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Soft-tissue Artefact Assessment and Compensation in Hip Joint Kinematics Using Motion Capture Data and Ultrasound Depth Measurements

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Abstract – Accurate location of the hip joint centre is a necessary component in biomechanical human motion analysis to measure skeletal parameters and describe human motion. In human movement analysis, the hip joint centre can be estimated using functional methods based on the relative motion of the femur to pelvis measured using reflective markers attached to the skin surface. Determination of the hip joint centre by functional methods suffers inaccuracy due to the soft tissue artefact, which is the relative motion between the markers and bone. Therefore, one of the main objectives in human movement analysis is the assessment and correction of the soft tissue artefact. Various studies have described the movement of the soft tissue artefact and minimized it invasively. The goal of this study is to present a non-invasive method to assess and reduce the soft tissue artefact effects using optical motion capture data and tissue thickness from ultrasound measurements during flexion, extension, and abduction of the hip joint. Results showed that the displacement of markers is 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, being relatively larger in flexion movement. This quantification of soft tissue artefacts was used as a basis for a correction procedure for hip joint centre and minimizing the soft tissue artefact effects. Results showed that our method reduces the error in the functional hip joint centre from 13.65-22.54 mm to 7.9-12.82 mm.

Keywords: Hip joint centre, Soft tissue artefact, Motion capture, Ultrasound depth measurement.

1. Introduction

The centre of rotation of the hip joint is needed for an accurate simulation of the joint performance in many applications such as preoperative planning simulation, human gait analysis, hip joint disorders, and surgical navigation systems. In general, determination of the hip joint centre (HJC) is more difficult than the other human joints because this joint is far from palpable bony landmarks (Piazza et al., 2001). A variety of approaches have been proposed to estimate location of HJC which can be divided into two categories: predictive methods and functional methods (Leardini et al., 1999). Predictive methods estimate the HJC based on regression equations between palpable bony landmarks and the joint centre (Bell et al., 1989). Functional methods are based on the relative motion of the femur to pelvis which is measured using reflective markers placed on the thigh (Camomilla et al., 2006). 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 (Hicks & Richards, 2005; Sangeux et al., 2011). The accuracy of predictive methods depends on identification of these anatomical landmarks and their error range in able-bodied adults was reported to be between 25-30 mm (Camomilla et al., 2006). This error is higher in people with pelvic deformities due to the assumption of hip symmetry for both legs in these methods (Bouffard, et al., 2012). The error associated with the predictive methods has led to an increased interest in identifying HJC using functional methods. Functional methods are divided into two categories: sphere fitting and coordinate transformation (Ehrig et al., 2006). The main limitation of functional methods is the soft tissue artefact (STA) due to skin deformation and muscle contraction which depends on markers locations, ranges of motion, and movement type (Leardini et al., 2005; Piazza et al., 2004). An error of 15-26 mm was reported for these methods for different ranges of motion (Piazza et al., 2004; Sangeux et al., 2011).

Several techniques have been presented to assess STA which are separated into five categories: intra-cortical pins, external fixators, percutaneous trackers, radiographic examinations, and magnetic resonance imaging (MRI) (Leardini et al., 2005). 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. The main drawbacks of techniques based on radiographic examinations are these methods are invasive due to 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 (Sangeux et al., 2006). MRI-based techniques require expensive medical imaging and they are not suitable for everyday clinical measurements and analyses (Yahia-Cherif et al., 2004). Several methods have been proposed to reduce the STA effects: the solidification model, multiple anatomical landmark calibration, pliant surface modelling, dynamic calibration, point cluster technique, global minimization, and techniques based on MRI (Leardini et al., 2005; Yahia-Cherif et al., 2004). The solidification model does not compensate the STA effects well as it can only identify erroneous frames (Cheze et al., 1995; Leardini et al., 2005). Dynamic calibration and multiple anatomical landmark calibration are based on invalid assumptions and time consuming because they require additional data acquisitions (Cappello et al., 2005). The limitations of the point cluster technique are an overabundance of markers and instability (Alexander & Andriacchi, 2001; Cereatti et al., 2006). The drawback of the global optimization technique is that it simplifies joints structures that are not subject-specific and cannot be applied to people with hip joint disorders (Lu & O'Connor, 1999; Stagni et al., 2009).

Despite the numerous methods proposed, the objective of a reliable non-invasive and clinical estimation and correction of STA in human hip joint kinematics is still a topic of research and interest. We proposed a method for assessing STA using optical motion capture analysis and ultrasound depth measurements (UDM) (Rouhandeh et al., 2014). In order to quantify STA, we processed the motion capture data using principal component analysis (PCA) to align the central axis of the bone in each movement type (Rouhandeh et al., 2014).

In this study, our goal is STA assessment and compensation using three key markers introduced by Yahia-Cherif et al. as reference. Yahia-Cherif et al. used MRI to measure the displacement of markers and determine the best skin marker configuration for use in hip joint kinematics studies which use optical motion capture systems (Yahia-Cherif et al., 2004). 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. The displacement of the markers was obtained by analyzing the marker trajectories versus bone trajectory in the images. The results showed that three non-collinear markers had the lowest displacement compared to the others. Our proposed method for assessing STA uses these three markers as reference and consists of optical motion capture analysis and UDM. It also eliminates the STA effects in determination of the HJC using SCoRE algorithm (Ehrig et al., 2006). Our proposed method is described in detail in the next section.

2. Materials and Methods

We propose a method consisting of ultrasound measurements and motion capture analysis to quantify and minimize STA non-invasively to determine the HJC using a functional method. Our solution is to first record each marker's position 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 of the upper thigh area contract and relax which cause change in the muscle thickness. These changes affect the positions of the markers attached to the skin relative to the underlying bone and introduce an STA error in the calculation of the HJC. As discussed previously, we use three key markers to assess STA during several movements of the hip joint. To this aim, the next step is eliminating STA from these points as our key points in quantification of STA. Therefore, we use ultrasound imaging to measure the changes in tissue thickness, UDM, at the marker positions for the same standing and extended positions. Next step is fitting curves to the 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 rotation matrix and a translation vector which transform the bone positions at three key markers of standing position to each of the other movement types. By applying the matrix and the vector to the other markers of standing position and comparing with the trajectories of markers of the other movement types, the STA can be quantified. The next step is the HJC calculation; and we calculate the HJC using a coordinate transformation technique, SCoRE algorithm (Ehrig et al., 2006). In order to have an accurate HJC location, we use the displacement of the markers from the previous step and eliminate STA effects from the markers' data used in the SCoRE algorithm. Our method to reduce STA effects improves the error in determination of the HJC to 7.9-12.82 mm, which has been reported 15-26 mm in the previous studies (Piazza et al., 2004; Sangeux et al., 2011. Our method is outlined in Fig. 1 and each step is described in the following subsections.

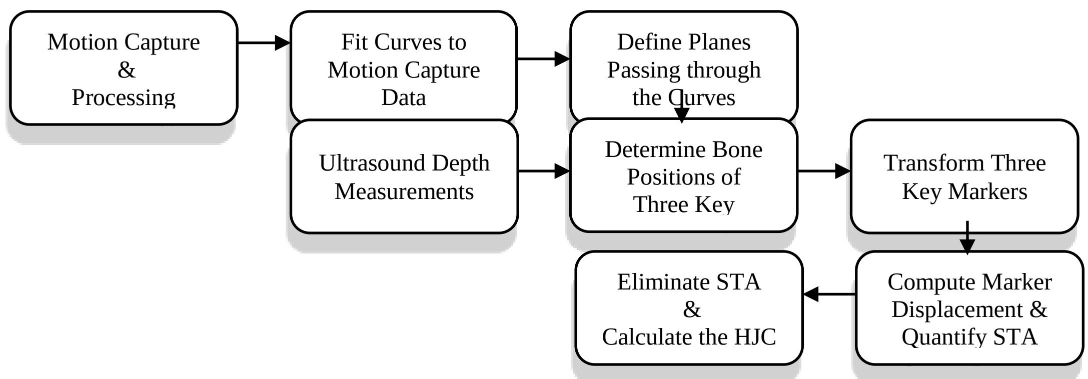

Fig. 1. Overall Process for STA Assessment and Compensation.

2. 1. 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 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 UDM 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 Room and b) Thigh Markers Configuration and Key Markers (red).

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

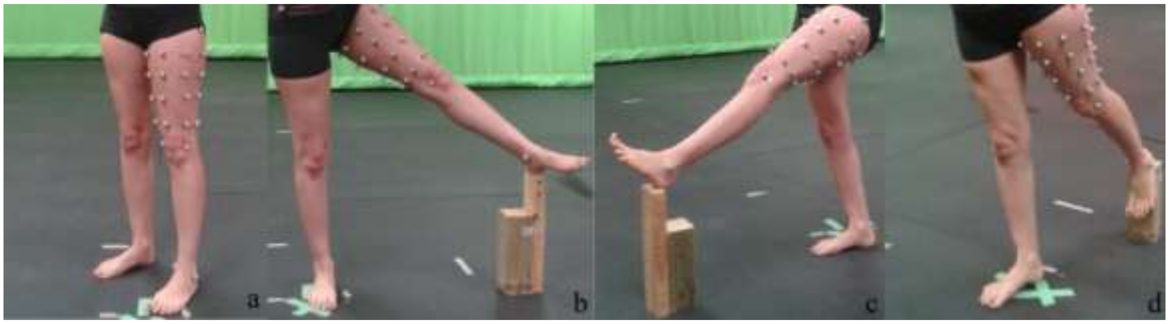

Fig. 3. Subject's Positions during Optical Motion Capture, a) Standing, b) Abduction, c) Flexion, and d) Extension.

2. 2. Ultrasound Depth Measurement

Depth measurements are obtained using an ultrasound imaging machine (Picus, Esaote Europe) and a standard linear probe (L10-5, 5MHz operating frequency, 4cm wide). Ultrasound is a non-invasive and low cost imaging modality which sends out high-frequency sound waves through the body and then measures the returning sound waves providing information about the depth of the tissue under measurement. On the ultrasound images, the bone is visible as a dense white line compared to the tissues surrounding it. 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 by placing the probe horizontally and perpendicular to the length of the femoral bone and the minimal distance is obtained (representing the curvature of the bone). The procedure of ultrasound depth measurements is shown in Fig. 4. Table. 1 shows the ultrasound depth measurements for one of the participants.

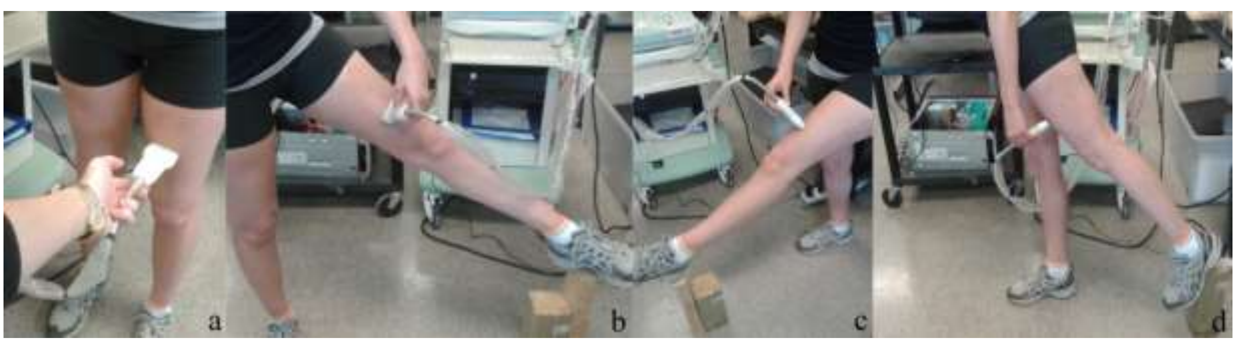

Fig. 4. Subject Positions during Ultrasound Depth Measurements, a) Standing, b) Abduction, c) Flexion, and d) Extension.

Table 1. 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 (1st Ring)	29	27	32	25

2. 3. Defining a Plane through the Curves Fitted to 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 spline. In order to determine the bone position at the three key markers, 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 three data points: one marker's data (one of the three 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.

2. 4. Bone Position at Three Key Markers Positions

Once the plane has been defined, we can apply the ultrasound depth measurements at the position of that key marker 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 key 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 key marker data and the data point on the curve which is very close to the marker, and the other vector between the key marker data and the bone point, these two vectors should be perpendicular; as the UDM is the minimal distance between the skin surface and the bone. Fig. 5 illustrates the curve fitted to the markers' data and a point on the underlying bone at the position of one of the key markers.

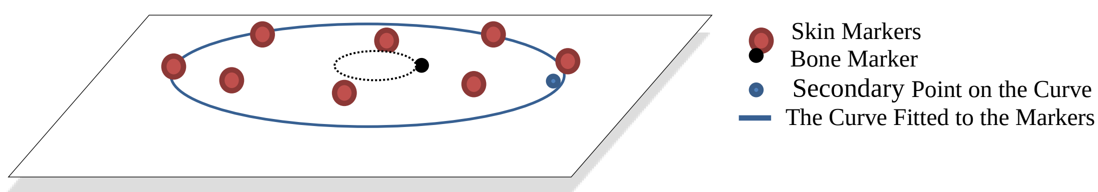

Fig. 5. Passing a Plane through Each Curve and Determining the Point on the Bone.

In Fig. 5, red markers are the markers data from motion capturing, small blue marker is secondary point on the curve close to the key marker and helps define the plane and determine the point on the bone, and the black marker is the bone position.

2. 5. Transformation of the Three Key Markers

In the previous step, the bone positions at the three key markers of all movement types of the hip joint were determined. These bone positions are assumed to be the data without the STA. By having these points, we can find a rotation matrix and a translation vector which transform the bone positions at the three key markers of the standing position to each of the other movements. We derive the matrix and vector by solving a linear least square problem recursively. Our objective function for each movement (compared with standing position) is given by Eqs. (1).

$$min_{\boldsymbol{R},t} \sum_{i=1}^{3} ||\boldsymbol{R}s_i + t - m_i||^2 \tag{1}$$

Where $\boldsymbol{R}$ is the rotation matrix (3×3), t is the translation vector (3×1), s_i is the vector of key marker i in standing position (3×1), and m_i is the corresponding key marker of the other movements (3×1).

2. 6. 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 and the translation vector for different movements has been determined, we can apply them to the other markers of standing position, compare with the trajectories of markers of the other movements, and compute the displacement of the markers.

2. 7. STA Compensation in Determination of HJC

In order to determine the HJC, we use the SCoRE algorithm (Ehrig et al., 2006). In this algorithm a local coordinate system for each moving segment of the joint (pelvis and femur head) is defined, and then these local systems for all time frames are transferred into a global reference system to estimate the HJC at a fixed point. As the SCoRE algorithm gives two centre positions, one for the pelvis and one for the femur head, its accuracy can be evaluated by the difference between these two centres. In this study, at first we transfer all the standing markers in a way that the markers on the left and right anterior superior iliac spine and the lower spine match the same markers locations in the other movements. Then we apply the SCoRE algorithm on the data, once on the markers positions before reducing STA and once when we recalculate the markers positions based on the STA quantification. For each of them, the SCoRE algorithm returns two centres and the distance between them shows the effectiveness of our method in minimizing STA effects.

3. 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, determine the bone positions at three key markers (as shown in Fig. 6), compute the transformation matrix and the translation vector and apply them to the other markers of the standing position (as shown in Fig. 6), then calculate the markers displacements for different movements (as shown in Fig. 7, Fig. 8, and Fig. 9). The error associated with data before reducing the STA effects and data after reducing the STA effects is shown in Table. 2.

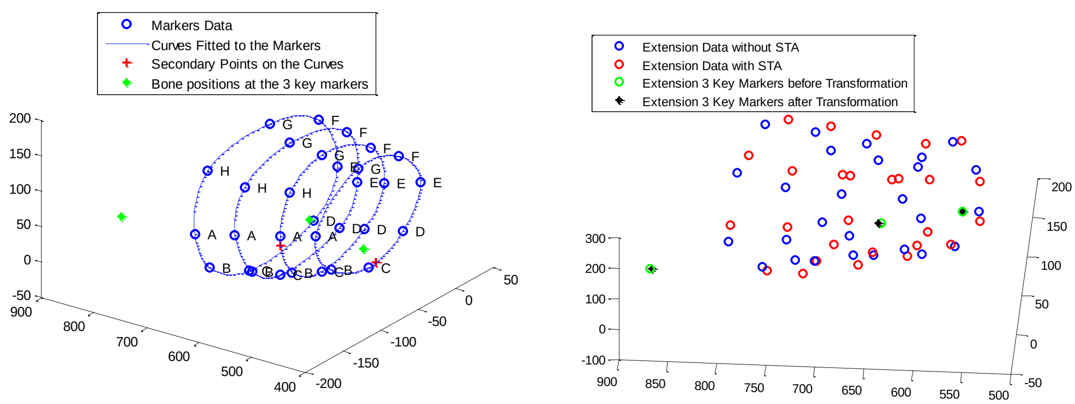

Fig. 6. Curve Fitting to Motion Capture Data and Determination of Bone Positions at 3 Key Points Positions of Standing Position (left), Transformation of Standing Markers to Extension Movement (right).

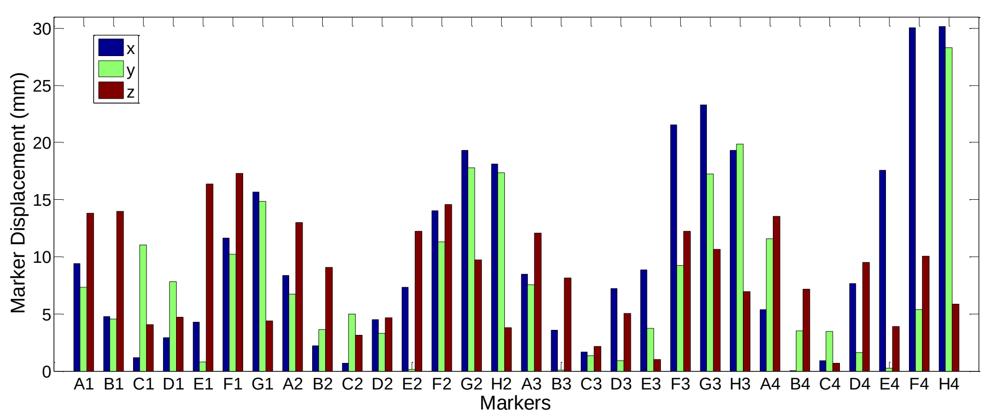

Fig. 7. Displacement of Markers (magnitude), Abduction.

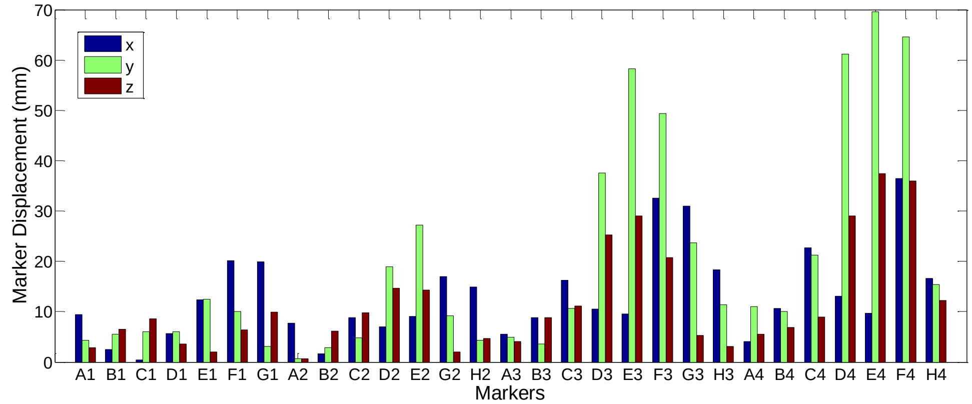

Fig. 8. Displacement of Markers (magnitude), Flexion.

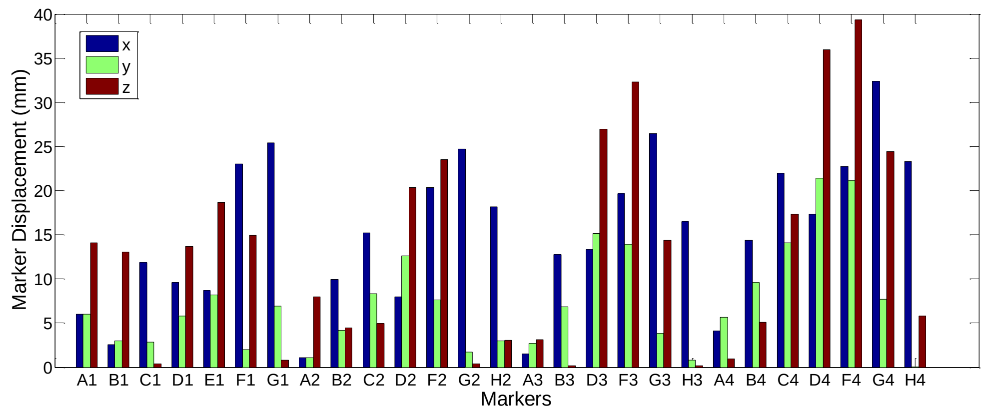

Fig. 9. Displacement of Markers (magnitude), Extension.

Table 2. Hip Joint Centre Location Error Using SCoRE Algorithm.

Movement Types	**Error with STA (mm)**	**Error without STA (mm)**
Standing Position	15.77	8.51
Flexion	20.36	11.07
Extension	13.65	7.90
Abduction	22.54	12.82

4. Conclusion

STA 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 flexion movement. This STA assessment was used to correct STA errors to more accurately determination the HJC location using the SCoRE algorithm. The error associated with the data before minimizing the STA and after minimizing the STA effects was in the range of 13.65-22.54 mm and 7.9-12.82 mm, respectively. The results showed the improvements obtained in our proposed method.

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