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Registration accuracy enhancement of a surgical navigation system for anterior cruciate ligament reconstruction: A phantom and cadaveric study

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ABSTRACT

Background: Recently, surgical navigation systems have been widely used to improve the results of various orthopaedic surgeries. However, surgical navigation has not been successful in anterior cruciate ligament reconstruction, owing to its inaccuracy and inconvenience. This study investigated the registration of preoperative and intraoperative data, which are the key components in improving accuracy of the navigation system.

Methods: An accurate registration method was proposed using new optical tracking markers and landmark retake. A surgical planning and navigation system for anterior cruciate ligament reconstruction was developed and implemented. The accuracy of the proposed system has been evaluated using phantoms and eight cadaveric knees. The present study investigated only the registration accuracy excluding the errors of optical tracking hardware and surgeon.

Results: The target registration errors of femoral tunnelling for anterior cruciate ligament reconstruction in phantoms were found to be 0.24 ± 0.03 mm and 0.19 ± 0.10° for the tunnel entry position and tunnel direction, respectively. The target registration errors measured using cadavers were 0.9 mm and 1.94°, respectively.

Conclusions: The preclinical experimental results showed that the proposed methods enhanced the registration accuracy of the developed system. As the system becomes more accurate, surgeons could more precisely position and orient the femoral and tibial tunnels to their original anatomical locations.

1. Introduction

Previous research studies have reported that conventional anterior cruciate ligament (ACL) reconstruction surgery is subject to a 10 to 40% failure rate, of which 70 to 80% of failures are caused by mislocalisation of the femoral and tibial tunnels. Most of these studies have suggested that a computer-assisted surgical navigation system could significantly increase accuracy in

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localising femoral and tibial tunnels [1–7]. Even though it has not shown a superior clinical outcome so far, computer-assisted navigation has advantages in localising anatomical positions by three-dimensional (3D) real-time tracking and guidance using an optical system. Accurate tunnelling in anterior cruciate ligament reconstruction (ACLR) surgery is important to avoid surgical complications such as short tunnel length and posterior wall breakage of the distal femur [8]. The ACLR tunnel should be long enough to tightly fix the reconstructed ligament, and the femoral tunnel requires enough of a margin from the posterior wall of the distal femur to avoid blowout. A computer navigation technique is useful in enhancing the surgical outcome by providing for accurate localization of the tunnelling.

There are two methods of passive navigation in ACLR: image-based and image-free. The image-based method uses fluoroscopic computed tomography (CT) in real-time during ACLR procedures that involve the risk of radiation overdose, whereas the image-free method uses a preoperatively generated 3D model from CT or intraoperative 3D bone morphing with an optical tracking system. The optical tracking system captures reference markers that are rigidly attached to the patient and surgical tools. Surgical navigation in ACLR has been applied and navigation system accuracy has been measured by examining the discrepancy between actual drilled and preoperatively planned tunnel positions and orientations, including surgeons' errors in drilling. However, including human error makes it difficult to compare two results from independent systems. Therefore, it is reasonable to evaluate only the registration accuracy and exclude the effects of human error. Various methods to evaluate the registration accuracy include fiducial localisation error, fiducial registration error (FRE), closest point registration error (CPRE), matched point registration error (MPRE), and target registration error (TRE) [9,10]. In ACLR, the tunnel entry point and tunnel axis orientation can be used for TRE.

Although many ACLR navigation systems have been developed during the past two decades, no reports of registration accuracies have been found, to date, even for frequently referred navigation systems such as Orthopilot, PRAXIM-Medivision, KneeNav, and Vectorvision because most of the literature by medical professionals have reported only clinical outcomes without attempting to measure the registration accuracy [11,12]. Picard et al. tested the KneeNav ACL system on 20 identical foam knees and found the distances from the ideal tunnel placement to the femoral tunnels to be 4.2 $\pm$ 1.8 mm and 2.7 $\pm$ 1.9 mm (mean $\pm$ standard deviation) for the traditional arthroscopic technique and KneeNav ACL, respectively [13]. Other studies have been found on accuracy comparison between the traditional and navigated ACL surgeries [14,15].

The present study investigated ACLR registration accuracy, which mainly determines overall system accuracy in ACLR navigation surgery. It analysed the factors affecting registration accuracy in ACLR navigation by conducting experiments with different optical tracking markers and landmark acquisition methods using phantom and cadaveric knees. The study aimed to analyse the registration accuracy of ACLR navigation under the hypothesis that the proposed optical tracking marker and landmark acquisition method could improve accuracy.

2. Methods

2.1. 3D navigation-guided surgery for ACLR

For navigated ACLR, patient-specific surgical procedures were preoperatively planned using each patient's CT images. A 3D femur model was obtained from a preoperative CT by an automatic segmentation algorithm using active contours [16]. After bone segmentation, the user planned tunnelling paths by using the 3D ACLR planning software that we developed (Figure 1a) [17]. In 3D preoperative planning, the tunnelling path was defined considering the patient's anatomy, to maximize the femoral tunnel length and posterior wall margin. To decide the femoral insertion position for tunnelling, a 3D-based quadrant method was implemented (Figure 1b) [18,19]. To localise the ACLR tunnelling in the operation room, the intraoperative patient data were registered to the preoperative CT. The Polaris optical tracking system (NDI spectra, Northern Digital, Inc.) [20] and the Image-Guided Surgery Toolkit (IGSTK) [21] were used to obtain the spatial information of tracking markers.

Intraoperatively, the reference frames with optical tracking markers were fixed to the femur and tibia using two 1.5-mm K-Wires (Kirschner wire). After fixing the tracking markers, approximately 20 landmark points were collected on the bone surface by using the probes and following the navigation software's directions (Figure 1a). The probe tip's 3D position was calculated relative to the corresponding reference tracking markers fixed on the femur or tibia. To obtain an accurate landmark, the point coordinates were captured by averaging 30 consecutive frames from the tracking cameras. If the collected landmark point was determined to be erroneous, Root Mean Square Error (RMSE) >0.1 mm from the 30 frames, the software induced the user to repeat the collection until an accurate landmark was obtained. The obtained landmarks were then registered to the planning CT by using the point-to-plane iterative closest point [22]. After registration, the navigation system could track the outside-in drilling guide relative to the patient (Figures 1a and 2a). Kim et al. described the detailed ACLR navigation system in 2015 [18].

2.2. Enhancement of registration accuracy in ACLR navigation

To enhance the registration accuracy, the conventional tracking marker (Figure 2b) was replaced with a newly designed tracking marker (Figure 2c) with a larger size between marker points and a short distance from the tracking target by considering the error factors in optical tracking (Figure 2d). As illustrated in Figure 2d, motion of reference markers may not be detected by the optical tracking system if displacement of any of the reference markers is less than the fiducial localisation error (FLE) (ε_0). Unlike translation, rotational motion of the patient can magnify the tracking error of points outside the *marker region* (Figure 2d). The

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