Non- invasive Assessment of Soft-tissue Artefacts in Hip Joint Kinematics Using Motion Capture Data and Ultrasound Depth Measurements

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***Abstract*— In human movement analysis, the hip joint centre can be estimated using a functional method based on the relative motion of the femur to the pelvis measured using reflective markers attached to the skin surface by an optical motion capture system. The principal source of errors in estimating the 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. Various studies have described the movement of soft tissue artefact and compensated for it invasively; examples include: 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 soft tissue artefact using optical motion capture data and tissue thickness from ultrasound measurements during flexion and abduction (both with the knee extended) of the hip joint. Results showed that the skin marker displacements caused by the artefact are non-linear and larger in areas closer to the hip joint. It was also found that the marker displacements are dependent on the movement type and relatively larger in abduction movement.**

I. Introduction

The accurate description of hip joint kinematics is critical to simulation of the joint performance in many applications such as preoperative planning simulation, human gait analysis, hip joint disorders, and surgical navigation systems. In human movement analysis, the hip joint is generally considered as a ball-and-socket joint and the hip joint center (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 center [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 to be 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]. Leading us to determine HJC using the functional methods, which are divided into two categories: sphere fitting and coordinate transformation methods [7]. The main limitation of functional methods is the soft tissue artefacts (STA) due to skin deformation and muscle contraction that are different depending on the marker's locations, ranges of motion (ROM), and movement type [8, 9]. An error of 15-26 mm was reported for these methods for different ranges of motion [4, 9]. There are various studies associated with describing STA, such as intra-cortical pins, external fixators, percutaneous skeletal trackers, and Roentgen photogrammetry [8]. These techniques are invasive and the use of them is limited. Also, several methods have been proposed to compensate and minimize STA; these include: the solidification model, multiple anatomical landmark calibration, global minimization, point cluster technique, dynamic calibration, and pliant surface modelling [8]. Dynamic calibration and multiple anatomical landmark calibration are based on invalid assumptions and time consuming because they require additional data acquisitions [10]. The limitations of the point cluster technique are an overabundance of markers and instability [11, 12]. The solidification model did not compensate the STA effects well as it can only identify erroneous frames [13]. The drawback of the global optimization technique is that it simplifies joints structures that are not subject-specific and cannot be applied to hip joint disorders population [14, 15]. The objective of a reliable non-invasive estimation of human HJC is still a topic of research and interest. With this goal in mind, the first crucial step is quantifying STA by describing its pattern and magnitude. In this study, we present our method for assessing STA using optical motion capture analysis and ultrasound depth measurements (UDM), which is the basis for our previous study [16, 17] and the work presented by Upadhyaya et al. [18] for continuous motion tracking and ultrasonic depth measurement (MTUDM). The procedure for MTUDM is based on capturing UDM at the same time performing motion capture. Our proposed method is described in detail in the next section.

II. Materials and Methods

In this study, the proposed method consists of ultrasound measurements and motion capture analysis. Previous investigation of STA using continuous motion tracking and

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ultrasonic depth measurement [18] suffers from two issues: 1) the probe must be kept at a perpendicular angle to the leg (almost impossible due to the weight of the probe, the general motion, and the issue determining what is perpendicular during an expanding and contracting muscle deformation); (2) the probe only captures the depth at one position along the leg which is a problem due to the fact that muscles are not linearly attached to the bone. In fact any type of depth measurement in vivo is both extremely difficult and costly. The other issue with STA, which is not directly mentioned from MTUDM, is how it affects motion capture, and this comes from two key elements: skin expansion and contraction along the latitude of leg, and the muscle deformation along the longitude of the leg. Regardless of the number of markers placed on the leg, they become displaced as the leg is raised and lowered.

We propose a new method that overcomes the inherent depth capture errors to provide an accurate measurement. Our solution to this is to first record the markers positions placed on the thigh and pelvis for a range of motions of the hip joint (standing, flexion and abduction); from this we determine the 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 position. Once the bone position has been determined we process the motion capture points using Principal Component Analysis (PCA) in order to align the central axis of the bone in each frame and determine the marker displacement (STA). This method is outlined in Figure 1 and each step is described in detail in the following subsections.

A. Motion Capture

Two healthy adult volunteers participated in this study after signing an informed consent form. Our optical motion capture system is a Vicon MX system consists of 10 infrared cameras. It is imperative to use large number of markers to attach to the skin surface as the skin and muscle create large STA, and this STA is assumed to be non-linear throughout the predefined movements. We use a total of 7 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.

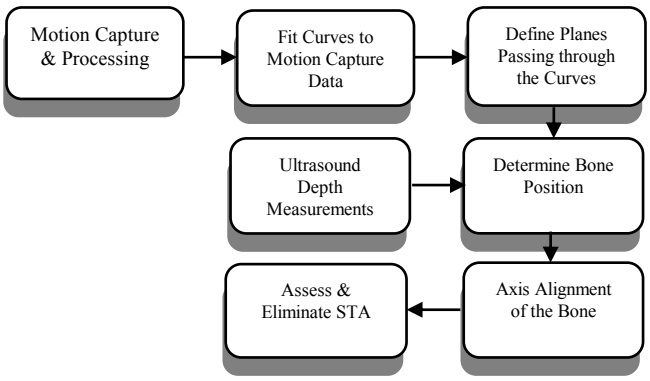

Figure 1. Overall Process for Assessing STA

The ankle markers are used for error correction and are not generally required. The main markers on the thigh are placed in ring formation, with between 6 to 8 markers per ring, and 4 rings, ~5cm apart. These positions are marked on the thigh and used for the ultrasound depth measurement in the second stage. This configuration is shown in Figure 2.

Participants are requested to move their left leg to 2 key motions, flexion and abduction, which starting from standing position. Markers trajectories are captured for these positions, standing position, flexion and abduction (as shown in Figure 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.

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 4 cm). Tissue thickness is measured at four positions of the rings of the markers: front, inside, back, and side of the thigh for all three hip joint positions (standing, flexion 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). Table 1 shows the ultrasound depth measurements for one of the participants.

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

Next step is generating smooth curves which pass through the data points of each 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 from each side, we need to define a plane containing the bone which passes through each curve fitted to the markers data.

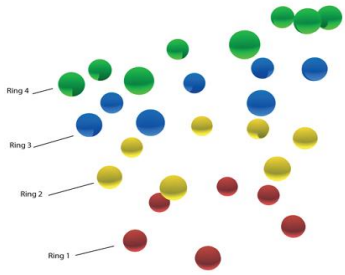

Figure 2. Markers Configuration

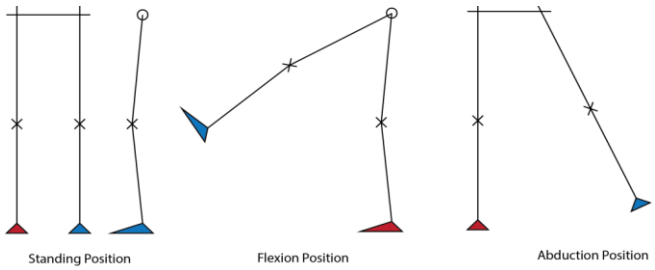

Figure 3. Subject Positions During Trial

TABLE I. ULTRASOUND TISSUE THICKNESS MEASUREMENTS OF A PARTICIPANT

Markers Positions & Movement Types		Tissue Thickness Measurements (mm)			
		Front	*Inside*	*Back*	*Side*
First Ring	Standing	27.2	41.2	56.3	27.1
	Flexion	30.8	38.7	58.8	31.8
	Abduction	25.1	46.4	57.6	35.3
Second Ring	Standing	38.2	52.2	68.8	43.5
	Flexion	39.1	43.7	67.6	41.3
	Abduction	35.4	50.6	72.9	49.5
Third Ring	Standing	47.9	67.1	66.5	44.6
	Flexion	48.3	56.5	61.8	48.9
	Abduction	38.1	57.1	76.5	55.3
Fourth Ring	Standing	55.3	78.8	73.5	55.9
	Flexion	59.4	62.4	61.2	57.6
	Abduction	46	64.7	79.4	68.8

The plane can be defined using 3 data points: one marker data on the same position as the ultrasound depth on that side is measured, 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. As the markers are not aligned perfectly, we determine the best fitting plane by adjusting the error in the plane by the other 3-5 markers in the same ring.

D. Bone Position

Once the plane has been defined, we can apply four ultrasound depth measurements for each markers ring to determine bone position. 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 that the ultrasound depth is measured 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. Figure 4 illustrates the curve fitted to the markers data and four points on the underlying bone.

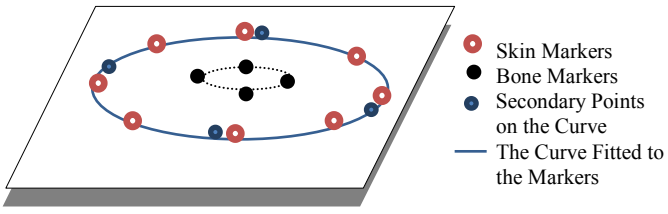

Figure 4. Passing a Plane through Each Curve and Determining Four Points on the Bone

In Figure 4, red markers are the marker data from motion capturing, small blue markers are secondary points on the curve to help with defining the plane and determining the points on the bone, and the black markers are the bone positions.

E. Bone Axis Alignment

The most important aspect of STA is to determine how the markers are displaced relative to the underlying bone due to the movement. In order to determine where each marker is moving, we find the central axis that runs down the centre of the points of the bone through the principal component analysis process and align this central axis for different frames.

F. Marker Frame-to-Frame Displacement

Due to muscle contractions and skin deformation, markers move frame-to-frame. Once the bone for different frames has been aligned, we can compare the markers positions frame-to-frame and compute markers displacement.

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 Figure 4), determine the bone positions (as shown in Figure 5), obtain the central axis of the bone markers (as shown in Figure 6), and calculate the marker displacements (as shown in Figure 7).

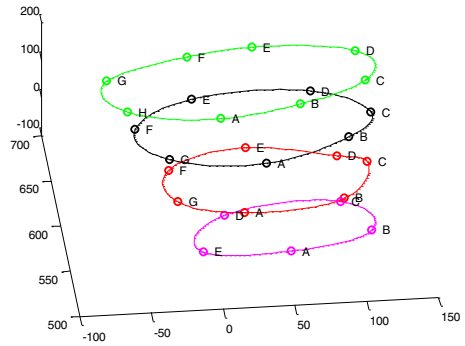

Figure 5. Curve Fitting to Motion Capture Data, Standing Position

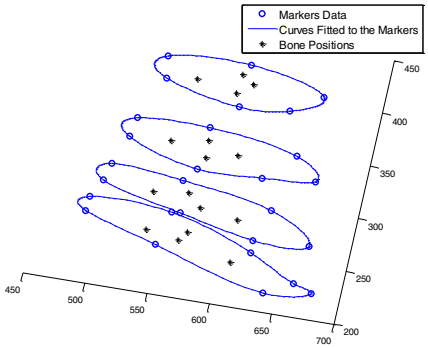

Figure 6. Determination of Bone Position, Flexion Position

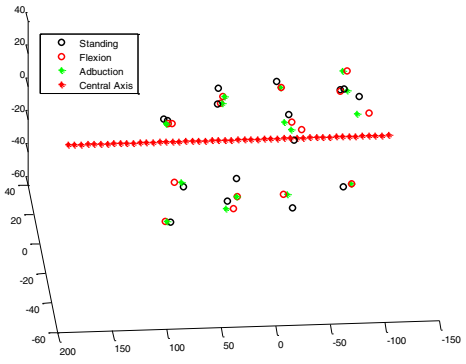

Figure 6. Alignment of the Bone Central Axes Computation Using PCA, (Standing, Flexion, and Abduction)

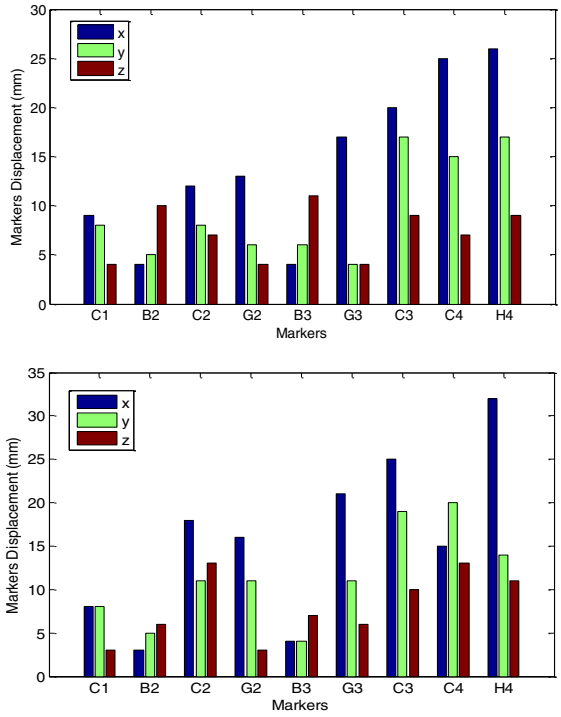

Figure 7. Markers Displacements (magnitude): Standing-Flexion (top), Standing-Abduction (bottom)

IV. Conclusion

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 marker displacement for typical movement types of the hip joint, flexion 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 marker displacements were dependent on the movement type and relatively larger in abduction movement. This STA assessment can be used in the future studies to correct STA errors in determination of hip joint center location to have an accurate HJC.

Acknowledgment

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