Development of subject-specific moving-axis knee model

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

Publication date:
2017

Document Version
Early version, also known as pre-print

DEVELOPMENT OF SUBJECT-SPECIFIC MOVING-AXIS KNEE MODEL

[1]Christine M Dzialo, [1,2]Peter H Pedersen, [2]Carsten W Simonsen [2]Kenneth K Jensen, [1]Mark de Zee, and [1]Michael S Andersen
[1]Aalborg University, [2]Aalborg University Hospital
Email: cdz@m-tech.aau.dk

INTRODUCTION

Musculoskeletal (MS) models are used by the scientific community to gain insight on how external forces and movements influence the human body internally. This allows researchers to quantify muscle, ligament, and joint contact forces without the use of invasive methods. Despite the complex knee structure, the knee is often idealized as a hinge joint. However, many studies have revealed tibial-rotation trends with respect to knee flexion [1]. A handful of researchers have already incorporated secondary kinematics into MS models [2-4] but only rarely on a subject-specific basis. The level of knee joint complexity that is required for a MS model to mimic reality and accurately simulate human movements is up for debate especially when the model is applied for critical applications. This stresses the importance of thorough validation by quantifying uncertainty and errors in the computational model when compared to ground truth data. The aim of this project was to develop a new model of the knee with a higher level of complexity, a subject-specific moving-axis knee model, and begin a validation process of the predicted secondary kinematics during a loaded knee bend using bi-planar x-rays measured using EOS technology (EOS Imaging SA, Paris, France).

METHODS

Various magnetic resonance imaging (MRI) acquisitions were acquired from ten adult males to enable subject-specific (SS) right knee joint model development of each individual. Manual segmentation was performed on full lower limb MRI (femur, tibia, patella, and talus bones) with Mimics Research 19.0 (Materialise, Belgium) and these surfaces were used to obtain SS joint centers though analytical shape fitting methods [4]. The anatomical reference frames (Figure 1) were defined for the right knee using ISB standards [5]. Segmented articular cartilage surfaces from two detailed knee MRI scans at roughly 0 and 90 degree-flexion (Figure 2.a-d) were used to define novel tibiofemoral (TF) and patellofemoral (PF) moving-axis (MA) joints using AnyBody Modeling System v. 6.1 (Anybody Technology A/S, Aalborg, Denmark).

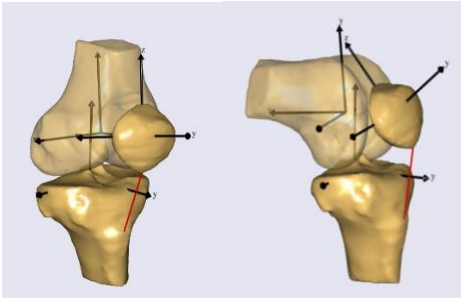

Fig 1: (*left*) Anatomical reference frames of femur, tibia, and patella for right knee MA model in initial position. X-axes point laterally from origin, y-axes point anteriorly, and z-axis point superiorly (*right*) MA model in TF flexion

A circle fitting function was used to determine the extension (EFC) and flexion facet centers (FFC) on the medial and lateral femoral condyles and trochlear groove (Figure 2.e).

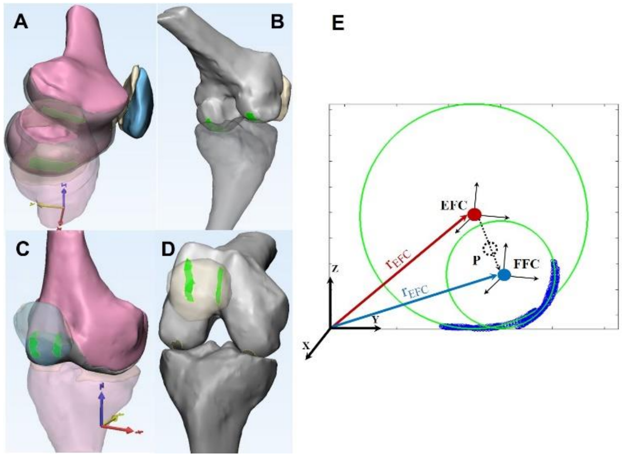

Fig 2: TF (A-B) and PF (C-D) contact surface selections for EFC (A & C) and FFC (B & D) with surface fitting example (E) for TF facet centers.

The model applies a linear interpolation scheme (E) between the EFC and FFC of the medial and lateral contact surface of the TF and PF joints estimated from the two MRI scans at roughly 0 and 90 degrees of flexion to estimate the secondary joint kinematics for knee flexion angles between these two measured poses [6]. For flexion angles lower than the "0" degree MRI, it was assumed the TF and PF joints rotated about their respective EFC axes. Once the TF angle reached the bone position of the "90" degree MRI, it was assumed that the TF and PF joints rotated about their respective FFC axes independent of the flexion angle. The subject-specific moving-axis knee models were each run from 0 to 120 degrees TF flexion and clinical translations and rotations were exported as a text file for data processing in custom MATLAB code.

$$p(\theta) = \begin{cases} r_{EFC} & "0"_{MRI} > \theta \\ r_{EFC}\left(1 - \frac{\theta}{"90"_{MRI}}\right) + r_{FFC}\left(\frac{\theta}{"90"_{MRI}}\right) & "0"_{MRI} \geq \theta \geq "90"_{MRI} \\ r_{FFC} & \theta > "90"_{MRI} \end{cases}$$

[Eq. 1]

To validate the SS MA knee models, EOS Imaging technology was employed to capture secondary knee joint kinematics of each subject during a quasi-static lunge. Each subject (n = 10) was positioned and scanned at five different tibiofemoral approximate flexion angles (0, 20, 45, 60, and 90) as shown in Figure 3. The 2D bone contours were segmented from the frontal and lateral images of the femur, tibia, and patella structures. Custom MATLAB code was used to register the 3D bone STLs to the respective bi-planar contours to determine the position of the subject's TF and PF joints in the EOS scanner.

Fig 3: The respective anterior posterior (AP) and lateral (LAT) images were taken at a 45-degree angle to the x-ray tubes, and reconstructed, due to the structure limitations of the EOS scanner.

RESULTS AND DISCUSSION

Mean tibiofemoral translations and rotations with standard deviation values from the moving-axis knee models (n = 10) are represented in Figure 4. These measurements are taken in the femoral reference frame with respect to the tibial reference frame using methods established by Grood & Suntay (1983). The tibiofemoral translations and rotations show similar trends when compared with other literature findings [1,5-8]. However, fine-tuning of the interpolation function in the moving-axis model may provide more accurate results.

EOS reconstructions were considered "gold standard" when determining how well the MA knee model mimic reality. Root mean square errors of TF anterior drawer (5.58 ± 1.91mm) and joint distraction (2.28 ± 1.16mm) indicate acceptable agreement in the first five subjects. Other clinical translations such as tibial internal rotation, adduction/abduction, and lateral tibia dislocation also provide reasonable comparisons with EOS outputs. For the remaining five subjects, the EOS reconstructions are in process.

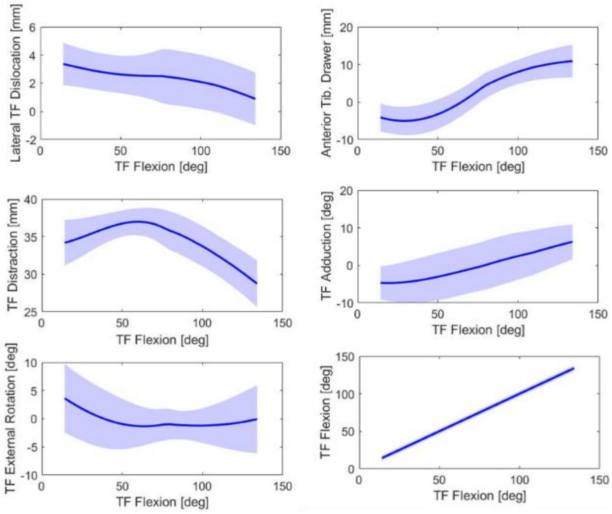

Fig 4: Mean and standard deviations of tibiofemoral clinical translations and rotations for subject-specific (n = 10) moving-axis knee models. Values are based on the femoral reference frame moving with respect to the tibial.

CONCLUSIONS

We have developed a new approach to construct the TF and PF joints in MS modeling. Initial results indicate that a piecewise linear model based off two passive MRI scans can accurately represent secondary kinematics of a loaded knee joint. Further EOS registrations need to be completed to ensure the moving-axis model represents the secondary knee joint kinematics of each subject. In addition, this study shows the potential of using EOS imaging to compare and validate knee models of varying complexity

REFERENCES

1. Victor JM, The Knee. Chap. **3**:37-67, 2014.
2. Delp SL, IEEE Trans Biomed Eng. **37**(8): 757-67, 1990.
3. Sandholm A, et al., Vis Comput. **27**(2):161-71, 2011.
4. Marra M, J. Biomech. **137**(2): 020904, 2015.
5. Grood E, J. Biomech. **105**(2):136-144, 1983.
6. Iwaki H, J Bone Joint Surg Br. **82**(8):1189-95, 2000.
7. Maderbacher G, J Arthroplasty. 31(9): 2038-42, 2016.
8. Al Hares G, Proc Inst mech Eng H. 229(6):439-51, 2015.

ACKNOWLEDGEMENTS

EU's KNEEMO Initial Training Network, grant no. 607510.