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In-vivo Quantification of Dynamic Hip Joint Center Errors and Soft Tissue Artifact

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Abstract

Hip joint center (HJC) measurement error can adversely affect predictions from biomechanical models. Soft tissue artifact (STA) may exacerbate HJC errors during dynamic motions. We quantified HJC error and the effect of STA in 11 young, asymptomatic adults during six activities. Subjects were imaged simultaneously with reflective skin markers (SM) and dual fluoroscopy (DF), an x-ray based technique with submillimeter accuracy that does not suffer from STA. Five HJCs were defined from locations of SM using three predictive (i.e., based on regression) and two functional methods; these calculations were repeated using the DF solutions. Hip joint center motion was analyzed during six degrees-of-freedom (default) and three degrees-of-freedom hip joint kinematics. The position of the DF-measured femoral head center (FHC), served as the reference to calculate HJC error. The effect of STA was quantified with mean absolute deviation. HJC errors were (mean $\pm$ SD) 16.6 $\pm$ 8.4 mm and 11.7 $\pm$ 11.0 mm using SM and DF solutions, respectively. HJC errors from SM measurements were all significantly different from the FHC in at least one anatomical direction during multiple activities. The mean absolute deviation of SM-based HJCs was 2.8 $\pm$ 0.7 mm, which was greater than that for the FHC (0.6 $\pm$ 0.1 mm), suggesting that STA caused approximately 2.2 mm of spurious HJC motion. Constraining the hip joint to three degrees-of-freedom led to approximately 3.1 mm of spurious HJC motion. Our results

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Conflicts of interest statement

The corresponding author and co-authors do not have a conflict of interest, financial or otherwise, that would inappropriately influence or bias the research reported herein.

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indicate that STA-induced motion of the HJC contributes to the overall error, but inaccuracies inherent with predictive and functional methods appear to be a larger source of error.

Keywords

femur; pelvis; hip joint centre; biomechanical model; functional hip joint center; dual fluoroscopy

1 Introduction

Biomechanical models generate predictions of important scientific and clinical variables related to the study of human movement [1–3]. In these models, joint centers define the linkage between neighboring body segments. Most often, positions of reflective markers adhered to the skin serve as the basis for calculating joint centers. Errors in definition of a joint center may negatively influence calculations of joint angles, joint moments, reaction forces and muscle forces [4, 5].

Substantial soft tissue surrounds the hip, which may affect the accuracy of hip joint center (HJC) measurements. Two primary methods exist to estimate the HJC from skin markers (SM). Predictive methods use anthropometrics and regression equations from the literature [6–8], whereas functional methods define the HJC from the relative movement between the femur and pelvis [9, 10]. We previously employed dual fluoroscopy (DF) with model-based tracking, an x-ray imaging technique that measures in-vivo bone location to submillimeter and subdegree accuracy [11], to quantify HJC errors during a standing, static trial. We found that functional methods were superior to predictive techniques, but both approaches exhibited errors that exceeded 10 mm [12].

When undergoing dynamic motion, soft tissue artifact (STA), a known drawback of skin marker motion capture, may exacerbate HJC errors. To our knowledge, prior studies have not directly measured the in-vivo position of the HJC during dynamic activities, and thus, the influence of STA on the accuracy of HJC estimates is unknown. Therefore, the purposes of this study were: 1) to measure pelvic STA during dynamic activities, and 2) to quantify the amount of spurious HJC movement due to STA.

2 Methods

2.1 Subjects

Eleven young, non-pathologic, adults provided informed consent to participate in this University of Utah IRB approved study (6 male, age: 23 ± 2 years, height: 173 ± 10 cm, BMI: 21 ± 2 kg/m²). All subjects were free of hip pathoanatomy as confirmed on an anterior-posterior (AP) radiograph. Subjects had not undergone previous lower limb surgery and were free from musculoskeletal injuries. The side to be imaged was chosen to provide balance between the number of right and left hips (6 right).

2.2 Activities

One static and six dynamic activities were analyzed (Fig. 1). The static (standing) trial was used to calculate anthropometrics that were input into regression equations to calculate predictive HJCs. Following the static, dynamic activities were performed in random order. The functional hip joint center activity determined the functional HJCs from a pre-defined motion that included hip flexion-extension, abduction-adduction and circumduction (i.e., the StarArc pattern) [13] (Video S1). For the abduction activity, subjects were instructed to abduct/adduct the hip being imaged to approximately 45°. For each rotation activity, subjects rotated to their end range of motion in a closed chain configuration. For walking activities, the treadmill was set to the subject's self-selected over-ground walking speed, as determined prior to data collection by a timed walk. The treadmill was inclined to 5° for inclined walking. To minimize radiation exposure, one trial was acquired for the static and functional activities. Two trials were obtained for all other activities; the trial that demonstrated the greatest range of motion and/or provided the clearest DF images was selected for further analysis. Due to restrictions in the allowable radiation exposure, no abduction trials were analyzed for two subjects, and no functional hip joint center activity was analyzed for one subject.

2.3 Skin Marker Motion Capture and Post-Processing

Subjects were imaged simultaneously using an optical motion capture system and DF (Fig. 1). The motion capture system utilized Vicon Nexus software (v1.8.5, Vicon Motion Systems, Oxford, UK) and 10 near infrared cameras to acquire reflective marker positions at 100 Hz. Activities were performed on a dual-belt, instrumented treadmill (Bertec Corporation, Columbus, OH, USA). Reflective markers were placed on the pelvis and thigh to locate bony landmarks and track segment motion [12]. Surface markers were placed on the left and right anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS) and iliac crests (ILC). A cluster of four markers on a rigid plate was strapped to the thigh with Velcro at a proximolateral position. Markers were also placed on the medial epicondyles of the knees and medial malleoli of the ankles to calculate leg length, which was required for predictive HJCs. Three dimensional (3D) skin marker positions were reconstructed and gap-filled in Vicon Nexus software. The Vicon and DF systems were synced temporally with an external trigger and spatially using a calibration cube that contained reflective markers with metal beads at their center [12].

2.4 Dual Fluoroscopy Data Collection and Model-based Tracking

Details regarding the DF imaging protocol and model-based tracking analysis were described previously [12]. The DF system consisted of two pairs of x-ray emitters and image intensifiers (Radiological Imaging Services, Hamburg, PA, USA) [11]. A high speed camera recorded video of the output screen on the image intensifiers at 100 Hz (Phantom Miro 3, Vision Research, Wayne, NJ, USA). The 3D position of each bone was found using model-based tracking (MBT) [14], which semi-automatically aligned digitally reconstructed radiographs from a computed tomography (CT) model of each subject with dual fluoroscopy images at each time frame. The total radiation exposure for each participant, including the

CT, was 10.72 mSv, which was 21% of the annual exposure considered safe for a radiation worker.

2.5 Soft Tissue Artifact

Static STA was defined as the distance between the reconstructed marker position, which was offset towards the bone by the marker base (2 mm) and radius (7 mm) during the static trial, and the bony landmark as found via DF. Dynamic STA was defined as a range of skin marker positions in each of the body segment's anatomical directions as measured by DF. In other words, dynamic STA was calculated as the range of motion, or peak-to-peak values, for each skin marker in the DF-measured body segment axes [15]. The effect of STA on HJC movement was quantified by taking the absolute distance to the mean position over the entire activity (i.e., mean absolute deviation). Pelvic STA was calculated for the pelvis' position and orientation by comparing solutions for SM and DF measurements, where DF served as the reference. Here, pelvic position STA was defined as the difference in the pelvis' origin as tracked using SM and DF measurements, and the pelvic orientation STA was defined as the angles between the pelvis tracked using SM measurements relative to the pelvis tracked using DF measurements.

2.6 Hip Joint Centers

The reference HJC was defined as the femoral head center (FHC). The FHC was determined from the center of a best-fit sphere to the femoral head of the subject-specific 3D CT reconstruction [16]. The FHC's position moved rigidly with the femur during dynamic motion (i.e., the FHC was embedded within the femoral anatomical frame) [17]. Five approaches to calculate the HJC were selected due to their common use in the literature and/or biomechanical motion analysis software programs. Three predictive HJCs based on anthropometrics included the Bell [7], Davis [6] and Harrington [8] methods. Two functional HJC algorithms included the Schwartz Transformational Technique (STT) [9] and Symmetric Center of Rotation Estimation (SCoRE) [10]. For each subject and activity, all five HJCs were generated from SM; these calculations were repeated using the DF solutions, yielding a total of 10 HJCs for comparison to the FHC. These 10 HJCs were generated relative to the pelvis' anatomical frame and moved rigidly with the pelvis during dynamic motion.

The Bell, Davis, Harrington and STT HJCs were generated in Visual3D (v5.02.11, C-Motion, Germantown, MD, USA). The SCoRE approach was implemented in a recent version of Vicon Nexus (v2.1.1, Vicon Motion Systems; Oxford, UK). The Bell and Davis HJCs were automatically created with the Coda and Helen Hayes pelvis segments, respectively, and the Harrington HJC was defined manually based on the equations in Visual3D's online documentation (Eq. Harrington2 in http://c-motion.com/v3dwiki/index.php?title=Hip_Joint_Landmarks). The STT HJC was calculated using Visual3D's *Add_Functional_Joint_Landmark* pipeline. The SCoRE HJC in Vicon Nexus required calibration and processing steps, as described in online documentation (http://vicon.com/documentation/nexus/v2.1/desktop/NexusWsN/BiomechanicsWF/About_SCoRE_and_SARA_in_Vicon_Nexus.htm) [10, 18].

The HJC positions were imported into MATLAB (v7.10, The Mathworks, Inc., Natick, MA, USA) for analysis [12]. For error analysis, all HJCs were transformed into the DF-measured pelvis anatomical coordinate system, which was defined according to the recommendations of the International Society of Biomechanics [19]. Hip joint center error was calculated as the distance between each HJC and the FHC in each anatomical direction as well as the linear distance.

2.7 Hip Joint Kinematic Constraint

Unless otherwise noted, hip joint center results were generated using kinematics from unconstrained, six degrees-of-freedom (6 DOF) hip motion. Many biomechanical models assume fewer degrees-of-freedom at the hip joint [20]. Thus, an additional analysis was performed that limited hip motions to rotations only (3 DOF). This was accomplished by restricting thigh segment translations to zero (relative to the pelvis) in the Visual3D model's inverse kinematics constraints.

2.8 Statistics

Individual comparisons between each HJC and the FHC were made using a paired t-test in MATLAB; P values were adjusted for multiplicity using the Holm step-down procedure [21]. Group-wise comparisons, including HJC errors calculated from SM versus those analyzed using the DF solutions and predictive versus functional HJC calculations, were made using a mixed effects linear regression model in Stata (v14.1, StataCorp LP, College Station, TX, USA). Here, predictor categorical variables were type of HJC (predictive and functional) and measurement system (SM and DF) and the interaction of type with measurement system. Mixed effects linear regression accounted for the lack of independence introduced by having six activities nested within five HJCs, which were nested within subjects. Adjusted means and adjusted mean differences were computed with significance tests using the method of average marginal effects [22]. Mean range of motion (ROM) was correlated with STA using MATLAB's *corrcoef* function. Significance was set at $P < 0.05$ for all tests.

3 Results

The FHC moved less than 1.0 mm relative to its mean location during all activities. All HJCs from SM underwent larger mean absolute deviation than the FHC (2.8 ± 0.7 mm vs. 0.6 ± 0.1 mm) (Table 1). With the hip joint constrained to rotations only (3 DOF), the HJCs from SM underwent 3.7 ± 1.0 mm mean absolute deviation, which, on average, was 0.9 mm more than unconstrained hip motion. For unconstrained motion and across all dynamic activities, pelvic positional error was 17.2 ± 5.3 mm, and rotational error was $0.1 \pm 6.5^\circ$ flexion-extension, $-0.2 \pm 1.9^\circ$ abduction-adduction, and $0.4 \pm 1.2^\circ$ internal-external rotation (Fig. 2).

During the static activity, mean STA was 15.7 mm anterior for the ASIS markers and 26.6 mm posterior for the PSIS markers (Fig. 3A). During the functional hip joint center activity, the mean STA for the thigh markers was 15.5 mm, 24.4 mm and 11.6 mm in the medial-lateral, anterior-posterior and superior-inferior directions, respectively (Fig. 3B). Mean STA

for the ILC markers was 7.4 mm, 12.6 mm and 12.5 mm in the medial-lateral, anterior-posterior and superior-inferior directions, respectively. The maximum STA for any subject during the functional joint center activity was 36.4 mm for the thigh markers in the AP direction. Also during the functional joint center activity, a moderately strong positive correlation ($r=0.71$, $p=0.02$) was found between mean STA and mean ROM (Fig. 3C). However, mean ROM was not correlated to error for the functional HJCs.

Qualitative plots of maximum HJC error demonstrated that almost all HJCs were located within the acetabulum during dynamic motion (Fig. 4). The functional joint center and inclined walk activities generally resulted in the maximum deviation from the FHC (Table S1). When considering all activities, and combining data from predictive and functional methods, the HJCs measured with SM had an error of 16.6 ± 8.4 mm, and HJCs from the DF solutions had an error of 11.7 ± 11.0 mm. When using SM solutions, functional methods had a lower error (12.5 ± 4.4 mm) than predictive (19.4 ± 9.2 mm). Individually, the lowest functional and predictive errors were the SCoRE (12.2 ± 4.8 mm) and Harrington (15.1 ± 7.0 mm) methods, respectively. Functional HJC errors improved when using DF solutions compared to SM solutions (1.3 ± 0.5 mm vs. 12.5 ± 4.4 mm, respectively), but predictive HJCs did not improve (18.6 ± 8.9 mm vs. 19.4 ± 9.2 mm, respectively). All HJCs measured from SM were statistically different than the FHC in at least one direction during multiple activities (Fig. S1–S6).

4 Discussion

The purposes of this study were: 1) to measure pelvic STA during dynamic motion, and 2) to quantify the amount of spurious HJC movement due to STA. The location of the FHC varied, on average, less than 1 mm from its mean position during dynamic motion, which suggests the hip does not experience substantial positional movement during the dynamic activities measured herein. Indirectly, this implies motion of the HJC estimated from skin markers arises from STA as opposed to natural positional movement. Deviations were relatively similar across SM HJCs, with small differences due to their location in the pelvic anatomical frame as well as to pelvic positional and orientation STA.

The HJC errors reported in this study are on par or slightly smaller than errors reported previously during a static activity using sphere fitting of ultrasound images [23] and an EOS system [24], as well as from CT images in a supine position [25]. As expected, the HJC errors from this study of dynamic activities were slightly larger than those we found previously during a static standing activity [12]. The results from this study confirm that functional methods have lower errors than predictive methods, and the two functional methods studied here, as implemented in Visual3D and Vicon Nexus, have similar HJC errors.

Of the predictive methods, the Harrington HJC performed the best. A recent review article summarizing HJC studies also found the Harrington HJC to be the most accurate predictive approach [26]. This review article also showed that in people with sufficient hip ROM, the geometric sphere fit method, a functional technique, was slightly more accurate than the Harrington method. The results of the current study support this conclusion when using skin

markers. However, when using dual fluoroscopy measurements, the HJC error decreased drastically to a mean error of 1.4 mm for functional techniques as compared to 15.1 mm for the Harrington HJC. The improved accuracy with functional techniques and DF solutions motivates future work to develop methods that minimize or incorporate STA correction during the functional trial. Also of note, the SCoRE and STT errors in the current study are lower than those summarized by Kainz and colleagues [26]. We suspect the improved accuracy in this study could arise from two sources. First, our subjects had a low BMI, which could have minimized STA. Second, our reference standard has been validated to an accuracy and bias of less than 1 mm and 1° during dynamic motion [11], whereas previous studies have not reported submillimeter and subdegree accuracy for the reference standard and did not measure the three dimensional position of bones during dynamic motion using the reference standard. The latter is important because previous studies that used the SCoRE and STT were unable to separate the contribution of skin motion artifact from errors due to the algorithm.

The FHC movement in the pelvis anatomical coordinate system established a reference point for HJC movement during dynamic activities (< 1 mm). While the SM HJC movement was greater than the FHC (2.8 ± 0.7 mm vs. 0.6 ± 0.1 mm), it was relatively small compared to the overall HJC error (16.6 mm for SM and 11.7 mm for DF solutions), which indicates that an accurate mathematical definition of the HJC is critical to reducing overall HJC errors. Reduction of STA would also reduce HJC error, as the dynamic HJC error depends only on the STA of the pelvis markers.

Soft tissue artifact induces HJC errors via multiple sources. For the predictive methods, the largest source of STA was the thickness of tissue relative to the ASIS and PSIS bony landmarks, which has been shown to affect pelvis depth measurements [27]. Accounting for soft tissue thickness in the skin marker offset from the raw measurement could further improve HJC measurements. Still, the lack of improvement when using the DF solutions for the predictive methods suggests that it was the basis of the regression itself that caused errors. Soft tissue artifact will affect the definition of the functional HJCs as well as the deviation during the dynamic activities. The large reduction in HJC error observed when using the DF solutions confirmed that SM movement relative to the bony anatomy was the primary contributor to HJC error for the functional methods.

While statistically different from the FHC, many HJC errors may not meet the threshold for what is considered clinically relevant, which has been suggested to be 30 mm [5]. However, differences of less than 30 mm may be important for biomechanical model calculations of muscle forces, joint moments and moment arms [28], given that in a recent OpenSim generic model [29] most muscles crossing the hip have moment arms less than 30 mm in at least one anatomical direction.

This study included a few limitations. First, the dynamic DF method required exposure to ionizing radiation. Second, the study population consisted of recreationally active young adults. Subjects with a higher BMI and more soft tissue will likely induce larger STA and larger dynamic HJC errors. Third, other HJC definitions could exhibit better accuracy than those studied here. For example, including only pelvic width or leg length could improve

accuracy in HJC measurements [27]. Furthermore, the geometric sphere fit technique to calculate the functional joint center was not employed in this study. We chose to include techniques that were already implemented in common software programs; application of geometric sphere fitting and custom code, such as the code that accompanies a recent publication [30], was beyond the scope of our primary objectives but could be examined in future work. In the future, we will evaluate the impact of STA on biomechanical model outputs of joint kinematics, kinetics and forces.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Research Highlights

- Hip joint center (HJC) errors and soft tissue artifact (STA) measured dynamically
- HJCs were generated from dual fluoroscopy (DF) and skin marker (SM) solutions
- HJC errors were 16.6 mm and 11.7 mm when using SM and DF solutions, respectively
- STA caused 2.2 mm (3.1 mm) of spurious HJC movement for 6 DOF (3 DOF) hip motion
- STA led to 17.2 ± 5.3 mm error in tracking the position of the pelvis

Figure 1.

Photographs of experimental setup and activities. Subjects were imaged simultaneously with dual fluoroscopy and skin marker motion capture systems during static and dynamic activities. The dual fluoroscopy system consisted of two pairs of x-ray emitters (not pictured) and image intensifiers (II). Reflective marker positions were tracked with infrared cameras. The DF system was covered with cloth to prevent infrared light scatter. All activities were performed on a dual-belt instrumented treadmill. The experimental setup shown was arranged for imaging a left hip.

Figure 2.

Pelvic STA during all activities. The pelvic position of the origin (top) and orientation (bottom) were compared between the pelvi tracked using SM and DF solutions. The darker shaded bars were tracked using unconstrained, 6 DOF kinematics, and the lighter shaded bars were tracked using constrained (rotations only), 3 DOF kinematics. Error bars represent ± 1 SD. Lat: Lateral. Med: Medial. Ant: Anterior. Post: Posterior. Sup: Superior. Inf: Inferior. Flex: Flexion. Ext: Extension. Add: Adduction. Abd: Abduction. Int: Internal rotation. Ext: External rotation.

Figure 3.

Soft tissue artifact during the static and functional hip joint center activities. During the static trial (A), soft tissue artifact was calculated as the distance between the reconstructed skin marker (SM) location, including an offset to account for the marker radius and base, and the corresponding dual fluoroscopy (DF) bony landmark. During the functional hip joint center trial (B), soft tissue artifact was defined as the range of values in each direction of the body segment's anatomical coordinate system. Also during the functional hip joint center trial, the mean soft tissue artifact was found to correlate significantly with the mean ROM (C). Scatter plot points are filled based on the mean distance of the STT and SCoRE HJCs to the femoral head center. LM: Lateral (+) Medial (-). AP: Anterior (+) Posterior (-). SI: Superior (+) Inferior (-).

Figure 4.

Maximum deviation from the femoral head center during dynamic activities. The hip joint center position at the maximum distance from the femoral head center was plotted with respect to each subject's acetabulum surface reconstruction. Right pelvi have been reflected to match the anatomical directions of left pelvi. See Supplemental Material Table S1 for a description of which dynamic activity resulted in the maximum distance from the femoral head center. SM: Skin Markers. DF: Dual Fluoroscopy. M: Male. F: Female.

Deviation from the mean hip joint center position during dynamic activities. Deviation was calculated as the distance to the mean location over all time frames. Data are reported as mean [95% confidence interval] across all subjects. An asterisk (*) indicates a significant difference between the skin markers (SM) hip joint center and the femoral head center (FHC) as measured by dual fluoroscopy (DF). Note that all HJCs measured from DF bony landmarks were zero. Harr: Harrington. Int: Internal. Ext: External. FuncJC: Functional Joint Center

Table 1

		Mean Absolute Deviation (mm)					
	HJC	Walk	Incline	FuncJC	Abduction	Int. Rotate	Ext. Rotate
SM	Bell	2.8 [2.4 3.2]*	3.7 [3.4 4.0]*	2.4 [1.9 2.8]*	3.0 [2.6 3.4]*	1.6 [1.3 1.8]*	2.9 [2.4 3.5]*
	Davis	3.2 [2.7 3.7]*	3.9 [3.4 4.4]*	2.7 [2.3 3.2]*	3.6 [2.8 4.4]*	1.7 [1.5 1.9]*	2.2 [1.7 2.7]*
	Harr.	3.0 [2.5 3.4]*	3.9 [3.5 4.2]*	2.5 [2.0 2.9]*	3.0 [2.6 3.4]*	1.6 [1.4 1.9]*	3.1 [2.5 3.7]*
	STT	3.0 [2.6 3.4]*	3.9 [3.6 4.3]*	2.5 [2.1 2.9]*	3.0 [2.6 3.5]*	1.6 [1.3 1.8]*	3.1 [2.6 3.7]*
	SCoRE	3.0 [2.5 3.4]*	3.9 [3.5 4.2]*	2.5 [2.1 2.9]*	3.0 [2.6 3.5]*	1.6 [1.3 1.8]*	3.1 [2.5 3.7]*
DF	FHC	0.6 [0.4 0.8]	0.7 [0.5 0.9]	0.6 [0.4 0.8]	0.5 [0.3 0.7]	0.6 [0.4 0.8]	0.7 [0.3 1.2]