Use of Ultrasound to Track Bone Trajectory for Human Motion Analysis

[1]Swati Upadhyaya, [2]WonSook Lee, [3]Zhen Qu, [4]Yuu Ono, [5]Chris Joslin

[1,2]School of Electrical Engineering and Computer Science,
University of Ottawa, Ottawa, ON, Canada

[3,4,5]Department of Systems and Computer Engineering
Carleton University, Ottawa, ON, Canada

e-mail: supad090@uottawa.ca[1], wslee@site.uottawa.ca[2]

Abstract - A new methodology has been described using ultrasound to possibly quantify the soft tissue artifact introduced in human motion analysis using marker based approach. Marker based motion analysis suffers from errors due to underlying bone movement with respect to skin. It is required to compensate these errors in order to make use of this method in finding center of rotation of hip joint for computer based surgical systems. Ultrasound is an affordable and portable imaging modality which could be used to observe underlying bone movement non-invasively. We analyzed typical movement types Flexion (with and without bent knee) and Abduction, used for functional hip joint center location using ultrasound. The aim of the experiment was to find out the trajectory underlying bone with respect to skin non-invasively. In our knowledge no one has used this method before. It was observed that for each motion type at least one participant had a nearly Gaussian trajectory in the plane of motion. A displacement of bone of upto 15mm from neutral position during Flexion with bent knee was observed for one participant. With this observation of change in the bone position with respect to skin with ultrasound, it could be used as a possible ad-hoc exercise to model the trajectory of displacement to compensate for the soft tissue errors in human motion analysis.

Keywords: Human motion analysis, Hip joint center, Soft tissue.

I. INTRODUCTION

Human motion analysis is used for determination of hip joint center and is categorized as functional technique of HJC determination [1-4][6].The non-invasive and easy implementation of the experimental procedures, along with results close to the true hip center in human studies [7][8][12], have made this method attractive for gait analysis as well as for determination of a reference point in navigation based surgeries[4][6]. The method involves placement of markers on thigh and pelvis over skin which are observed by a position sensing system while the subject makes movements. The marker trajectory is then either fit onto a sphere [2] and the center of sphere is calculated to be HJC or coordinate transformation techniques are used [6][7]. These results are validated with a gold standard data and are found to give accuracy within 20 mm as reported by a recent study on humans by Sangeux et al [8]. This method of HJC calculation suffers from a source of error known as soft tissue artifact (STA) [14]. This error source tends to change the position of markers placed on skin with respect to underlying bone and hence results in error when an estimate of bone is made from the markers [21-25]. Many studies have evaluated the effect of STA by measuring the movement of skin markers relative to underlying bone through bone pins [10], and external fixtures [21]. Apart from several other measures to compensate for this error source [14], Alexander et al [20] described a method to determine the position of bone through modeling of marker trajectory mathematically. They proposed that for a particular movement type, the trajectory of skin markers relative to underlying bone could be standardized and modeled. For stepping stair movement, the trajectory was observed to be Gaussian [20]. This method was also validated using invasive Ilizarov external fixation device on shank to provide bone embedded marker positions and the center of mass location as well as orientation errors were reduced by 29% and 19% respectively using interval deformation technique [20].

From the above mentioned method, it appeared that ultrasound could be a potential tool to assess the trajectory information of underlying bone. In our knowledge there were no studies found to quantify the reason behind soft tissue artifact through non-invasive procedure using ultrasound. Hence in order to identify how the underlying bone is moving with respect to the skin this experiment was conducted to see real time bone trajectory with respect to markers on skin while the standard movements [2] are made. Ultrasound is low-cost and safe imaging modality which has been used recently to validate functional HJC providing gold standard data [8] [15]. Hence it was presumed that femur bone data and its depth variation might be visible in real time motion through ultrasound. Preliminary results from "Flexion Bend" profile were submitted for a conference [Upadhyaya S, Lee W, Qu Z, Ono Y, Joslin C "Use of Ultrasound with Motion Capture to Measure Bone Displacement during Movement made For Functional Hip Joint Center Determination"]. Here we have presented an extension of the study to other profiles "Flexion Full" and "Abduction".

II. METHODS AND MATERIALS

Four human subjects participated in the study. Setup consisted of ultrasound imaging machine (Picus, Esaote Europe) and linear probe (L10-5, 5 MHz operating frequency, width 4 cm). The motion capture system consisted of 6 VICON MX40 cameras at the frame rate of 120 Hz. 9 retro reflective markers were used, 3 each on thigh and back and 3 on probe with an extension to track the position of probe movement.

The participant held the probe and stood upright for the neutral pose as seen in Fig. 1. For three motion types, Flexion Bend (with bent knee), Flexion Full (without bent knee) and Abduction, probe was placed vertically (Probe's longer edge parallel to the bone) at front and side on the thigh. The movement was started with a quick movement perpendicular to the bone to synchronize the motion data with ultrasound along with time stamps. After the quick movement the participant flexed or abducted the leg. The ultrasound recording was started with the bumpy movement up to 6 seconds as the limit for ultrasound machine was to capture at 30 Hz for total 180 frames. The VICON motion capture was started before

ultrasound measurement while participant stood still and was stopped only after ultrasound recording was stopped.

Figure 1. Setup with participant handling the ultrasound probe. Ultrasound machine was covered with cloth to avoid reflections and 1 out of 6 VICON cameras is visible.
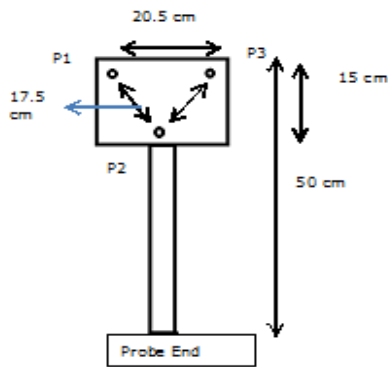

Figure 2. Ultrasound probe and marker attachment.

III. RESULTS

A) Calculation of tissue thickness with movement :

For ultrasound data, the surface of the bone was visible as a bright intensity band against noisy speckled background. The edge tracking software "EdgeTrak"[5], was used to get a set of open contour points which provide the position of bone with respect to the skin surface. All the ultrasound data consisted of 180 frames and 100 contour points were generated for each frame using a scaling factor which converted pixels to mm. From this contour data, variation in depth of edge of bone was calculated using mean of y coordinates for each frame. The trajectory of bone movement with respect to the skin is reported in Figure 3. The initial twitch given to ultrasound probe generated a spike which was considered for synchronization with VICON data.

As shown in Fig. 2, the probe attachment had three markers which was used to define probe frame of reference (FOR). The local x was in direction of vector P1P3, y was towards the thigh and z perpendicular to ultrasound image plane. The centroid of the three points was calculated and transformed in local for

$$Cglobal = P2 + R*Clocal \qquad (1)$$

where Cglobal is centroid of three points on probe attachment, R is orientation matrix associated with probe FOR, Clocal is the centroid in probe FOR and P2 is origin of probe FOR. Once Clocal is obtained, it is translated in local FOR in y direction to reach upto the thigh skin surface. The synchronized ultrasound data, 1 for 4 VICON frames, is then used to get the bone location in local FOR as bone is in the xy plane defined by probe FOR. This bone location is then transformed back in

global/laboratory FOR using (1). The distance between this calculated marker on bone and markers on thigh is calculated with respect to neutral position which provides change in thickness of tissue over time for markers placed at different position on thigh, Fig. 4.

B) Synchronization between ultrasound and VICON:

The synchronization was made through analysis of graphs while the starting point of movement was considered with an increasing slope in VICON data and after spike in ultrasound data. Numbers of frames were converted to time domain using the conversion of 30Hz for ultrasound and 120Hz for VICON data. Every 4 samples of VICON data contained 1 ultrasound sample. Rough approximation was made using stamping in the graph.

In Fig. 3 it was observed that the bone trajectory followed a near to Gaussian form for Flexion with bent knee with probe at front and side, Flexion full on front and Abduction on side for at least 1 participant. Maximum displacement of bone with respect to neutral position in terms of depth from skin on thigh and maximum relative displacement of virtual marker placed on skin where probe was placed are reported in Table 1 for three movement types. For synchronized data, it was observed that the variation in soft tissue depth and movement were related.

Fig. 4 shows the change in tissue thickness calculated as described above for 1 participant with "Flexion Bend" profile when probe was placed at the front. Tissue thickness decreases as hip is flexed for the marker placed on front of thigh and increases for the one placed at back of thigh and returns to neutral as it is brought back to starting point. Only 1 dimension data from probe placed at front is included, hence thickness change for marker 3 placed on side remains nearly constant. This provides proof of concept that, if the bone thickness using ultrasound is available for entire motion type, bone displacement with respect to markers on skin can be found. Henceforth the marker trajectory in bone frame of reference could be estimated using this data.

From Table 1 and Fig 5 it is noted that the bone displacement was more in the direction of movement than in the perpendicular direction. For Flexion, maximum movement was observed when probe was placed in front and for Abduction, when it was placed on side. The data is an average for 4 participants.
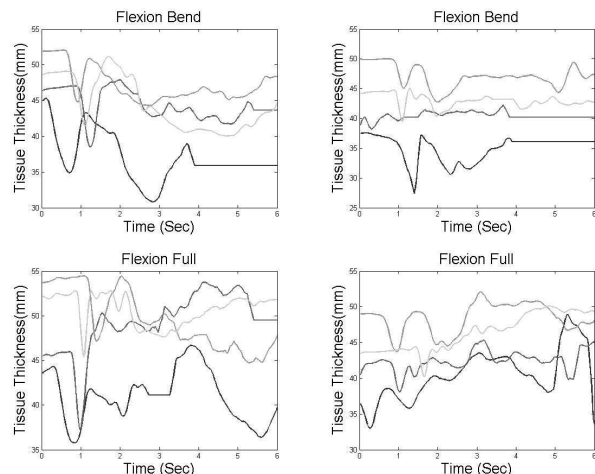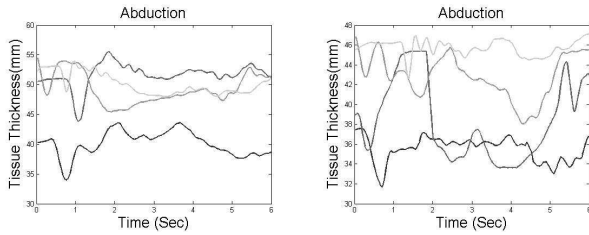
Figure 3. Change in tissue thickness on thigh quantified as variation of bone displacement observed in ultrasound for 4 participants. Probe on thigh (a) front (b) side (lateral). Legend: Participant No.
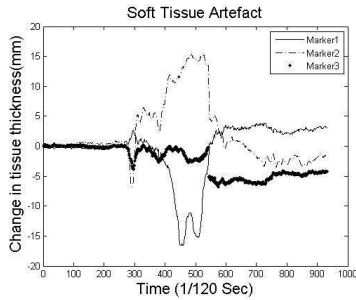

Figure 4. Change in tissue thickness for markers placed at different positions on thigh. Marker 1: Thigh front, Marker 2: Thigh back, Marker 3: Thigh side (lateral).

IV. LIMITATIONS

Ultrasound data was noisy and some of the frames were missing due to misplacement of probe during the motion. These frames were manually identified and the value was treated as an outlier with mean value treatment. Ultrasound data for participant 2 were very noisy with frames missing the bone edge for more than 100 frames out of 180 with probe facing side in "Flexion Bend".

The probe attachment was heavy making it difficult for participant to hold it rigidly during the motion. Also, synchronization is done based on manual observation and analysis of graph based data. In future these limitations are expected to over-come by attaching the probe through a foam based attachment rigidly onto the thigh and improvising automatic synchronization based on time stamps or an external trigger. For all the profiles, few data points are against the observed trend which is assumed to be due to excessive pressing of ultrasound probe which alters the tissue thickness and change is not observed. The change is observed if only the probe was held neutrally without pressing the skin too much.

Table I: Displacement of bone w.r.t skin.

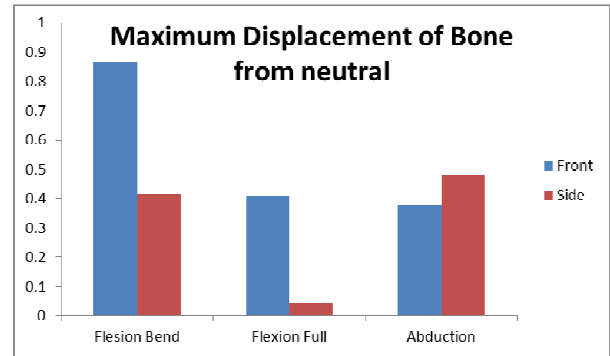| Movement type	Probe location (On thigh)	Average Bone Movement wrt skin (cm)
Flexion Bend	Front	0.486
	Side	0.161
Flexion Full	Front	0.070
	Side	-0.271
Abduction	Front	0.173
	Side	0.227

Figure 5. Maximum Displacement of bone during three movement types with probe in front and side.

V. DISCUSSION

An attempt has been made to use ultrasound as an ad-hoc exercise to provide information about trajectory of bone with respect to skin during particular movement types. With an exception of one participant, the entire movement pattern looks Gaussian in Flexion bend profile. It was expected that bone thickness becomes lesser in the direction of movement due to pressing against the muscles. It was also observed that while bone was displaced in the direction of movement, it also got displaced slightly towards the direction perpendicular to the movements towards lateral side of the body (through placement of probe on side during Flexion or on front during Abduction). Alexander et al [20] have provided a way to compensate for errors posed by such movements for one particular motion type.

With our experiments we have shown that Ultrasound could be used to model subject specific trajectory. If the limitations are taken into account, the trajectories look Gaussian for two planes, Sagittal (Flexion) and Frontal (Abduction) and could be modeled for mathematical compensation of soft tissue artifact.

In Leardini et al[14], it is mentioned that skin markers are not appropriate for estimation of underlying bone. Our experimental study has proved that during movement the underlying bone position is not constant to the skin at all times. Rather, the bone displaces linearly with the motion from its neutral position in the direction of movement upto 15 mm with our 4 human subjects for "Flexion Bend". This seems in line with cadaver studies [9] performed with transcutaneous bone pins or intracortical pins [10][14] which have shown that there is displacement up to 10mm between the markers attached on skin and the one directly on bone. This data suggests ultrasound could be a useful tool to assess soft tissue displacement and since linear movement is observed, algorithms could be proposed to translate the marker at each time instant to compensate for the bone movement to get a better estimation of underlying bone and hence HJC.

REFERENCES

[1] Piazza S, Erdemir A, Okita N, Cavanagh P. Assessment of the functional method of hip joint center location subject to reduced range of hip motion. Journal Of Biomechanics March 2004;37 (3):349.

[2] Camomilla V, Cereatti A, Vannozzi G, Cappozzo A. An optimized protocol for hip joint centre determination using the functional method. Journal Of Biomechanics . June 2006;39(6):1096-1106.

[3] Cappozzo A, Della Croce U, Leardini A, Chiari L. Human movement analysis using stereophotogrammetry: Part 1: theoretical background. Gait & Posture February 2005;21(2):186-196.

[4] Siston R, Delp S. Evaluation of a new algorithm to determine the hip joint center. Journal Of Biomechanics January 2006;39(1):125-130

[5] Min L, Kambhamettu C, Stone M. Automatic contour tracking in ultrasound images. Clinical Linguistics & Phonetics. September 2005;19(6/7):545-554

[6] Ehrig R, Taylor W, Duda G, Heller M. A survey of formal methods for determining the centre of rotation of ball joints. Journal Of Biomechanics December 22, 2006;39(15):2798-2809.

[7] Peters A, Baker R, Morris M, Sangeux M. A comparison of hip joint centre localisation techniques with 3-DUS for clinical gait analysis in children with cerebral palsy. Gait & Posture June 2012;36(2):282-286.

[8] Sangeux M, Peters A, Baker R. Hip joint centre localization: Evaluation on normal subjects in the context of gait analysis. Gait & Posture July 2011;34(3):324-328.

[9] Cereatti A, Donati M, Camomilla V, Margheritini F, Cappozzo A. Hip joint centre location: An ex vivo study. Journal Of Biomechanics May 11, 2009;42(7):818-823.

[10] De Momi E, Lopomo N, Cerveri P, Zaffagnini S, Safran M, Ferrigno G. In-vitro experimental assessment of a new robust algorithm for hip joint centre estimation. Journal Of Biomechanics May 29, 2009;42(8):989-995.

[11] Heller M, Kratzenstein S, Ehrig R, Wassilew G, Duda G, Taylor W. The weighted optimal common shape technique improves identification of the hip joint center of rotation in vivo. Journal Of Orthopaedic Research October 2011;29(10):1470-1475.

[12] Bouffard V, Begon M, Champagne A, Farhadnia P, Venditolli P, Lavigne M, and Prince F Hip joint center localisation: A biomechanical application to hip arthroplasty population World J Orthop. 2012 August 18; 3(8): 131–136. Published online 2012 August 18. doi: 10.5312/wjo.v3.i8.131

[13] Ehrig R, Heller M, Kratzenstein S, Duda G, Trepczynski A, Taylor W. The SCoRE residual: A quality index to assess the accuracy of joint estimations. Journal Of Biomechanics April 29, 2011;44(7):1400-1404.

[14] Leardini A, Chiari L, Croce U, Cappozzo A. Human movement analysis using stereophotogrammetry: Part 3. Soft tissue artifact assessment and compensation. Gait & Posture February 2005;21(2):212-225.

[15] Peters A, Baker R, Sangeux M. Validation of 3-D freehand ultrasound for the determination of the hip joint centre. Gait & Posture April 2010;31(4):530-532.

[16] Kratzenstein S, Kornaropoulos E, Ehrig R, Heller M, Pöpplau B, Taylor W. Effective marker placement for functional identification of the centre of rotation at the hip. Gait & Posture July 2012;36(3):482-486.

[17] Lopomo N, Sun L, Zaffagnini S, Giordano G, Safran M. Evaluation of formal methods in hip joint center assessment: An in vitro analysis. Clinical Biomechanics March 2010;25(3):206-212.

[18] Chiari L, Croce U, Leardini A, Cappozzo A. Human movement analysis using stereophotogrammetry: Part 2: Instrumental errors. Gait & Posture February 2005;21(2):197-211.

[19] Della Croce U, Leardini A, Chiari L, Cappozzo A. Human movement analysis using stereophotogrammetry: Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics. Gait & Posture February 2005;21(2):226-237.

[20] Alexander E, Andriacchi T .Correcting for deformation in skin-based marker systems. Journal of Biomechanics March 2001; 34(3):355–361

[21] Ryu T, Choi H, Chung M. Soft tissue artifact compensation using displacement dependency between anatomical landmarks and skin markers – a preliminary study. International Journal of Industrial Ergonomics. January 2009; 39(1): 152–158

[22] Andriacchi T, Alexander E. A point cluster method for in vivo motion analysis: Applied to a study of knee kinematics. Journal Of Biomechanical Engineering . December 1998;120(6):743

[23] Leardini A, Chiari L, Croce U, Cappozzo A. Human movement analysis using stereophotogrammetry: Part 3. Soft tissue artifact assessment and compensation. Gait & Posture .February 2005;21(2):212-225.

[24] Akbarshahi M, Schache A, Fernandez J, Baker R, Banks S, Pandy M. Non-invasive assessment of soft-tissue artifact and its effect on knee joint kinematics during functional activity. Journal Of Biomechanics.May 7, 2010;43(7):1292-1301

[25] Stagni R, Fantozzi S, Cappello A, Leardini A. Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects. Clinical Biomechanics . March 2005;20(3):320-329.