± 3.14	49.69 ± 4.78	-12.05 ± 9.29	-9.38 ± 10.51	3.79 ± 6.73	-1.38 ± 4.71
EOS_45	7.75 ± 2.91	42.36 ± 9.07	-26.82 ± 10.26	-28.72 ± 13.26	6.29 ± 7.16	-1.23 ± 5.71
EOS_60	9.84 ± 3.92	33.69 ± 11.39	-36.67 ± 6.94	-44.36 ± 15.60	8.05 ± 6.55	-0.44 ± 8.13
EOS_90	12.36 ± 4.19	17.28 ± 10.21	-46.58 ± 4.66	-66.50 ± 13.60	10.21 ± 4.42	1.58 ± 11.08
Average (20-60)	**7.67 ± 3.33**	**41.91 ± 8.41**	**-25.18 ± 8.83**	**-27.49 ± 13.12**	**6.04 ± 6.82**	**-1.02 ± 6.18**
Average (0-90)	**7.75 ± 3.61**	**38.79 ± 7.76**	**-22.99 ± 8.02**	**-27.25 ± 12.00**	**5.76 ± 6.25**	**-0.34 ± 7.06**
min	3.28 ± 3.57	17.28 ± 10.21	-46.58 ± 4.66	-66.50 ± 13.60	0.46 ± 6.39	-4.81 ± 5.70
max	12.36 ± 4.19	51.72 ± 3.34	7.15 ± 8.95	12.73 ± 7.01	10.73 ± 4.94	5.88 ± 7.99
ROM	9.08 ± 4.73	34.44 ± 9.59	53.73 ± 9.62	79.23 ± 15.03	10.27 ± 6.00	10.69 ± 8.31

Supplementary Table 8—Kinematic measures ± standard deviation of the **INT-TF: MA-PF model** output for quasi-static lunge conditions **with respect to femur reference frame**. Average (± SD) are calculated for each clinical measure.

Condition	Translations (mm)			Translations (mm)		
	ML	AP	SI	Flexion	Rotation	Tilt
EOS_0	4.92 ± 6.19	50.95 ± 3.24	6.43 ± 9.78	7.64 ± 8.27	-2.78 ± 8.59	-2.43 ± 9.42
EOS_20	4.80 ± 4.87	46.70 ± 5.78	-11.44 ± 8.97	-11.10 ± 8.09	-0.51 ± 7.45	-2.42 ± 7.20
EOS_45	5.53 ± 4.04	37.54 ± 9.60	-23.56 ± 9.76	-27.09 ± 8.03	0.62 ± 6.68	-2.36 ± 6.64
EOS_60	5.95 ± 3.37	28.71 ± 11.20	-30.52 ± 6.79	-38.51 ± 8.60	0.90 ± 6.12	-2.62 ± 6.59
EOS_90	6.13 ± 2.45	14.19 ± 9.32	-36.15 ± 4.98	-54.08 ± 9.01	0.71 ± 4.79	-3.43 ± 8.37
Average (20-60)	**5.43 ± 4.09**	**37.65 ± 8.86**	**-21.84 ± 8.51**	**-25.57 ± 8.24**	**0.33 ± 6.75**	**-2.46 ± 6.81**
Average (0-90)	**5.47 ± 4.18**	**35.62 ± 7.83**	**-19.05 ± 8.06**	**-24.63 ± 8.40**	**-0.21 ± 6.73**	**-2.65 ± 7.64**
min	2.98 ± 4.13	14.19 ± 9.32	-36.20 ± 4.93	-54.08 ± 9.01	-3.74 ± 7.87	-7.47 ± 8.50
max	7.76 ± 4.13	50.95 ± 3.24	6.43 ± 9.78	7.64 ± 8.27	2.48 ± 5.13	1.66 ± 6.18
ROM	4.78 ± 2.85	36.76 ± 9.66	42.64 ± 8.08	61.72 ± 13.17	6.22 ± 4.25	9.13 ± 5.95

Supplementary Table 9—ANOVA table for patellofemoral clinical measures taken from the origin of the patella anatomical coordinate system relative to the femoral anatomical coordinate system. *(α=0.05/18=0.002778) Bonferroni adjustments were made for multiple comparisons.

Clinical Measure	Lunge Angle	(I) model	(J) model	Mean Difference (I-J)	Std. Error	P-value	99.722% Confidence Interval for Differences	
							Lower Bound	Upper Bound
Lateral Shift (mm)[a]	20[b]	EOS	TF (H)____PF (H)	-3.953	1.148	0.155	-11.250	3.344
		EOS	TF (H)____PF (MA)	-3.295	0.974	0.170	-9.485	2.896
		EOS	TF (MA)____PF (H)	-3.697	1.134	0.207	-10.902	3.509
		EOS	TF (MA)____PF (MA)	-2.912	0.981	0.331	-9.146	3.322
		EOS	TF (Int)____PF (H)	-3.290	1.078	0.289	-10.141	3.560
		EOS	TF (Int)____PF (MA)	-2.673	0.965	0.457	-8.804	3.458
	45[b]	EOS	TF (H)____PF (H)	-5.811	1.263	0.027	-13.835	2.212
		EOS	TF (H)____PF (MA)	-3.363	1.246	0.514	-11.283	4.557
		EOS	TF (MA)____PF (H)	-5.510	1.272	0.040	-13.595	2.575
		EOS	TF (MA)____PF (MA)	-3.053	1.225	0.720	-10.839	4.732
		EOS	TF (Int)____PF (H)	-5.126	1.243	0.054	-13.021	2.770

		EOS	TF (Int)____PF (MA)	-2.903	1.199	0.808	-10.518	4.713
	60[b]	EOS	TF (H)____PF (H)	-6.459	1.262	0.013	-14.479	1.562
		EOS	TF (H)____PF (MA)	-2.365	0.954	0.737	-8.427	3.698
		EOS	TF (MA)____PF (H)	-6.140	1.273	0.020	-14.228	1.948
		EOS	TF (MA)____PF (MA)	-2.093	0.918	1.000	-7.925	3.740
		EOS	TF (Int)____PF (H)	-5.876	1.258	0.025	-13.871	2.120
		EOS	TF (Int)____PF (MA)	-1.981	0.915	1.000	-7.793	3.831
Anterior-Posterior Displacement (mm)[a]	20[b]	EOS	TF (H)____PF (H)	1.044	0.576	1.000	-2.618	4.706
		EOS	TF (H)____PF (MA)	3.748*	0.529	0.001	0.386	7.111
		EOS	TF (MA)____PF (H)	0.589	0.645	1.000	-3.510	4.689
		EOS	TF (MA)____PF (MA)	3.127	0.600	0.012	-0.687	6.941
		EOS	TF (Int)____PF (H)	-1.502	0.743	1.000	-6.225	3.222
		EOS	TF (Int)____PF (MA)	1.481	0.445	0.186	-1.349	4.312
	45[b]	EOS	TF (H)____PF (H)	3.860	0.834	0.026	-1.437	9.157
		EOS	TF (H)____PF (MA)	7.031*	0.598	0.000	3.234	10.829
		EOS	TF (MA)____PF (H)	2.201	0.602	0.111	-1.626	6.028
		EOS	TF (MA)____PF (MA)	5.537*	0.455	0.000	2.648	8.426
		EOS	TF (Int)____PF (H)	-1.724	0.648	0.545	-5.840	2.391
		EOS	TF (Int)____PF (MA)	3.102	0.550	0.007	-0.394	6.598
	60[b]	EOS	TF (H)____PF (H)	3.347	1.090	0.279	-3.576	10.271
		EOS	TF (H)____PF (MA)	6.744*	0.872	0.001	1.205	12.282
		EOS	TF (MA)____PF (H)	0.841	0.712	1.000	-3.686	5.368
		EOS	TF (MA)____PF (MA)	4.611*	0.630	0.001	0.610	8.612
		EOS	TF (Int)____PF (H)	-1.558	0.767	1.000	-6.429	3.314
		EOS	TF (Int)____PF (MA)	3.423	0.706	0.019	-1.062	7.908
Proximal-Distal Displacement (mm)[a]	20[b]	EOS	TF (H)____PF (H)	7.438	1.486	0.015	-2.002	16.879
		EOS	TF (H)____PF (MA)	5.157	1.522	0.169	-4.516	14.830
		EOS	TF (MA)____PF (H)	5.291	1.026	0.013	-1.228	11.809
		EOS	TF (MA)____PF (MA)	3.259	1.167	0.440	-4.155	10.673
		EOS	TF (Int)____PF (H)	4.284	0.785	0.008	-0.705	9.273
		EOS	TF (Int)____PF (MA)	3.681	0.944	0.076	-2.314	9.677
	45[b]	EOS	TF (H)____PF (H)	6.721	1.188	0.007	-0.826	14.268
		EOS	TF (H)____PF (MA)	1.352	1.019	1.000	-5.122	7.825
		EOS	TF (MA)____PF (H)	4.664	0.898	0.012	-1.042	10.370
		EOS	TF (MA)____PF (MA)	-0.164	0.726	1.000	-4.776	4.448
		EOS	TF (Int)____PF (H)	5.236*	0.813	0.003	0.072	10.400
		EOS	TF (Int)____PF (MA)	1.979	0.761	0.604	-2.858	6.816
	60[b]	EOS	TF (H)____PF (H)	9.297*	1.078	0.000	2.450	16.144
		EOS	TF (H)____PF (MA)	1.396	0.618	1.000	-2.528	5.320
		EOS	TF (MA)____PF (H)	7.463*	0.997	0.001	1.128	13.797
		EOS	TF (MA)____PF (MA)	0.283	0.497	1.000	-2.877	3.443
		EOS	TF (Int)____PF (H)	7.187*	1.017	0.001	0.728	13.646
		EOS	TF (Int)____PF (MA)	1.040	0.522	1.000	-2.275	4.356
Patellar Flexion (deg)[a]	20[b]	EOS	TF (H)____PF (H)	11.884	2.388	0.016	-3.286	27.054
		EOS	TF (H)____PF (MA)	13.013	3.478	0.097	-9.084	35.110
		EOS	TF (MA)____PF (H)	9.461	2.026	0.025	-3.413	22.334
		EOS	TF (MA)____PF (MA)	9.905	2.768	0.125	-7.684	27.495
		EOS	TF (Int)____PF (H)	7.520	2.106	0.126	-5.862	20.902
		EOS	TF (Int)____PF (MA)	9.239	2.827	0.204	-8.722	27.200
	45[b]	EOS	TF (H)____PF (H)	19.807*	2.007	0.000	7.057	32.557
		EOS	TF (H)____PF (MA)	16.731*	2.347	0.001	1.816	31.647
		EOS	TF (MA)____PF (H)	16.612*	2.268	0.001	2.202	31.022
		EOS	TF (MA)____PF (MA)	13.123*	1.897	0.001	1.072	25.173
		EOS	TF (Int)____PF (H)	14.487	2.348	0.003	-0.429	29.403
		EOS	TF (Int)____PF (MA)	12.855*	1.967	0.002	0.360	25.351
	60[b]	EOS	TF (H)____PF (H)	22.388*	2.335	0.000	7.554	37.222
		EOS	TF (H)____PF (MA)	15.394*	2.385	0.002	0.237	30.551
		EOS	TF (MA)____PF (H)	18.875*	2.603	0.001	2.334	35.416
		EOS	TF (MA)____PF (MA)	11.654*	1.424	0.000	2.604	20.704

		EOS	TF (Int)____PF (H)	16.752*	2.594	0.002	0.269	33.236
		EOS	TF (Int)____PF (MA)	10.897*	1.549	0.001	1.054	20.740
Patellar Rotation (deg)[a]	20[b]	EOS	TF (H)____PF (H)	-1.019	1.642	1.000	-11.455	9.417
		EOS	TF (H)____PF (MA)	3.706	2.099	1.000	-9.629	17.042
		EOS	TF (MA)____PF (H)	-0.748	1.652	1.000	-11.246	9.750
		EOS	TF (MA)____PF (MA)	3.967	2.210	1.000	-10.075	18.008
		EOS	TF (Int)____PF (H)	-0.487	1.707	1.000	-11.335	10.361
		EOS	TF (Int)____PF (MA)	3.819	2.216	1.000	-10.259	17.896
	45[b]	EOS	TF (H)____PF (H)	-6.069	1.526	0.068	-15.765	3.626
		EOS	TF (H)____PF (MA)	0.032	1.562	1.000	-9.895	9.959
		EOS	TF (MA)____PF (H)	-5.703	1.589	0.123	-15.798	4.392
		EOS	TF (MA)____PF (MA)	0.427	1.687	1.000	-10.290	11.145
		EOS	TF (Int)____PF (H)	-5.590	1.719	0.209	-16.512	5.331
		EOS	TF (Int)____PF (MA)	0.079	1.804	1.000	-11.385	11.543
	60[b]	EOS	TF (H)____PF (H)	-7.030	2.515	0.438	-23.009	8.950
		EOS	TF (H)____PF (MA)	0.323	1.828	1.000	-11.291	11.938
		EOS	TF (MA)____PF (H)	-6.610	2.622	0.686	-23.267	10.046
		EOS	TF (MA)____PF (MA)	0.838	1.966	1.000	-11.655	13.332
		EOS	TF (Int)____PF (H)	-6.481	2.666	0.796	-23.418	10.457
		EOS	TF (Int)____PF (MA)	0.672	2.021	1.000	-12.170	13.515
Patellar Tilt (deg)[a]	20[b]	EOS	TF (H)____PF (H)	1.349	2.216	1.000	-12.731	15.429
		EOS	TF (H)____PF (MA)	3.469	2.625	1.000	-13.209	20.147
		EOS	TF (MA)____PF (H)	1.142	2.236	1.000	-13.068	15.351
		EOS	TF (MA)____PF (MA)	2.709	2.524	1.000	-13.326	18.745
		EOS	TF (Int)____PF (H)	1.463	2.309	1.000	-13.208	16.135
		EOS	TF (Int)____PF (MA)	2.497	2.449	1.000	-13.061	18.054
	45[b]	EOS	TF (H)____PF (H)	2.011	2.367	1.000	-13.029	17.051
		EOS	TF (H)____PF (MA)	4.742	2.892	1.000	-13.633	23.117
		EOS	TF (MA)____PF (H)	1.912	2.216	1.000	-12.169	15.994
		EOS	TF (MA)____PF (MA)	3.986	2.693	1.000	-13.122	21.095
		EOS	TF (Int)____PF (H)	2.542	2.134	1.000	-11.018	16.101
		EOS	TF (Int)____PF (MA)	3.665	2.701	1.000	-13.494	20.824
	60[b]	EOS	TF (H)____PF (H)	1.549	2.307	1.000	-13.112	16.210
		EOS	TF (H)____PF (MA)	5.167	2.301	1.000	-9.453	19.787
		EOS	TF (MA)____PF (H)	1.485	2.263	1.000	-12.895	15.864
		EOS	TF (MA)____PF (MA)	4.409	2.100	1.000	-8.935	17.753
		EOS	TF (Int)____PF (H)	1.756	2.265	1.000	-12.635	16.147
		EOS	TF (Int)____PF (MA)	3.930	2.079	1.000	-9.282	17.142