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Multi-slice ultrasound image calibration of an intelligent skin-marker for soft tissue artefact compensation

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ABSTRACT

In this paper, a novel multi-slice ultrasound (US) image calibration of an intelligent skin-marker used for soft tissue artefact compensation is proposed to align and orient image slices in an exact H-shaped pattern. Multi-slice calibration is complex, however, in the proposed method, a phantom based visual alignment followed by transform parameters estimation greatly reduces the complexity and provides sufficient accuracy. In this approach, the Hough Transform (HT) is used to further enhance the image features which originate from the image feature enhancing elements integrated into the physical phantom model, thus reducing feature detection uncertainty. In this framework, slice by slice image alignment and calibration are carried out and this provides manual ease and convenience.

1. Introduction

Currently, multi-slice US is crucial for at least two types of clinical applications: (a) spatial compounding in which multiple B-mode slices are taken from different viewpoints and are averaged to reduce the speckle noise (Entrekin et al., 2002; Groves and Rohling, 2004) and (b) motion estimation for improving elastography results (Zahiri-Azar and Salcudean, 2006; Eskandari and Salcudean, 2008). Elastography is a non-invasive procedure in which stiffness of the diagnostic region is imaged and based on the stiffness distribution, the presence of tumours and cancerous growths are detected and quantified. Although electronic beam steering should be able to capture multi-slice US using a single transducer without the need for physical alignment and calibration, it is not feasible due to the following reasons: (a) for steering angles of $> \pm 15^\circ$, the effective aperture size decreases and significant artefacts appear due to grating lobes (Rao and Varghese, 2009; Lu et al., 1994) and (b) for non-coincident scan planes, this system cannot be used because US signal transmission and reception use a single transducer. Another option is to use mechanical steering of a single transducer to capture multi-slice US (Choi, 2008). Although mechanical steering provides a larger steering angle and sweeping area, it suffers from slowness of mechanical manoeuvrability and vibrations, which results in artefacts in the captured slices. To circumvent all the above-mentioned limitations of electronic or mechanical beam steering, a dual transducer system to capture the internal tissue motion was proposed in Abeysekera and Rohling (2011), Abeysekera et al. (2012), which showed an order of magnitude accuracy improvement in motion tracking.

However, the targeted application of the proposed new type of calibration technique is for the kinematic analysis of knee joints aiming to compensate soft-tissue-artefacts (STA). STA originates due to a number of factors (e.g. skin sliding, gravitational forces on soft tissue masses, muscular contraction and deformation etc.) and makes non-invasive skin-mounted optical motion tracking of bones highly erroneous and inconsistent due to the relative motion of the skin marker to the underlying bone. It has been reported in the literature that STA induced error can be more than 30 mm for some body segments during a particular motor function (Sangeux et al., 2006; Cappozzo et al., 1996). Fig. 1 (a) shows an illustration of our kinematic analysis concept in 2 dimensions with the red arrow indicating the relative position of the skin-mounted sensor to the underlying bone in the knee (the femur in this case). To compensate STA, the position of the bone relative to the skin-mounted sensor was determined by registering the bones surface in an initial US frame with the bones surface in subsequent US frames (Masum et al., 2012a). Once the position of the skin-mounted sensor (from the optical tracking system) and the position of the bone relative to the sensor (from the image registration) are known, these two distance vectors can be added together to find the true 3D position of the bone as shown in Fig. 1(b). In our previous study, we proposed an *intelligent* skin-mounted sensor which contains ultrasound (US) transducers that can

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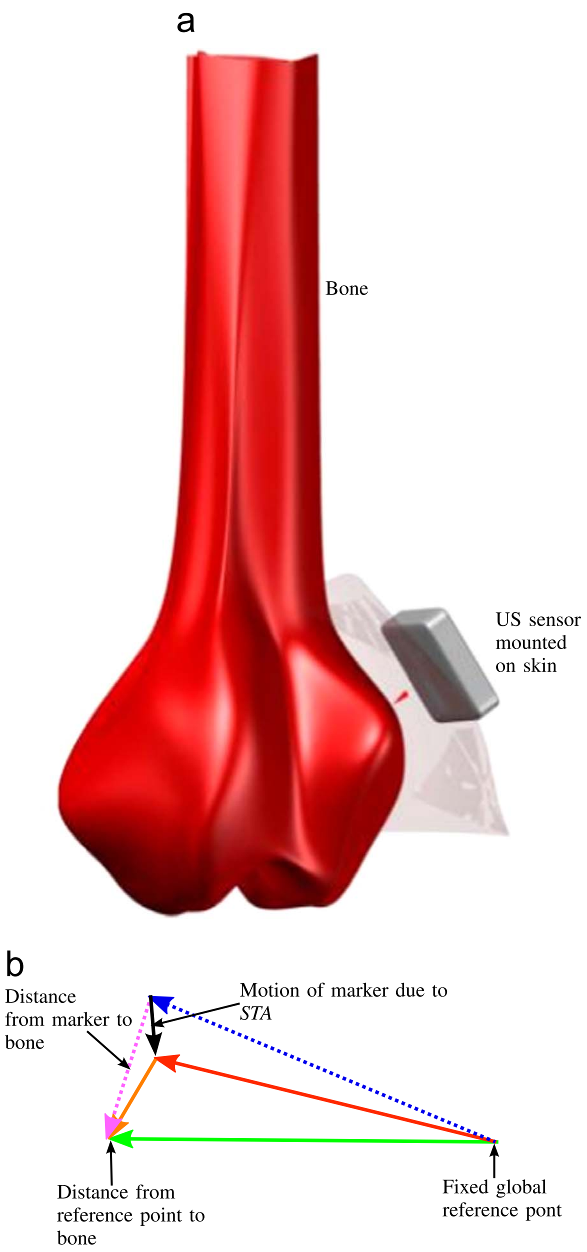

Fig. 1. (a) US sensor attached to the skin, (b) Illustration of the concept for STA compensation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

record images of the internal muscle tissue and bone surface while the patient is performing a particular activity (Masum et al., 2012a), thus eliminating so called STA induced errors with a very high accuracy. From that study of internal US image registration based novel STA compensation procedures (Masum et al., 2012b, 2012a, 2014a, 2014b), it should be obvious that an H-shape is the most optimized geometric orientation of the US sensor arrays to capture three image slices essential for 3D kinematic analysis using only 2D US image slices. However, to fully capture the internal motion of bone movements for kinematic analysis, six motion parameters are necessary. In that procedure, five out of the six motion parameters required to describe the 3D rigid body relative motion were extracted by registering any two orthogonal US slices to their previous counterparts. However, the remaining out-of-plane rotation was measured by using the same registration technique but incorporating two parallel US slices (Masum et al., 2014a). To ensure the consistency of 2D image acquisition in an exact H-shaped pattern, a sophisticated and accurate probe calibration needs to be performed beforehand, and this is the focus of this article.

Therefore, a combined wedge and wire phantom is proposed to calibrate three image slices in an H-shaped pattern with a high accuracy for the above-mentioned US sensor based kinematic analysis technique described in our earlier work. In this calibration framework, the phantom is easy to manufacture, requires only two wedges for a single slice instead of four and provides features with symmetry, thus facilitating significantly efficient visual alignment when compared to the current methods proposed in the literature.

2. Methods

2.1. Phantom construction

To facilitate multi-slice US calibration, a suitable phantom was designed and constructed. To ensure rigidity and durability, and reduce distortion in the phantom geometry during the manufacturing process, the basic building block of the proposed phantom was designed to be a triangular shaped transparent block (dimensions, $H \times L \times W = 76 \times 76 \times 12$ mm). The block was constructed of clear acrylic as acrylic has a very high scratch and impact resistance. For cutting the triangular blocks from acrylic glass, a Computer Numerical Controlled (CNC) laser cutter was used which produces high precision acrylic blocks with polished and clean edges. At first, two triangular blocks (separated at a distance of 12 mm and forming an opposing wedge pair) were held carefully in the correct alignment with a high precision jig and heat welded on a 12 mm thick acrylic base plate. Then a piece of straight steel wire with diameter 0.206 mm (AWG 29) and length 12 mm was placed midway across the hypotenuse face of each triangular block and affixed using silicon glue which provides rigidity as well as quick detachability for misalignment correction or sterilization. Again, another piece of straight steel wire having the same diameter and length was positioned and glued across the inner side between the wedges at exactly 12 mm below (vertically) from the two wires previously affixed on the wedge faces, so that a vertical image plane can capture all the three wires when perfectly aligned. Then, to allow calibration of all three image slices in an H-shape pattern, two more wedge pairs with wire fixations were replicated and positioned on the same acrylic base plate. All the fixations in this phantom were verified using a Coordinate Measuring Machine (CMM) which ensures reliability of the design intent during construction.

Fig. 2 shows a CAD model of the basic part of the proposed wedge and wire phantom. In this model, three pieces of steel wire are embedded to appear as sharp line features when captured from the top for an appropriate vertical alignment of the phantom submerged in a water tank. These pieces of steel wire were selected empirically after imaging various diameter wires. By embedding these wire pieces in the phantom model, clean and sharp line features are visible in the captured US images which reduces feature detection uncertainty as well as eliminates the need for segmentation.

2.2. Multi-slice US calibration

The purpose of US probe calibration is to find transformation matrices between the appropriate coordinate systems (Chen et al., 2009; Prager et al., 1998). For the H-shaped multi-slice calibration, the goal is to compute the transformation between the three image planes (I_1, I_2, I_3) and their corresponding phantom wedge pairs (W_1, W_2, W_3), where every wedge pair has its local coordinate system. If the three image slices are perfectly calibrated in the H-shaped pattern, then the three transformation matrices ($\mathbf{T}_{I_1 \to W_1}$, $\mathbf{T}_{I_2 \to W_2}$, $\mathbf{T}_{I_3 \to W_3}$) should be equal (i.e. $\mathbf{T}_{I_1 \to W_1} = \mathbf{T}_{I_2 \to W_2} = \mathbf{T}_{I_3 \to W_3}$), where $\mathbf{T}_{I_i \to W_i}$ denotes transformation from the ith image coordinate to the ith wedge pair coordinate of the proposed phantom geometry. This equality comes from the fact that the proposed phantom geometry is equipped with three identical wedge pairs with three line features precisely located in an H-shape for the corresponding image slices and these line features appear in the same position and orientation in each slice when calibrated. An illustration of the proposed multi-slice calibration is shown in Fig. 3, from this figure it is apparent that when exactly calibrated, the three image slices capture the three wire pieces in the same position and orientation, and the scans are identical. Due to this similarity and identical wedge pair based construction of the phantom geometry, it is possible to calibrate the three US slices one by one. This not only reduces the complexity but enhances the intuitive understanding in this new type of calibration problem.

Consider a single image slice and the corresponding wire embedded wedge pair which represents a basic unit of the phantom structure. This is illustrated in Fig. 4. Translations and rotations of the image plane when scanning the wedge pair are in 3D space. Hence it is necessary to consider the effects caused due to all six degrees of freedom (DOF) for guiding the alignment and calibration. The style

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