Medical Engineering and Physics 000 (2018) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Measuring relative positions and orientations of the tibia with respect to the femur using one-channel 3D-tracked A-mode ultrasound tracking system: A cadaveric study

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A R T I C L E I N F O

Article history:
Received 23 June 2017
Revised 11 April 2018
Accepted 30 April 2018
Available online xxx

Keywords:
A-mode ultrasound
Motion tracking
Tibiofemoral kinematics
Non-invasive
Cadaver experiment
Position and orientation

A B S T R A C T

The purpose of this study is to investigate the technical feasibility of measuring relative positions and orientations of the tibia with respect to the femur in an in-vitro experiment by using a 3D-tracked A-mode ultrasound system and to determine its accuracy of angular and translational measurements. As A-mode ultrasound is capable of detecting bone surface through soft tissue in a non-invasive manner, the combination of a single A-mode ultrasound transducer with an optical motion tracking system provides the possibility for digitizing the 3D locations of bony points at different anatomical regions on the thigh and the shank. After measuring bony points over a large area of both the femur and tibia, the bone models of the femur and tibia that were segmented from CT or MRI images were registered to the corresponding bony points. Then the relative position of the tibia with respect to the femur could be obtained and the angular and translational components could also be measured. A cadaveric experiment was conducted to assess its accuracy compared to the reference measurement obtained by optical markers fixed to intra-cortical bone pins placed in the femur and tibia. The results showed that the ultrasound system could achieve $0.49 \pm 0.83°$, $0.85 \pm 1.86°$ and $1.85 \pm 2.78°$ (mean $\pm$ standard deviation) errors for Flexion–Extension, Adduction–Abduction and External–Internal rotations, respectively, and -2.22 ± 3.62 mm, -2.80 ± 2.35 mm and -1.44 ± 2.90 mm errors for Anterior–Posterior, Proximal–Distal and Lateral–Medial translations, respectively. It was concluded that this technique is feasible and facilitates the integration of arrays of A-mode ultrasound transducers with an optical motion tracking system for non-invasive dynamic tibiofemoral kinematics measurement.

1. Introduction

Detailed knowledge of the skeletal knee kinematics is very important to assess pathologies of the lower limb [1–3]. Accurately measured tibiofemoral kinematics is also useful for evaluation of surgical techniques such as implantation of artificial knee implants [4,5] and for the development and validation of computer models (e.g. musculoskeletal models) capable of simulating normal and pathological human movement [6,7].

Reconstruction of three-dimensional (3D) human movement based on skin-mounted markers has become the standard procedure in clinical human motion analysis [8], where the skin-mounted markers are typically taken to represent movement of the bony segment beneath the skin. However, the spatial reconstruction of the musculoskeletal system and calculation of its kinematics via a skin marker based multi-link model are subject to Soft Tissue Artifacts (STA) [9]. The markers follow skin movement, but generate errors when used to represent motion of the underlying bony segments.

A wide variety of studies have investigated the quantification and influences of STA in the lower limb during different motor tasks [5,10–21]. These studies found that STA were greater for the thigh than for the shank, with STA errors as high as 50 mm [7]. In terms of kinematics, an average error of 4.4° and 13.1° was found for the three rotation angles and 13.0 and 16.1 mm for the three translations for walking and running, respectively [11]. In addition, the flexion–extension rotation of the knee joint was found to be determined reliably by skin-mounted markers. However, the remaining motions in the knee joint were more severely affected by STA, which resulted in inaccuracies of relative kinematic outcomes

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https://doi.org/10.1016/j.medengphy.2018.04.015

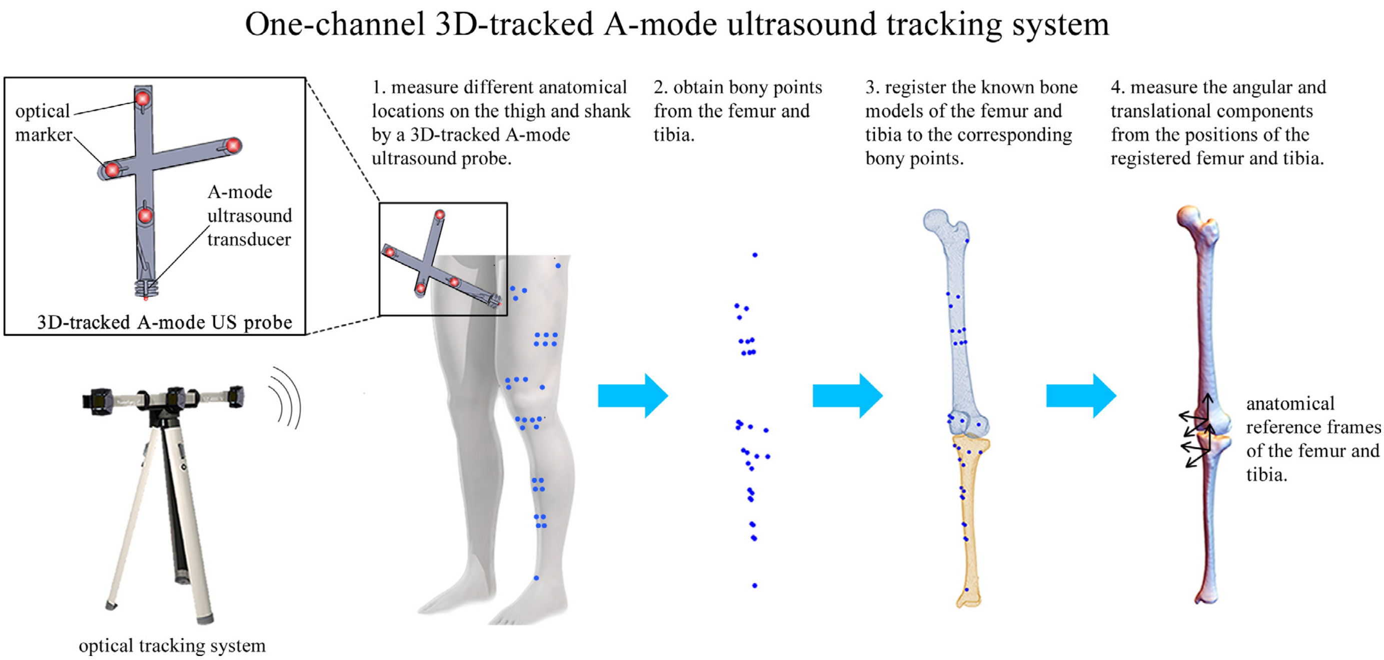

Fig. 1. A schematic of the working principle of the one-channel A-mode ultrasound tracking system.

[12]. To reduce the STA introduced by skin-mounted markers, researchers apply optimization techniques [22,23] and improve the knee model based on advanced joint motion constraints [9]. Although these techniques indeed lead to globally reduced measurement errors of skin markers, the inherent mismatch between skin and bone movement is difficult to remove under all circumstances. Andersen et al. showed that the inclusion of optimized idealized knee joint constraints did not eliminate or reduce the effects of STA and did not improve the validity of the tibiofemoral kinematics derived from skin markers on the thigh and shank [16].

A method to effectively reduce STA is to utilize intra-cortical bone pins rigidly fixed to the bone and equipped with optical markers. This approach has been shown to provide a very accurate estimation of the movement of the femur and tibia in the knee joint [10,11]. However, the invasiveness of this method severely limits its in-vivo applicability. Alternatively, fluoroscopic systems have been used to quantify joint motion in vivo [2,14,15,24,25]. Reported accuracies are in the order of 1 mm and 2°, depending whether a dual or a single fluoroscopic system was used and whether intact knees or implants were involved. In addition to the radiation, a drawback of the fluoroscopic systems is the limited field of view that restricts the patient's natural movement. Recently, fluoroscopic systems that are mobilized by robots which can follow the patient during gait have been proposed, allowing for more natural kinematics [2,26]. These types of robotized fluoroscopic systems are, however, still radiative, high in cost and workload. As such it is difficult to implement them in clinical practice on large patient cohorts.

Ultrasound (US) technology is a rapidly developing field with the advantages of non-invasiveness and non-radiation. It has become possible to register US images to the segmented bone in computer-aided orthopedic surgery [27]. The feasibility of estimating knee joint kinematics based on conventional B-mode (Brightness-mode) ultrasound transducers has also been shown [28]. As ultrasound is capable of detecting the bone boundaries through the soft tissue under dynamic motion, the combination of ultrasound technique with a motion tracking system (e.g. optical tracking system) provides a possibility to digitize the detected bone boundaries into 3D bony points. Compared to a conventional B-mode transducer, an A-mode transducer (i.e. single element ultrasound transducer) is cheaper and smaller in size and more accurate for biometric measurement, e.g. depth [29,30].

Hence, in this study we aimed to demonstrate the feasibility of measuring relative positions and orientations of the tibia with respect to the femur when an ultrasound tracking system was applied in a static fashion. A cadaveric experiment was conducted to assess the accuracy of measured angular and translational measurements compared to reference measurements obtained by optical markers fixed to the intra-cortical bone pins placed in the femur and tibia. Demonstration of this feasibility of accurately measuring the relative positions and orientations of the tibia and femur by one-channel 3D-tracked A-mode ultrasound tracking system in this static study would point towards a level of feasibility of reconstructing tibiofemoral kinematics by combining arrays of A-mode ultrasound transducers with an optical tracking system (i.e. multi-channel 3D-tracked A-mode ultrasound tracking system) to quantify tibiofemoral kinematics in dynamic conditions.

2. Methods

In this study, we developed a one-channel 3D-tracked A-mode ultrasound tracking system by combining one A-mode ultrasound transducer with optical tracking markers. The 3D-tracked A-mode ultrasound probe was used to measure bony points over a large area of both the femur and the tibia. After this measurement, the known bone models of the femur and the tibia were registered to the corresponding bony points. Then the relative position and orientations of the tibia with respect to the femur was quantified from the position of the registered femur and the registered tibia. The working principle of our proposed system is shown in Fig. 1.

2.1. The cadaveric experimental setup

After obtaining ethical approval, one frozen, intact left cadaveric leg (from foot to femoral head) was obtained from the anatomical department of the Radboud University Medical Center (RUNMC). After thawing, two intra-cortical bone pins were screwed into the proximal–anterior part of the femur and the middle shaft of

Please cite this article as: K. Niu et al., Measuring relative positions and orientations of the tibia with respect to the femur using one-channel 3D-tracked A-mode ultrasound tracking system: A cadaveric study, Medical Engineering and Physics (2018), https://doi.org/10.1016/j.medengphy.2018.04.015