Subject-specific Computational Modeling of Human Patellofemoral Joint Motion for Routine Clinical Practice

Jeffry Hartanto[1], Wee Kheng Leow[1], Andy Khye Soon Yew[2], Joyce Suang Bee Koh[2], Tet-Sen Howe[2]

[1]National University of Singapore, Singapore, SG, [2]Singapore General Hospital, Singapore, SG

Email: jhartanto@comp.nus.edu.sg

INTRODUCTION: Knee joint is prone to injuries that restrict the joint motion. To restore normal joint motion, detailed pre-operative planning is important. One approach to subject-specific pre-operative planning is to model joint function computationally, and to use the model to predict possible surgical outcome. While existing models are useful for medical research, they are not suitable for routine clinical applications due to their complexity and requirement of complex auxiliary data, such as motion capture data and multiple computed tomography (CT)/ magnetic resonance imaging (MRI) scans. This paper proposes a contact surface model that requires only a single CT scan of a subject's knee. As a start, we aim to demonstrate that the motion of the patellofemoral (PF) joint can be modeled with sufficient accuracy. Although this contact surface model is preliminary, it nevertheless opens up a useful approach for routine clinical application of pre-operative planning of knee joint surgery.

METHODS: CT scans of five cadaver knees (age: 53–78 years; 4 males and 1 female; 3 left and 2 right knees) were captured between 0° and 120° flexion angles at intervals of 30°. For each subject, the 3D models of the femur and the patella were segmented and constructed from the CT scans. The models at 0° served as the input of the contact surface model, and the models at the other flexion angles served as the ground-truth data. Modeling of PF joint motion consists of three stages: (1) model construction, (2) patella pose estimation and (3) patella motion generation. In (1), three landmarks called groove landmarks (Fig. 1) are placed at distinctive features on the femoral groove. They are used to define in-plane translation and flexion of patella pose with respect to the femur. To model tilting and internal/external rotation of the patella, two additional landmarks called refinement landmarks are placed on each side of patella (Fig. 1). A termination landmark (Fig. 1) is placed in the medial area of femoral condyle to denote the lowest position of the patella with respect to the femur. In (2), a motion plane, *P*, is constructed by fitting a plane to the groove landmarks to locate intersection curves on the bone models. For an approximation of combined cartilage thickness, our model uses the distance of closest point, *D*, between the intersection curves of the bone models at 0° (Fig. 2). With three distinctive points that describe a patella pose (Fig. 2), three motion paths are generated in the normal direction of femoral intersection curve that maintain constant gap *D* between the two bones, until they reach the termination landmark (Fig. 3). Next, *P* is centered at each refinement landmark to find their respective intersection curves. Then, two refinement paths that maintain their respective distances at 0° are generated, similar to motion path generation (Fig. 3). In (3), the generated patella poses over the full motion range is obtained by rigidly transforming the patella pose at 0° along the motion paths and refinement paths.

RESULTS: To measure the accuracy of the contact surface model, it was necessary to identify the generated poses that correspond to each flexion angle from 30° to 120° at intervals of 30°. This was performed by identifying the generated patella poses that best matched the ground-truth poses in terms of the Hausdorff distance between a generated pose and a ground-truth pose. Next, the modeling error was measured in terms of 3D translation and rotation from the ground-truth pose to the corresponding generated pose. The translation and rotation were each measured as a vector with respect to the ground-truth pose based on the algorithm in [1]. Table 1 summarizes the translation and rotation errors in terms of the magnitudes of the vectors, as well as the signed-magnitudes of the vectors resolved into three principle directions, namely medial-lateral (M–L), anterior-posterior (A–P), and inferior-superior (I–S). Three symbols are used to denote each signed-magnitudes: + for significant magnitude (> 0.1 mm for translation, > 0.1° for rotation) in the medial, anterior, and inferior directions; – for significant magnitude in the lateral, posterior, and superior direction; and 0 for insignificant magnitude in the principle directions. Table 1 shows that the translation error pattern varies across different subjects and flexion angles, with the translation errors varying from 0.3 to 2.7 mm. For rotation errors, most of them are less than 0.1°. Subject S4's rotation error along the superior direction at 120° flexion angle is slightly larger (0.17°).

DISCUSSION: When compared to the previous works that modeled and validated PF joint motion [2, 3], the reported translation errors range from 0.47 to 0.88 mm, and the reported rotation errors range from 0.3° to 0.75°. In comparison, the rotation error of our approach is significantly smaller, whereas the translation error is comparable for subjects S1, S2, and S3, and slightly larger for S4 and S5. Nevertheless, these amounts of errors are clinically insignificant for pre-operative planning of knee surgery. Therefore, our model is deemed to be sufficiently accurate for pre-operative planning of knee surgery. This preliminary study has a few limitations. Firstly, the constant gap *D* disregards the varying cartilage thickness across different subjects and different knee flexion angles. One possible approach is to model the change of cartilage thickness based on a generic subject. Another limitation of this study is the small dataset size which might not capture sufficient variations across subjects. Future work may include modeling other joints' motion, and application of the model to the planning of various knee surgeries, such as medial patellofemoral ligament (MPFL) reconstruction.

SIGNIFICANCE: The proposed model requires only a single CT scan of a patient's knee to estimate the full range of PF joint motion, which is the minimum amount of information acquired for the diagnosis of a patient's condition. With sufficiently small error for estimating PF joint motion, the contact surface model is more feasible than existing modeling methods used for routine clinical practice of knee surgery planning, such as MPFL reconstruction.

REFERENCES: [1] Horn, B. et al. J. Opt. Soc. Am. A., Opt., Image, Sci., Vis. 5:1127–1135, 1988. [2] Fellows, R. et al. J. Biomech. 38:1643–1652, 2005. [3] Otake, Y. et al. SPIE Medical Imaging. 9786:97860B, 2016.

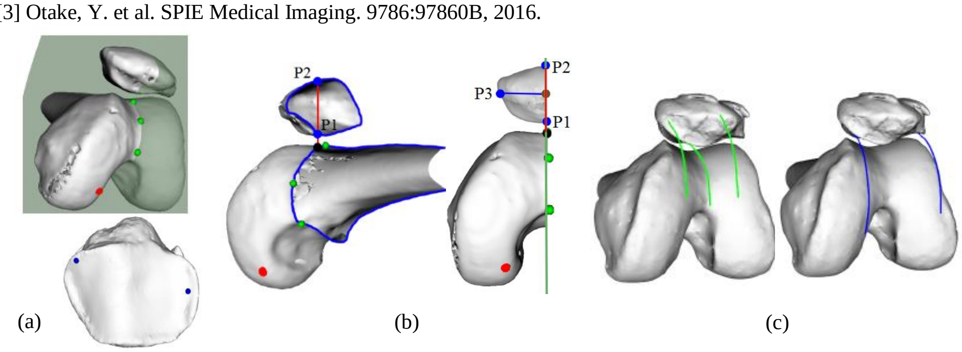

Fig.1. Three stages in contact surface model. (a) Landmarks and motion plane. Motion plane (green plane) is the plane that fits the groove landmarks (green dots). Termination landmark (red dot) denotes the end of patella motion. Refinement landmarks (blue) account the tilting and external/internal rotation of patella motion. (b) Intersecting curves and distinctive points on the patella. Intersection curves (blue) are obtained by intersecting the motion plane (green) with the patella and femur models. Part of bone models are removed for visual clarity. Surface normal at the closest point on the femur (black dot) intersects the patella intersecting curves at two distinctive points P1 and P2. Surface normal of motion plane (green line) at mid-point (brown dot) of the two distinctive points intersects the patella surface at a third distinctive point P3. (c) The five paths that estimate full range of patella motion. Three motion paths (green) and two refinement paths (blue).

Table 1

Errors of generated patella pose at various flexion angles. Refer to main text for explanation of these symbols.

(a) Translation errors.

	30°	60°	90°	120°
S1	0.86 + + 0	0.34 + + –	0.48 – + –	0.61 + 0 0
S2	0.30 + – 0	0.75 0 + +	0.96 – – +	1.80 + – +
S3	0.54 0 + –	0.68 – + 0	0.75 – + 0	0.68 – + –
S4	0.57 + – –	1.32 + – –	0.96 + – +	0.95 + – 0
S5	1.41 – + +	2.30 – + +	2.16 – + +	2.67 0 + +

(b) Rotation errors.

	30°	60°	90°	120°
S1	0.013 0 0 0	0.00 0 0 0	0.00 0 0 0	0.00 0 0 0
S2	0.01 0 0 0	0.02 0 0 0	0.06 0 0 0	0.06 0 0 0
S3	0.01 0 0 0	0.02 0 0 0	0.02 0 0 0	0.05 0 0 0
S4	0.02 0 0 0	0.02 0 0 0	0.06 0 0 0	0.17 0 0 –
S5	0.00 0 0 0	0.00 0 0 0	0.03 0 0 0	0.07 0 0 0