World Academy of Science, Engineering and Technology
International Journal of Bioengineering and Life Sciences
Vol:8, No:6, 2014

Quantification of Soft Tissue Artefacts Using Motion Capture Data and Ultrasound Depth Measurements

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***Abstract*—**The centre of rotation of the hip joint is needed for an accurate simulation of the joint performance in many applications such as pre-operative planning simulation, human gait analysis, and hip joint disorders. In human movement analysis, the hip joint center can be estimated using a functional method based on the relative motion of the femur to pelvis measured using reflective markers attached to the skin surface. The principal source of errors in estimation of hip joint centre location using functional methods is soft tissue artefacts due to the relative motion between the markers and bone. One of the main objectives in human movement analysis is the assessment of soft tissue artefact as the accuracy of functional methods depends upon it. Various studies have described the movement of soft tissue artefact invasively, such as intra-cortical pins, external fixators, percutaneous skeletal trackers, and Roentgen photogrammetry. The goal of this study is to present a non-invasive method to assess the displacements of the markers relative to the underlying bone using optical motion capture data and tissue thickness from ultrasound measurements during flexion, extension, and abduction (all with knee extended) of the hip joint. Results show that the artefact skin marker displacements are non-linear and larger in areas closer to the hip joint. Also marker displacements are dependent on the movement type and relatively larger in abduction movement. The quantification of soft tissue artefacts can be used as a basis for a correction procedure for hip joint kinematics.

***Keywords*—**Hip joint centre, motion capture, soft tissue artefact, ultrasound depth measurement.

I. Introduction

THE hip joint centre (HJC) location can be determined using two general approaches: predictive methods and functional methods [1], [2]. Predictive methods estimate the HJC based on regression equations between palpable bony landmarks and the joint centre [3]. Functional methods are based on the relative motion of the femur to pelvis which is measured using reflective markers placed on the thigh [2]. The palpated bony landmarks used in the most common predictive methods are anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), leg length/height, and depth/width of the pelvis [4], [5]. The accuracy of predictive methods depends on identification of these anatomical landmarks and the error range of them in able-bodied adult was reported between 25-30mm [2]. This error is higher in people with pelvic deformities due to the assumption of hip symmetry for both legs in these methods [6]. The error associated with the predictive methods has led to an increased interest in identifying hip joint centre using the functional methods. Functional methods are divided into two categories: sphere fitting and coordinate transformation [7]. The main limitation of functional methods is soft tissue artefact (STA) due to skin deformation and muscle contraction which depends on markers locations, ranges of motion, and movement type [8], [9]. An error of 15-26mm was reported for these methods for different ranges of motion [4], [9].

Several studies have described patterns and magnitudes of STA by different techniques. These studies can be categorized into five categories: intra-cortical pins, external fixators, percutaneous trackers, radiographic examinations, and magnetic resonance imaging (MRI) [8]. Techniques based on intra-cortical pins, external fixators, and percutaneous trackers can represent relatively accurate measurements of the bone motion; but the use of these techniques is limited as the procedures of applying them are invasive and subjects may experience pain during them. The error in techniques based on intra-cortical is caused by movement of the pins in the bones [10]. The error in techniques based on external fixators and percutaneous trackers occurs due to movement restriction of the bone and joint which is caused by using these devices [11] [12]. The main drawbacks of techniques based on radiographic examinations are these methods are invasive by cause of radiation exposure, the 3D measurements of the STA are estimated from two planes which provide 2D information, and these techniques require extensive processing of image data [13]-[15]. MRI-based techniques require expensive medical imaging and they are not suitable for everyday clinical measurements and analyses [16].

Despite the numerous methods proposed, the objective of a reliable non-invasive and clinical estimation of soft tissue artefacts in human hip joint kinematics is still a topic of research and interest. [16]. Yahia-Cherif et al. used magnetic resonance imaging to measure the markers displacements and determine the best skin markers configuration for using in hip joint kinematics studies which use optical motion capture systems [16]. They used nine reflective markers injected with a contrast agent attached to the thigh skin of two subjects at specific anatomical locations. Then, the motion of the bone and the markers were tracked in dynamic MRI while the subjects performed hip internal rotation, external rotation, flexion, extension, abduction, and adduction. Markers displacements were obtained from the analyzing the markers trajectories versus bone trajectory in the images. The results showed that three markers had the least displacements comparing to the others. Our STA assessment was used to

This research is funded and supported by an NSERC Collaborative Health Research Project.

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correct STA errors in more accurately determination of the HJC location [18]. Our proposed method is described in detail in the next section.

II. Materials and Methods

We propose a method consisting of ultrasound measurements and motion capture analysis to quantify STA non-invasively in determination of HJC using functional methods. Our solution to this is first record the markers positions placed on the thigh and pelvis for a range of motions of the hip joint (standing, flexion, extension, and abduction). When the thigh moves, the muscles attached to the femur contract and relax which cause changes in the thickness of the muscles. These changes affect the positions of the markers attached to the skin relative to the underlying bone and introduce STA error in calculation of HJC. As discussed before, we want to use three key markers to assess STA during several movements of hip joint. To this aim, next step is eliminating STA from these points as our key points in quantification of STA. So, we use ultrasound imaging to measure the changes in thickness of tissue, UDM, at the marker positions for the same standing and extended positions. Next step is fitting curves to markers positions and applying UDM data in order to determine bone positions and eliminating STA effects from the markers. Once the bone positions at three key markers have been determined, we attempt to find a matrix which transforms the bone positions at three key markers of standing position to each of the other movements. By applying the matrix to the other markers of standing position and comparing with the trajectories of markers of the other movements, the STA is quantified. This method is outlined in Fig. 1 and each step is described in the following subsections.

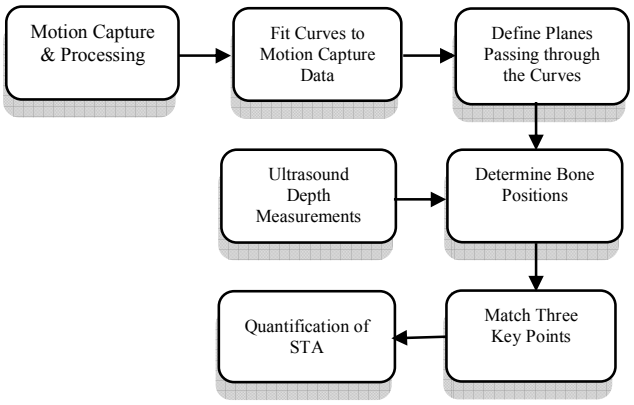

Fig. 1 Overall process for assessing STA

A. Motion Capture

Our optical motion capture system is a Vicon MX system consisting of 10 near-infrared cameras. We use a total of 8 markers at palpable bony landmarks (i.e. where the bone is very close to the surface and thus movement is minimal): 3 on the hip area, left and right anterior superior iliac spine and the lower spine, 2 on either side of the knee, medial and lateral femoral epicondyles, and 2 on either side of the ankle, medial and lateral malleolus, and one on grater trochanter. The main markers on the thigh are placed in 4 ring formation, ~5cm apart, with between 6 to 8 markers per ring. These positions are marked on the thigh and used for the ultrasound depth measurement in the second stage. The motion capture room, markers configuration, and three key markers (red) are shown in Fig. 2.

Fig. 2 a) Motion capture lab and b) Thigh markers configuration and key markers (red)

Participants are requested to move their left leg to 3 key motions, flexion, extension, and abduction, which starting from standing position. Markers trajectories are captured for these positions, standing position, flexion, and abduction (as shown in Fig. 3). To have the same range of motion of the hip joint for ultrasound depth measurement, the positions are determined using non-reflective blocks that are setup ahead of capture with a specific configured distance.

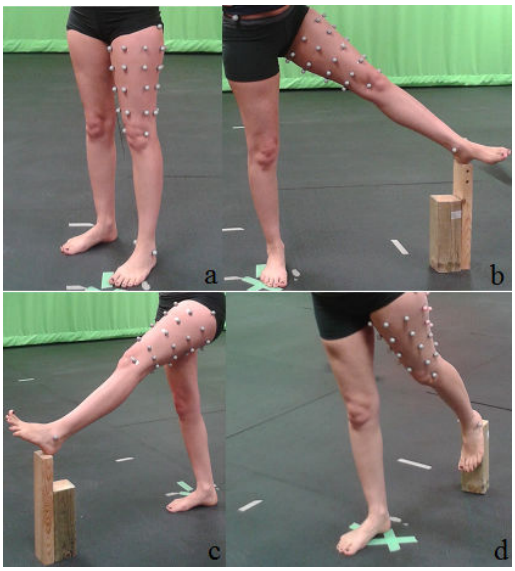

Fig. 3 Subject positions during optical motion capture, a) Standing, b) Abduction, c) Flexion, and d) Extension

B. Ultrasound Depth Measurement

Depth measurements are obtained using an ultrasound imaging machine (Picus, Esaote Europe) and a standard linear probe (L10-5, 5 MHz operating frequency, width 4cm). Fig. 4 shows the ultrasound machine used in this study.

Fig. 4 Ultrasound machine

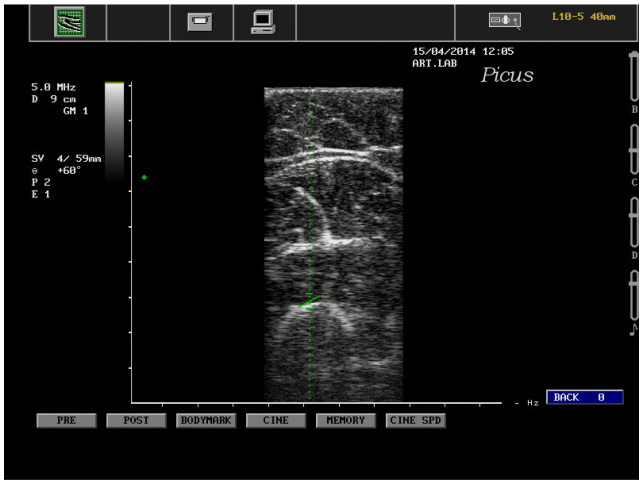

Fig. 5 Ultrasound image of tissue thickness

Ultrasound is a non-invasive and low cost imaging modality which sends out high-frequency sound waves through the body and then measure the returning sound waves which have information about the depth of the tissue under measurement. On the ultrasound images, the bone is visible as dense white line compared to the tissues surrounded it, as shown in Fig. 5.

In our experiment, tissue thickness is measured at the positions of the three key markers for all four hip joint movements (standing, flexion, extension and abduction). The tissue thickness is determined with placing the probe horizontally and perpendicular to the length of the femoral bone and the minimal distance obtained (representing the curvature of the bone). The procedure of ultrasound depth measurements is shown in Fig. 6. Table I shows the ultrasound depth measurements for one of the participants.

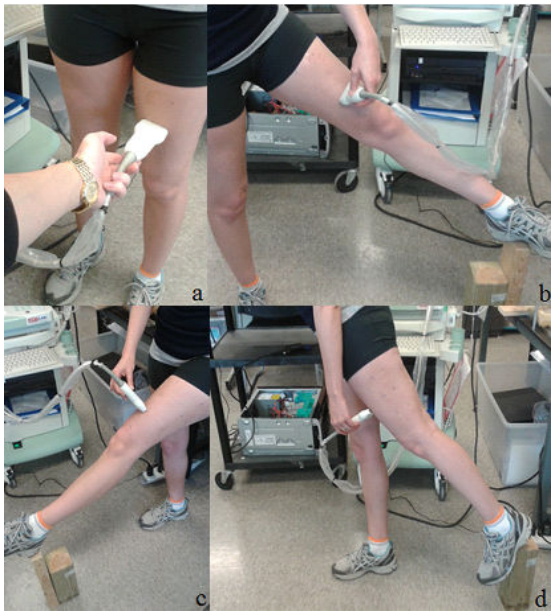

Fig. 6 Subject positions during ultrasound depth measurements, a) Standing, b) Abduction, c) Flexion, and d) Extension

TABLE I
ULTRASOUND DEPTH MEASUREMENTS AT THE POSITIONS OF THREE KEY MARKERS OF ONE OF THE PARTICIPANTS

Markers Positions	Movement Types & Ultrasound Depth Measurements (mm)			
	Standing	*Flexion*	*Extension*	*Abduction*
First Point (Greater Trochanter)	38	41	50	44
Second Point (2nd Ring)	39	47	38	30
Third Point (1stRing)	29	27	32	25

C. Define a Plane through the Curves Fitted to the Three Key Markers

Next step is generating smooth curves which pass through the key data points of the ring formation of the motion capture data. To this end, we use a piecewise polynomial form (ppform) of a spline. In order to determine the bone position at the key points, we need to define a plane containing the bone which passes through each curve fitted to the markers data of the rings. The plane can be defined using 3 data points: one marker data (one of the key markers), one data point on the curve that is very close to the marker, and one other marker data on opposite side of the first marker data.

D. Bone Positions at the Three Key Markers Positions

Once the plane has been defined, we can apply the ultrasound depth measurements for that marker to determine the bone position at that side. The point on the bone should satisfy three conditions: 1) this point should lie on the plane from the previous step, 2) the distance between the bone

position and the marker data on the position should be equal to the ultrasound depth measurement, 3). If we define two vectors, one between the marker data and the data point on the curve which is very close to the marker, and the other vector between the marker data and the bone point, this two vectors should be perpendicular; As the ultrasound depth measurement is the minimal distance between the skin surface and the bone. Fig. 7 illustrates the curve fitted to the markers data and four points on the underlying bone.

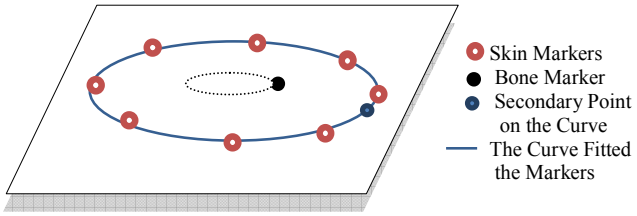

Fig. 7 Passing a plane through each curve and determining the point on the bone

In Fig. 7, red markers are the markers data from motion capturing, small blue marker is secondary point on the curve close to the key marker to help with defining the plane and determining the point on the bone, and the black marker is the bone position.

E. Transformation of the Three Key Points of Standing Position to each of the other Movements

In the previous steps, the bone positions at the three key points of all movement types of hip joint were determined which are the point data without STA. By having these data, we can find a matrix which transforms the bone positions at the three key markers of standing position to each of the other movements. The transformation matrix is 3×3 which has 9 unknown elements. The elements of the matrix can be determined by solving system of linear equations in 9 variables. These equations were obtained from the three key markers.

F. Markers Frame-to-Frame Displacements

The most important aspect of STA is to determine how the markers are displaced relative to the underlying bone due to the movement. Due to muscle contractions and skin deformation, markers move frame-to-frame. Once the transformation matrix for different movements has been determined, we can apply the matrix to the other markers of standing position, compare with the trajectories of markers of the other movements, and compute the markers displacements.

III. Results

By processing the motion capture data using MATLAB and curve-fitting toolbox, we are able to fit the curves passing through the markers data (as shown in Fig. 8), determine the bone positions at three key markers (as shown in Fig. 9) to compute the transformation matrix, and calculate the markers displacements (as shown in Figs. 10-12).

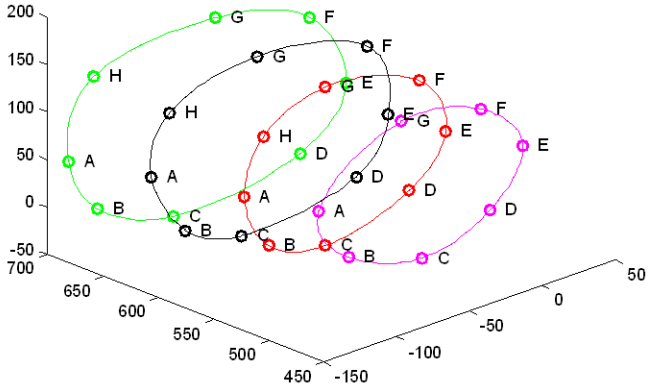

Fig. 8 Curve fitting to all motion capture data including 3 key markers, standing position

The points on the curves are the positions of the markers attached to the skin and labeled by the alphabets.

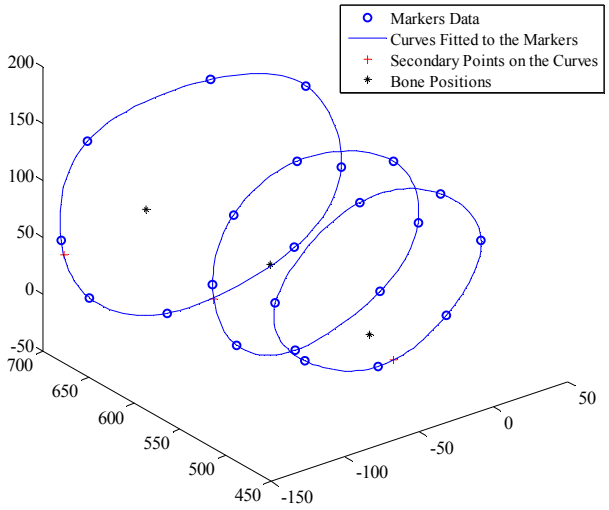

Fig. 9 Determination of bone positions at 3 key points positions, standing position

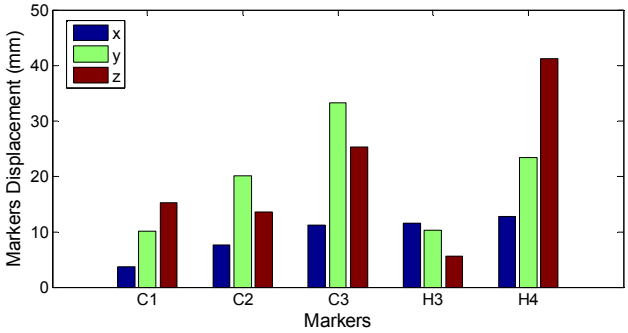

Fig. 10 Markers displacements (magnitude), flexion

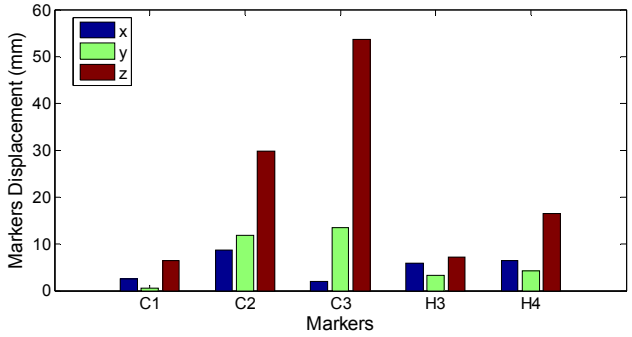

Fig. 11 Markers displacements (magnitude), extension

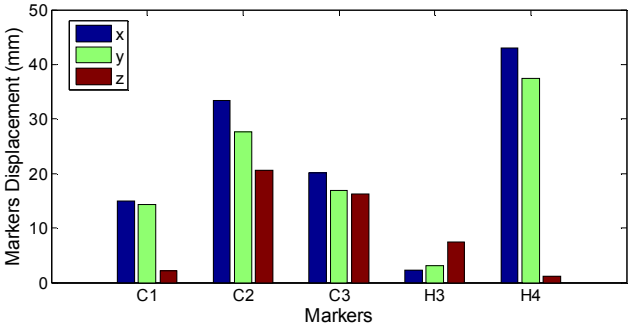

Fig. 12 Markers displacements (magnitude), abduction

IV. Conclusion

Soft tissue artefact is the most significant source of error in human movement analysis. In this study, we presented a method to assess soft tissue artefact noninvasively using optical motion capture data and tissue thickness from ultrasound measurements. We computed the displacements of the markers relative to the underlying bone for typical movement types of the hip joint, flexion, extension, and abduction with knee extended. The results showed that the markers movements are non-linear and larger in areas closer to the hip joint. The markers displacements were dependent on the movement type and relatively larger in abduction movement. Statistical analysis showed that during the abduction movement the markers displacements in the X-direction are larger than in the Y-direction and Z-direction; however during the extension and flexion movements, the markers displacements in the Z-direction are larger than in the X-direction and Y-direction. This STA assessment can be used in the future studies to correct STA errors in determination of hip joint centre location to have an accurate HJC.

Acknowledgment

The work in this paper is funded and supported by an NSERC Collaborative Health Research Project.

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