Augmented Reality-Based Surgical Guidance for Anterior and Posterior Cruciate Ligament Reconstruction

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INTRODUCTION

Anterior and posterior cruciate ligament (ACL and PCL) reconstructions are common knee arthroscopic surgeries. ACL and PCL reconstruction have small incision sites, thus enabling fast recovery of the patient. However, an arthroscope provides a limited view due to the small size of the camera lens, and a small incision restricts the motion of surgical instruments. As a result, finding the exact bone drilling position that was preoperatively determined to connect a new ligament between the femur and tibia is challenging during surgery. A previous study verified that the complication ratio of ACL and PCL reconstruction is 9.0 % and 20.1 %, respectively, which are particularly high compared to other knee arthroscopic surgeries [1].

Augmented reality (AR)-based surgical guidance can assist in difficult ACL and PCL reconstruction. Hu et al. [2] proposed AR-based non-invasive drilling guidance for the femur in open knee surgery. To implement the non-invasive system, they performed the registration between the depth data of the femur obtained from RGBD sensors and the pre-scanned femur model. However, this method is suitable for open knee surgery and is not for arthroscopic surgeries such as ACL and PCL reconstruction. Recently, Chen et al. [3] introduced non-invasive AR for knee arthroscopy. However, to reflect knee movements occurring during surgery in AR, it is necessary to manually select four anatomical landmarks in the arthroscopic view. Manual selection is inconvenient and may be inconsistent, interfering with surgical procedures.

In this study, we propose a non-invasive AR-based surgical guidance for ACL and PCL reconstruction with compensation of the intraoperative knee movement. Unlike preoperative CT and MR, which are taken under the extension state, the knee is under the flexion state during surgery, which requires compensation for the knee movement. The proposed method estimates knee movement without direct bone exposure or manual intervention by exploring the correlation between the knee surface and the internal bones (femur and tibia) based on a finite element method. The proposed method can enhance the AR for knee arthroscopic procedures, overlaying drilling guidance and position of instruments inside the knee joint, which lead to more accurate bone drilling for ACL or PCL reconstruction.

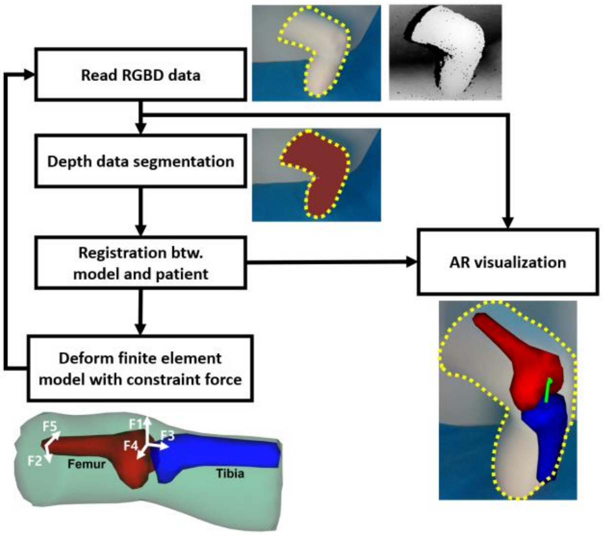

Fig. 1 Flowchart of the proposed AR-based surgical guidance.

MATERIALS AND METHODS

A. Correlation model between knee surface and bone

Fig. 1 shows the entire process of the proposed method. First, we defined individual finite element models for the knee surface, femur, and tibia (Fig. 2). For the femur and tibia, a tetrahedral co-rotational finite element was used to simulate a large displacement accurately. The 533 and 451 tetrahedral elements were used for the femur and tibia, respectively. On the other hand, for the knee surface, the hexahedral element was used for its rounded shape and computational efficiency. In our study, the knee surface consisted of 10 (width) × 10 (length) × 80 (height) hexahedral elements. We assumed that both the knee surface and internal bones have isotropic elastic behavior. According to the previous study, Young's modulus of bones was set to 1000 MPa [4]. For the knee surface, Young's modulus was set empirically because it was a mixture of diverse soft tissues.

We introduced a mapping between finite element models [5] to make motions of internal bones according to the shape deformation of the knee surface. In each simulation loop, the hexahedron elements of the knee surface propagate displacement to corresponding internal tetrahedron nodes of bones. The forces generated due to the displacement of the tetrahedron node are inversely propagated to the hexahedron elements. A collision controlled between the femur and tibia was implemented to prevent overlapping the two models.

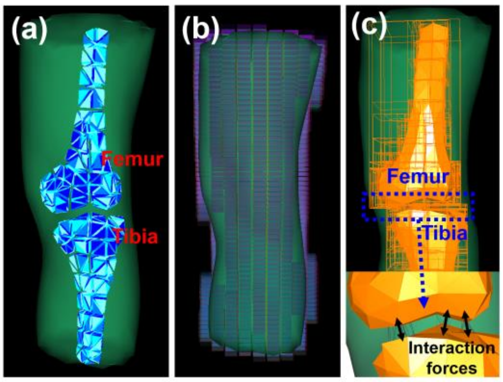

Fig. 2 (a) Tetrahedral finite element for femur and tibia. (b) Hexahedral finite element for knee surface. (c) Collision model and interaction forces between the femur and tibia

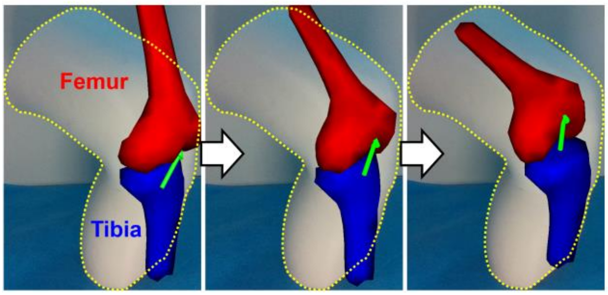

Fig. 3 AR visualization result. The green arrow represents the drilling guidance.

B. Registration and AR visualization

The proposed method repeats the processes shown in Fig. 1 to deform the correlation model and visualize AR in real time. First, the three-dimensional depth information of the knee surface is segmented from the entire data of the RGBD sensor using color and distance information. Next, the iterative closest points algorithm is used for the registration between the depth data of the knee surface and the correlation model. Based on the registration result, the magnitude and direction of the constraint forces (F1 to F5 in Fig. 1), which are required for the correlation model deformation, are updated. To apply consistent criteria for all patients' knee data, the direction of each constraint force is determined using the principal component analysis for the three-dimensional points constituting the femur. The point of application of the constraint forces is set to both ends of the femur. In the following simulation loop, if the registration accuracy between the depth data and the correlation model is improved, the magnitude of constraint forces is decreased, maintaining its direction. If the registration accuracy is reduced, the magnitude of constraint forces is increased, and the direction is reversed. F1 and F2, which are constraint forces applying in the same direction along the knee flexion, take effect in entire simulation loops. The other constraint forces (F3, F4, and F5) are applied alternately for every 30 simulation loops.

RESULTS

Extension and flexion state knee CT were photographed for the experiment. Extension state CT was used to implement a correlation model between knee surface and internal bones. Flexion state CT was used to make knee phantom to evaluate the proposed method. The C++ programming language and SOFA framework [6] were used to simulate the deformation of the correlation model. OpenCV was used to calibrate the RGBD sensor and to implement the AR.

Fig. 3 shows the deformation of the correlation model and visualized AR over time. During knee deformation, the AR was updated to 10 frames per second (fps); after the deformation was completed, it was updated to 15 fps. The time to complete the deformation was about 70 seconds, which is acceptable during ACL or PCL reconstruction, and the 'Read RGBD data' step consumed most time. The shape of internal bones was not changed due to the high Young's modulus, and the soft tissues around the bone are also not significantly deformed. Instead, the knee model was flexed with significant deformation between the femur and tibia. The simulated correlation model was extracted as an STL file and compared with flexion state CT to measure the target registration error (TRE). The mean TRE towards the entire femur surface was 7 mm, which is acceptable for bone tunneling.

DISCUSSION

The proposed AR-based surgical guidance utilized the shape information of the knee surface to estimate the location of internal bones. The method is less invasive and easier to introduce than existing surgical guidance using invasive patient-attached markers. In addition, the proposed method does not require direct bone exposure or manual intervention for registration. The evaluation of the bone drilling with the proposed AR guidance and external factors which degrade RGBD data acquisition in the operating room remains as future work.

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