DETERMINATION OF THE MECHANICAL AXIS OF THE FEMUR USING 3D-2D MODEL TO X-RAY REGISTRATION

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INTRODUCTION

For a successful total knee arthroplasty (TKA) and long prosthesis lifespan, correct alignment of the implant components as well as proper soft tissue balancing are of major importance. Studies show that an alignment within +/-3° varus/valgus is correlated with a better outcome (Baethis2004). While conventional planning methods only rely on 2D X-ray images, computer assisted techniques incorporate 3D information acquired from CT imaging or other pre- or intraoperative data. In order to avoid harmful radiation and to visualize soft tissues, MRI imaging was introduced for TKA planning. However, MRI imaging also has its disadvantages such as high costs and long acquisition times. Moreover, geometric distortion in MRI images (Moro-oka2007) might lead to a less accurate implant positioning (Conteduca2012).

A modality which is not considered for TKA planning, yet, is ultrasound (US) imaging. US imaging is a suitable method to visualize various structures within the knee joint (Razek2008). Similar to MRI imaging, US imaging is radiation free and is able to capture bone as well as soft tissue information. It is inexpensive and widely available. Furthermore, dynamic 3D-US imaging allows examination of joints in motion.

Currently, a reconstruction of the bony knee morphology based on US imaging is developed at our research institute. However, compared to CT and MRI imaging, it only captures local surface information whereas a US based acquisition of the entire bone geometry or the mechanical axis respectively would be quite cumbersome and time consuming. Different other approaches for an acquisition of the mechanical axis, being crucial for TKA planning, could be implemented. This work investigates whether a weight-bearing full leg X-ray registered with the local 3D-US knee dataset can be used for this purpose. Moreover, as exact X-ray calibration data might not be available – since it is not mandatory for standard routine X-rays – the impact of incorrect calibration data (i.e. uncalibrated X-rays) on the accuracy of the estimated mechanical axis is investigated.

MATERIALS AND METHODS

Figure 1 shows an overview of the developed workflow. Before transferring the mechanical axis from the X-ray to the surface model, both data have to be spatially aligned, therefore, a 3D-2D registration algorithm (Markelj2012) is used. As the algorithm for surface reconstruction from US images was still under development, a surface model of the distal femur obtained from CT data has been used in order to evaluate the general approach. For the initial feasibility study and for the definition of a known ground truth of the pose, the 2D X-ray was generated from a CT dataset of the entire femur with a known perspective projection matrix.

For 3D-2D registration, first, the initial transform is applied using manual alignment. Then, the optimal transformation is estimated iteratively using a projective, feature-based approach (Markelj2012). In each iteration step, the 3D model is projected using the current translation and rotation and the contour of the projection is segmented and compared to the contour of the 2D image which only has to be segmented once. The quality of the current pose is quantified by the similarity measure which is the sum of distances between the contour points. This measure is optimized using the downhill simplex algorithm. It determines a new rotation and translation which is applied for the next iteration. Finally the mechanical axis can be transferred into the model coordinate system.

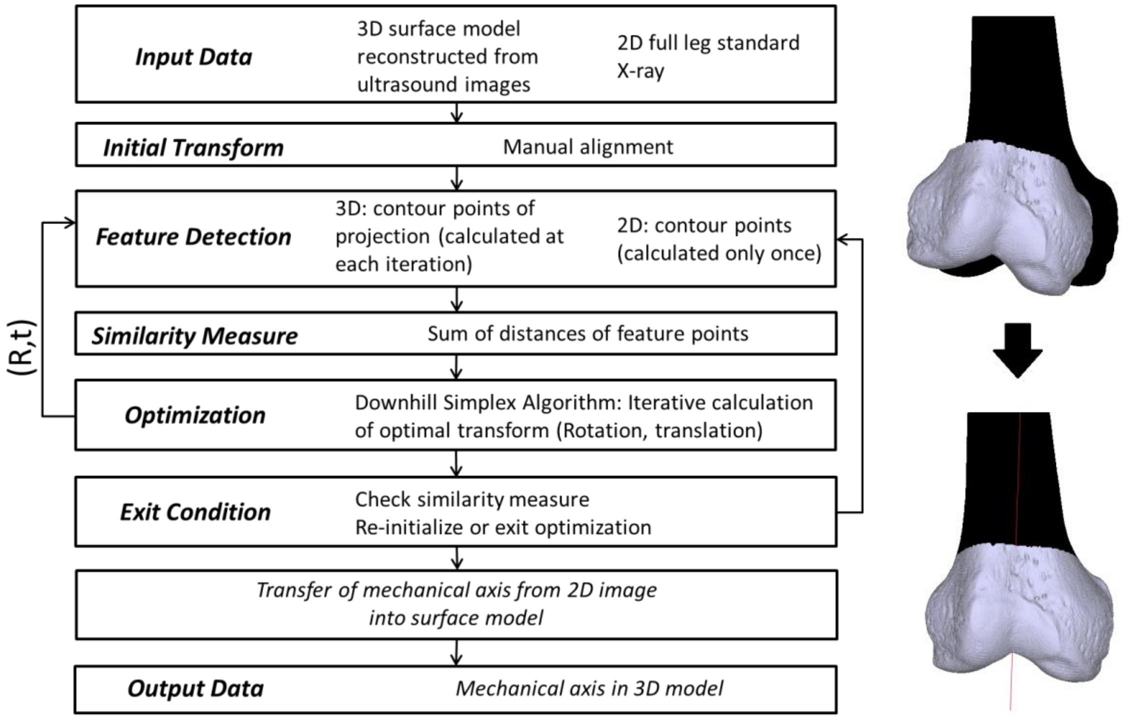

Figure 1: Determination of the mechanical axis.

The above described algorithm is tested using two set-ups. First, the registration results and accuracy of the mechanical axis in the frontal plane is measured. For this, the model is placed in three different ground truth positions and to simulate variability of the user dependent manual alignment step an initial uniform distributed random error in the range of +/-10mm in-plane translation, +/-150mm out-of-plane translation and +/-10° rotation is added. Secondly, the calibration parameters such as the position of the centre ray (Cx, Cy) and the source to image-detector distance (SID) were altered. The resulting error of the mechanical axis in the frontal plane was measured.

RESULTS

For the accuracy test using the correct calibration parameters for the projection, the registration errors and the difference between the ground truth and the estimated mechanical axis in the frontal plane are shown in the first row in Figure 2. When an incorrect calibration is applied, the accuracy of the axis estimation is illustrated in the following rows. The last graph shows the results when all three calibration parameters are incorrect.

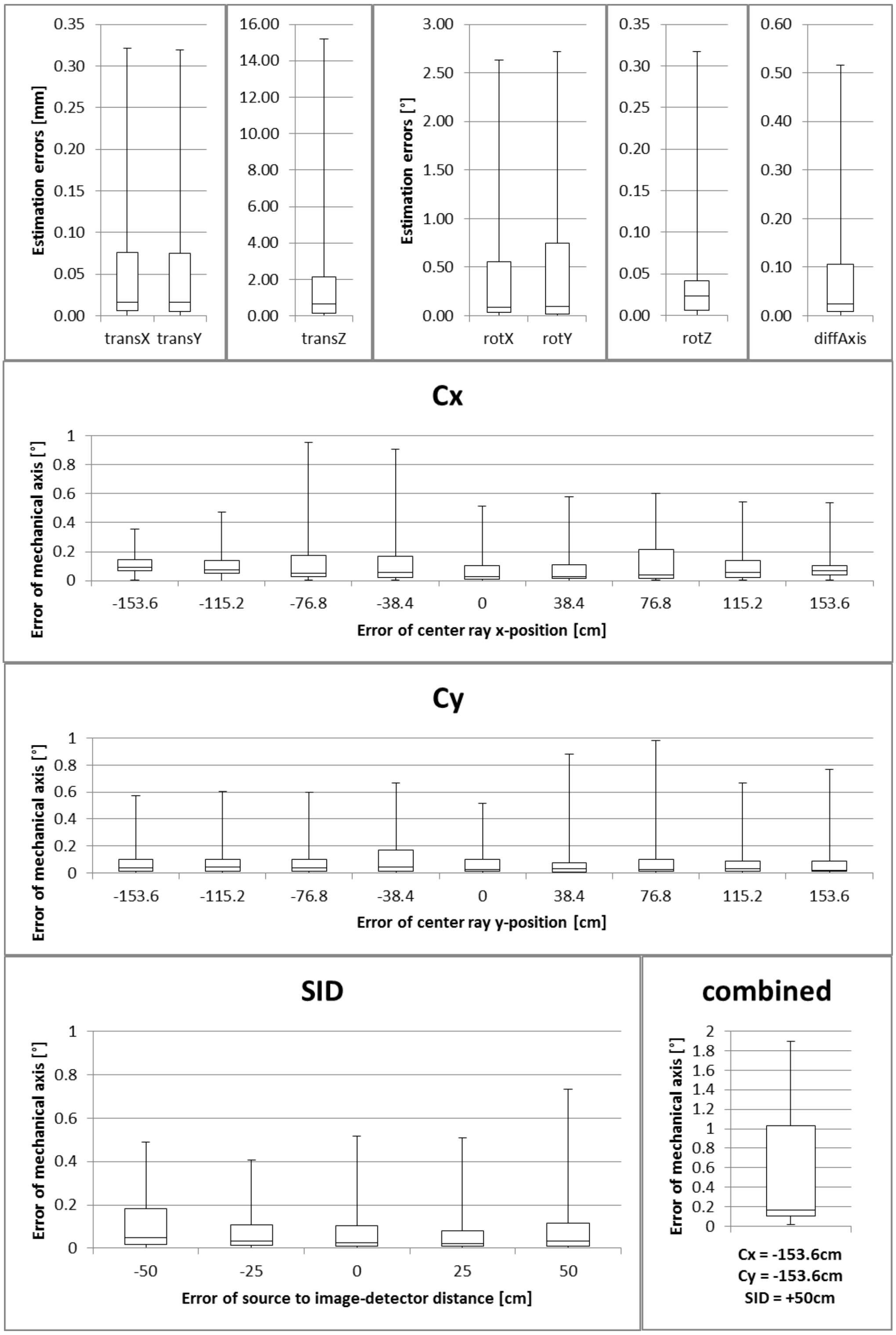

Figure 2: Accuracy of mechanical axis determination and influence of incorrect calibration data.

DISCUSSION

The registration results are comparable with other existing algorithms (Fregly2005). Even though numerous 3D-2D registration techniques exist, most of them are used for pose estimation rather than for determination of the mechanical axis. The effect of incorrect calibration data was also investigated in the context of pose estimation (Tersi2014). This work shows that using 3D-2D registration, the mechanical axis of the local surface model can be determined with high accuracy in the frontal plane using one 2D image. Even if the calibration data is not available, the accuracy remains sufficient for TKA planning. In this study, idealized 2D and 3D image information was used. In the future, this method should be tested using clinical X-ray images and 3D-US data.

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