

Evaluation of a new algorithm to determine the hip joint center

Robert A. Siston^a, Scott L. Delp^{a,b,*}

^a*Mechanical Engineering Department, Stanford University, Stanford, CA 94305-5450, USA*

^b*Bioengineering Department, Stanford University, S-321 James H. Clark Center, 318 Campus Drive, Stanford, CA 94305-5450, USA*

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Abstract

Accurately locating the hip joint center is a challenging and important step in many biomechanical investigations. The purpose of this study was to test the accuracy and robustness of a “pivoting” algorithm used to locate the hip center. We tested the performance of this algorithm with data acquired by manipulating a ball and socket model of the hip through several motion patterns. The smallest mean errors of 2.2 ± 0.2 mm occurred with a circumduction motion pattern, while the largest errors of 4.2 ± 1.3 mm occurred with single-plane motion (e.g., flexion/extension). Introducing random noise with an amplitude of 30 mm increased the errors by only 1.3 ± 0.5 mm with a circumduction motion pattern. The pivoting algorithm performs well in the laboratory, and further work is warranted to evaluate its performance in a clinical setting.

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1. Introduction

Locating the center of the hip is required to calculate hip and knee joint rotations and moments in gait analysis (Cappozzo et al., 1975; Kirkwood et al., 1999; Stagni et al., 2000), to estimate the moment arms of muscles spanning the hip (Delp and Maloney, 1993) and to align implants during total knee replacement (Krackow, 1995). The hip center may be determined with radiographic methods (Bell et al., 1990; Kirkwood et al., 1999) or by estimating its position relative to anatomic landmarks that are accessible without imaging (Andriacchi et al., 1980; Bell et al., 1989; Seidel et al., 1995; Tytkowski et al., 1982). Researchers have also used functional methods that estimate the center of rotation of the femur relative to the pelvis from

kinematic data (Cappozzo, 1984; Leardini et al., 1999; Marin et al., 2003; Piazza et al., 2001; Shea et al., 1997).

Locating the hip center for computer-assisted total knee replacement (Delp et al., 1998; Krackow et al., 1999) requires a method that is fast and accurate even with a limited range of motion and noisy kinematic data. Piazza et al. (2001) and Marin et al. (2003) have presented accurate functional methods that estimate the hip center, but these algorithms require an initial guess of the solution and several iterations of an optimization function. Optimizations can take several minutes to calculate a hip joint center from motion data (Marin et al., 2003), but it is undesirable to increase operative time while awaiting the results of an optimization function. Also, a limited range of motion can lead to a numerical instability for some algorithms (Seidel et al., 1995). Piazza et al. (2004) presented a new algorithm to estimate the hip center and studied how different motion patterns affect its performance in vivo. Their study, based on kinematics measured in human subjects, has provided encouraging results; however, the true hip center was unknown in their experiments. Thus, it is unclear if their reported errors should be attributed to

*Corresponding author. Bioengineering Department, Stanford University, S-321 James H. Clark Center, 318 Campus Drive, Stanford, CA 94305-5450, USA. Tel.: +1 650 723 1230; fax: +1 650 724 1922.

E-mail address: delp@stanford.edu (S.L. Delp).

the new algorithm or to the collected motion data. In general, it is unknown how noise in kinematic data affects the performance of various algorithms that calculate the hip center.

Our goal was to evaluate the computational speed and accuracy of an algorithm similar to the one first presented by Piazza et al. (2004) in the presence of limited motion and noisy kinematic data. This paper provides a detailed description of a “pivoting” algorithm and reviews how we used a mechanical linkage, where a true hip center was known, to test the algorithm’s performance with six motion patterns and with the introduction of simulated noise in kinematic data.

2. Methods

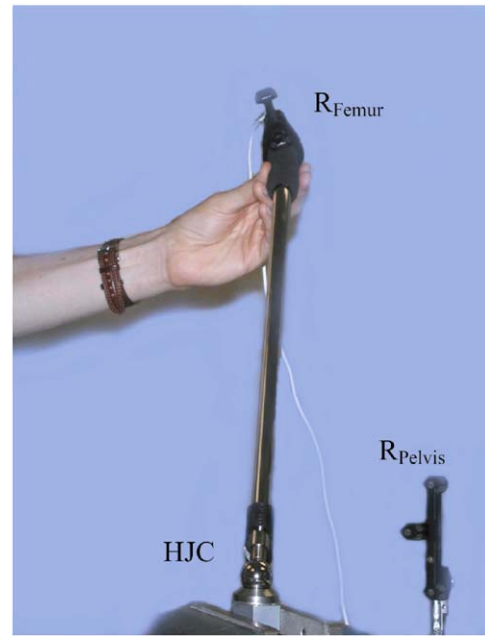
We conducted a series of experiments using two rigid segments representing a pelvis and femur that were connected using a ball joint to simulate the hip (Fig. 1A). A Polaris optical tracking system (Northern Digital Inc., Waterloo, Ontario) was used to sample at 30 Hz the position and orientation of Traxtal AdapTrax reference frames (Traxtal Inc., Toronto, Ontario) attached to the femur and pelvis portions of the model. This tracking system is accurate to within 2 mm with the measurement volume used in this study (Traxtal Inc., Toronto, Ontario).

For each experimental trial, we manually rotated the femur segment through a prescribed motion pattern. Six motion patterns were investigated, including single-plane and multi-plane motions (Table 1). In our setup, “flexion/extension” was defined as motion in the plane parallel to the camera, and “ab/adduction” was in the plane perpendicular to the camera. The rod was able to move freely about the ball joint without constraints, so unlike in an in vivo study, there was no difference between “flexion/extension” and “ab/adduction”. Each motion pattern took approximately 10 s to complete and was repeated ten times.

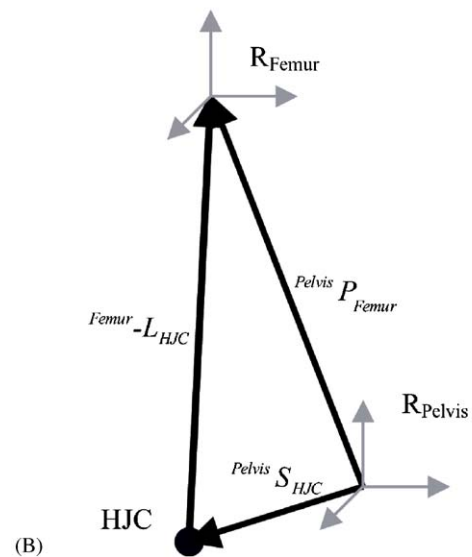
The pivoting algorithm is based on vector addition. In the pelvic reference frame, the position of the femoral reference frame (${}^{\text{Pelvis}}P_{\text{Femur,Calc}}$) can be calculated by adding a vector from the origin of the pelvic reference frame to the hip joint center (HJC) to another vector from the HJC to the origin of the femoral reference frame (Fig. 1B). This can be expressed as

$${}^{\text{Pelvis}}P_{\text{Femur,Calc}} = [{}^{\text{Pelvis}}R]_{\text{Femur}}^{\text{Femur}} - L_{\text{HJC}} + {}^{\text{Pelvis}}S_{\text{HJC}}, \quad (1)$$

where ${}^{\text{Femur}}-L_{\text{HJC}}$ is a vector, in the femoral reference frame, originating at the HJC and terminating at the origin of the femoral frame, ${}^{\text{Pelvis}}S_{\text{HJC}}$ is a vector, in the pelvic reference frame, beginning at the origin of the pelvic reference frame and terminating at the HJC and ${}^{\text{Pelvis}}R_{\text{Femur}}$ is a rotation matrix between the pelvic and



(A)



(B)

Fig. 1. (A) The mechanical linkage and (B) a graphical description of the reference frames and the vectors used to locate the center of rotation, HJC. R_{Femur} and R_{Pelvis} label the reference frames on the femur and pelvis, respectively. The femoral reference frame was located approximately 500 mm from the ball joint.

femoral reference frames that transforms ${}^{\text{Femur}}-L_{\text{HJC}}$ into the pelvic reference frame. Eq. (1) is expressed with vector notation but also can be expressed as a set of three scalar equations (one equation for each of the x , y , and z -coordinates of the vectors). The pivoting algorithm assumes: (1) the magnitude of ${}^{\text{Pelvis}}S_{\text{HJC}}$ remains constant (i.e., the hip center is fixed in the pelvis) and (2) the magnitude of ${}^{\text{Femur}}-L_{\text{HJC}}$ also remains constant (the leg length is constant).

Eq. (1) simultaneously locates the hip joint center in the femoral and pelvic reference frames. Given two

Table 1
Prescribed motion patterns

Motion pattern	Description
15	Flex to 15°, return to neutral, extend to 15°, return to neutral
30	Flex to 30°, return to neutral, extend to 30°, return to neutral
Cir15	1 path of circumduction, with maximum flexion and adduction angles of 15°
Cir30	1 path of circumduction, with maximum flexion and adduction angles of 30°
15–15	Motion pattern 15, then adduct to 15°, return to neutral, abduct to 15°, return to neutral
30–30	Motion pattern 30, then adduct to 30°, return to neutral, abduct to 30°, return to neutral

known positions and orientations of the femoral reference frame, Eq. (1) can be written twice, producing a set of six scalar equations with six unknowns—the x , y , and z -components of ${}^{\text{Femur}}L_{\text{HJC}}$ and ${}^{\text{Pelvis}}S_{\text{HJC}}$. This system of six equations can then be solved to uniquely identify these vectors, under most circumstances (see Section 4). ${}^{\text{Pelvis}}S_{\text{HJC}}$ identifies the HJC in the pelvic reference frame and after reversing ${}^{\text{Femur}}L_{\text{HJC}}$ so that it begins at the origin of the femoral reference frame, ${}^{\text{Femur}}L_{\text{HJC}}$ identifies the HJC in the femoral reference frame.

During the motion trials, we measured the position (${}^{\text{Pelvis}}P_{\text{Femur,Meas}}$) and orientation (${}^{\text{Pelvis}}R_{\text{Femur}}$) of the femoral reference frame with respect to the pelvic reference frame. Eq. (1) was written one time for each of the n measured positions of the femoral reference frame during each motion trial, resulting in a set of $3n$ scalar equations that was written in matrix notation

$$\begin{bmatrix} P_{x,\text{Meas}1} \\ P_{y,\text{Meas}1} \\ P_{z,\text{Meas}1} \\ \vdots \\ P_{x,\text{Meas}n} \\ P_{y,\text{Meas}n} \\ P_{z,\text{Meas}n} \end{bmatrix} = \begin{bmatrix} R_{11,\text{Meas}1} & R_{12,\text{Meas}1} & R_{13,\text{Meas}1} & 1 & 0 & 0 \\ R_{21,\text{Meas}1} & R_{22,\text{Meas}1} & R_{23,\text{Meas}1} & 0 & 1 & 0 \\ R_{31,\text{Meas}1} & R_{32,\text{Meas}1} & R_{33,\text{Meas}1} & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{11,\text{Meas}n} & R_{12,\text{Meas}n} & R_{13,\text{Meas}n} & 1 & 0 & 0 \\ R_{21,\text{Meas}n} & R_{22,\text{Meas}n} & R_{23,\text{Meas}n} & 0 & 1 & 0 \\ R_{31,\text{Meas}n} & R_{32,\text{Meas}n} & R_{33,\text{Meas}n} & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} -L_x \\ -L_y \\ -L_z \\ S_x \\ S_y \\ S_z \end{bmatrix}. \quad (2)$$

This system of scalar equations, written in the familiar $Ax = b$ notation, was over-determined when $n > 2$, so we solved for the vectors ${}^{\text{Femur}}L_{\text{HJC}}$ and ${}^{\text{Pelvis}}S_{\text{HJC}}$ that minimized the square of the difference between the measured (${}^{\text{Pelvis}}P_{\text{Femur,Meas}}$) and calculated (${}^{\text{Pelvis}}P_{\text{Femur,Calc}}$) positions of the femoral reference frame. We used the Matlab “backslash” command, which uses QR factorization, to solve our system of equations and used ${}^{\text{Femur}}L_{\text{HJC}}$ as the hip center in our experimental trials.

To establish the true HJC in the femoral reference frame, we used a digitizing probe (Northern Digital Inc., Waterloo, Ontario) to measure the three-dimensional coordinates of approximately 200 points on the surface of the ball of the joint. We used Gauss–Newton optimization (Forbes, 1989) to determine the best-fit sphere to these points and compared the center of this sphere to the HJC calculated by the pivoting algorithm.

We evaluated the algorithm’s sensitivity to noisy data by introducing random noise of varying amplitudes (5, 10, 15, 20, and 30 mm) into the measured position of the femoral reference frame from the “Cir30” and “15” motion trials. Andriacchi et al. (1998) and Lucchetti et al. (1998) have classified the motion of reflective skin markers to be within this range. We also applied the “sphere-fitting” algorithm from Piazza et al. (2001), one commonly used to determine the HJC from kinematic data, to this noisy motion data to investigate any differences between the two algorithms in their ability to maintain accuracy in the presence of noisy data. For both algorithms, we computed the center of rotation with these noisy data and determined the change in the location of the HJC.

One-way analysis of variance (ANOVA) tests were performed to identify statistical differences in the mean errors for the six motion patterns, and the Tukey–Kramer method was used to further investigate significant results. The Student’s t -test was used to investigate differences between the ability of the pivoting and sphere-fitting algorithms to maintain accuracy with noisy data. The level of statistical significance was set at $\alpha = 0.05$.

3. Results

The mean errors for the pivoting algorithm with multi-plane motion patterns (“Cir15”, “Cir30”, “15–15”, “30–30”) were significantly smaller ($p < 0.001$) than the mean errors for single-plane motion patterns (“15”, “30”) (Fig. 2). The smallest mean error of 2.2 ± 0.2 mm occurred with 30° of circumduction (“Cir30”). While a statistically significant difference was found between the “Cir 30” motion pattern and the other multi-plane motion patterns ($p < 0.001$), the magnitude of this

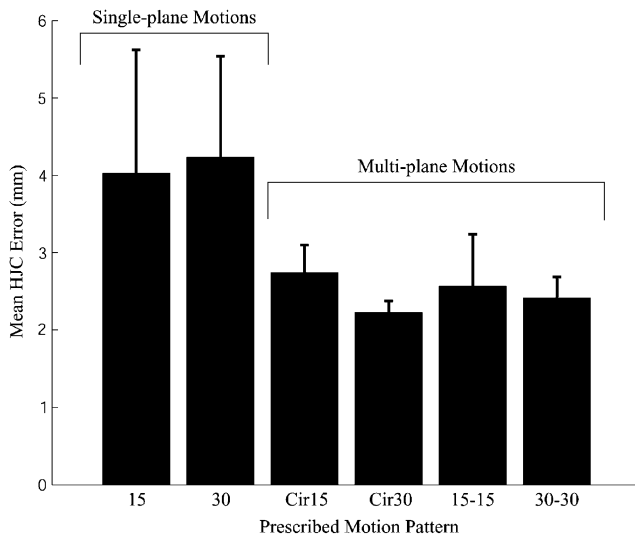


Fig. 2. Mean error in estimation of the hip joint center (HJC) for each prescribed motion pattern. The mean errors for multi-plane motions (Cir15, Cir30, 15–15, 30–30) are significantly smaller than the mean errors for single-plane motion (15, 30). See Table 1 for a description of all motion patterns. Each error bar represents one standard deviation.

difference was less than the reported accuracy of the measurement system. There was not a statistically significant difference between the other multi-plane motion patterns. The largest mean error of 4.2 ± 1.3 mm occurred with the single-plane motion “30”.

Introducing random noise caused only small increases in mean error with the pivoting algorithm but large increases in mean error with the sphere-fitting algorithm. Applying the largest amount of input noise (30 mm) to the “Cir30” motion pattern increased the mean error of the calculation of the hip center with the pivoting algorithm by 1.3 ± 0.5 mm. When 30 mm of input noise was applied to the sphere-fitting algorithm, the mean error increased by 16.2 ± 16.4 mm (Fig. 3). As measured by the change in the calculated HJC for each technique, there was a significant difference ($p < 0.001$) between the ability of the pivoting algorithm and the sphere-fitting algorithm to reject noise with the “Cir 30” motion pattern. Motion pattern “15” was the most sensitive to noise. When 30 mm of input noise was applied, the mean error associated with the pivoting and sphere-fitting algorithms increased by 15.8 ± 12.3 and 100.5 ± 79.2 mm, respectively. For all motion patterns, the pivoting algorithm computed the hip center in less than 1 s.

4. Discussion

We used a mechanical model to investigate the performance of an algorithm that determines the hip center from kinematic data. Piazza et al. (2001), using a mechanical linkage and a sphere-fitting algorithm,

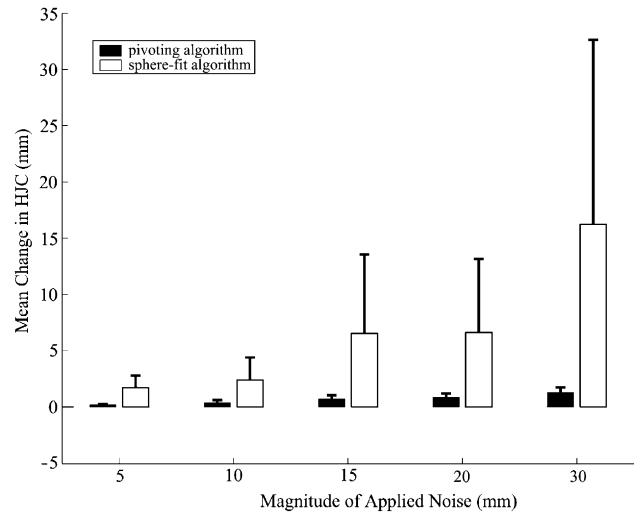


Fig. 3. Mean change in hip joint center (HJC) error magnitudes with varied amplitudes of random noise for the “Cir 30” motion pattern with the pivoting and sphere-fitting algorithms. The mean changes associated with the pivoting algorithm are significantly smaller than the mean changes from the sphere-fitting algorithm. Each error bar represents one standard deviation.

reported a best-case mean error of 4.4 ± 0.2 mm in hip center location while using a motion pattern that most resembled our motion pattern “30–30” and a worst-case mean error of 9.1 ± 1.5 mm with a path of circumduction of 15° . The errors reported by Piazza et al. (2001) are smaller than previous studies but are larger than the results from the pivoting algorithm described here, which yielded errors of 2.4 ± 0.3 and 2.7 ± 0.4 mm with motion patterns “30–30” and “Cir15”, respectively.

To ensure that the improvements in the mean errors reported here were due to the pivoting algorithm’s performance, we applied the sphere-fitting algorithm from Piazza et al. (2001) to the motion data from our study. Consistent with Piazza et al. (2001), we found that the sphere-fitting algorithm yielded its smallest errors with motion pattern “30–30” (2.6 ± 0.8 mm) and similar mean error magnitudes for single-plane motions (7.0 ± 4.0 mm). For all motion patterns, the sphere-fitting algorithm produced mean errors that were larger than the mean errors from the pivoting algorithm but were smaller than those reported by Piazza et al. (2001), suggesting that the improved accuracy reported in the current study resulted from the pivoting algorithm and the quality of the input data. However, these differences in error are small relative to the large differences in the ability of the two algorithms to reject noise and remain accurate in the presence of noisy input data.

Random noise may be present during motion-analysis studies. We evaluated the performance of the pivoting algorithm with random noise because its magnitude during motion analysis has been characterized (Andriacchi et al., 1998; Lucchetti et al., 1998). We have shown that, in the presence of random noise, the

pivoting algorithm is significantly more accurate than a sphere-fitting algorithm.

The pivoting-algorithm is useful for gait analysis with stereophotogrammetric systems and for computer-assisted surgery, and it is important to discuss the systematic noise for each application. For gait analysis, a special hip motion trial that involves motion in both the sagittal and frontal planes (Bell et al., 1990; Leardini et al., 1999; Piazza et al., 2004) is used to determine the hip center from kinematic data. While the pattern of systematic noise due to skin-motion artefact, a main source of error during gait analysis, has been characterized for tasks such as walking and cycling (Cappozzo et al., 1996), the systematic noise associated with special hip motion trials to determine the HJC has not been characterized. Given the variety of noise observed by Cappozzo et al. (1996) during primarily planar motions, it is difficult to predict and therefore, simulate, the effects of systematic noise associated with multi-planar motions like circumduction and more complex motions like the “30–30” pattern from this study. During computer-assisted surgery, reference frames are attached directly to the bone with screws, so skin-motion artefact is not present, although other sources of errors may exist. Future work is needed to characterize the systematic noise associated with determining the HJC from kinematic data for gait analysis and computer-assisted surgery and then subsequently examine the effects of that noise on all algorithms that determine the hip center from kinematic data.

The use of a mechanical linkage, instead of human subjects, might be considered a limitation of this study. However, the use of a mechanical linkage provides a good vehicle for evaluating a new algorithm. Piazza et al. (2004) applied a pivoting algorithm to data with limited ranges of motion recorded in human subjects and presented a best-case mean error of 5.0 mm and a worst-case mean error of 18.0 mm, but their experiment lacked a true gold standard. Our analysis with the mechanical linkage provides a gold standard and complements their study.

There are two important mathematical differences between the pivoting algorithm and other algorithms used to functionally determine the hip center. First, unlike other methods (Shea et al., 1997; Leardini et al., 1999; Piazza et al., 2001), the pivoting algorithm does not fit a sphere to the data. Because of this, the pivoting algorithm yields a system of linear equations instead of the quadratic terms associated with a sphere. Second, this system of equations resulting from the pivoting algorithm does not require an initial guess of the solution or several iterations of an optimization routine, making its performance computationally faster than algorithms that iteratively optimize a solution from an initial guess (Piazza et al., 2001; Marin et al., 2003).

With purely planar motion, the pivoting algorithm and sphere-fitting algorithm are theoretically not able to uniquely determine the position of the HJC in the direction that is perpendicular to the plane of motion. The algorithms are only able to determine a line of an infinite number of solutions instead of a single, unique, solution. Despite this limitation, we were able to achieve unique solutions with both algorithms with motion patterns “15” and “30” in this experiment due to some out-of-plane motion in the experimental data. This shortcoming with planar motion supports the need for the special hip motion trials that are used to determine the HJC from kinematic data. Piazza et al. (2004) demonstrated the difficulty in functionally determining the HJC from planar motion and concluded that special hip motion trials are important to functionally determine the HJC and can be performed even in subjects with limited ranges of motion.

The pivoting algorithm is an accurate and fast technique to locate the hip center, and its performance is minimally affected by reasonable limits of motion and the presence of noisy motion data. These qualities suggest that the pivoting algorithm may be superior to previously described methods for determining the hip center. However, additional work is needed to comprehensively evaluate this method in a clinical setting.

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