Radiographic and non-invasive determination of the hip joint center location: Effect on hip joint moments

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Radiographic and non-invasive determination of the hip joint center location: effect on hip joint moments

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Abstract

Objective. To determine which of four non-invasive measures is most accurate in locating the hip joint center.

Background. The location of the joint centers must be accurately determined in three dimensions for calculation of the moments of force during gait. It is not known which of the several non-invasive methods available for location of the hip center is most accurate.

Design. Hip center location was determined using standardized X-rays and four non-invasive methods which utilized measured distances between bony landmarks in 10 healthy subjects. Hip moments during gait were obtained from optical tracking, force plate and anthropometric data.

Results. The most accurate non-invasive method of locating the hip center was by taking the midpoint of a line connecting the antero-superior iliac spine and the symphysis pubis and moving inferiorly 2 cm. Using this approach the hip center was located 0.7 cm medial and 0.8 cm superior to its true location determined using the standardized X-rays. The 95% confidence interval of the maximum error difference in moments measured between this method and the standardized X-rays ranged from −0.15 to 0.4 Nm/kg in the frontal plane, −0.03 to 0.07 Nm/kg in the sagittal plane and −0.05 to −0.03 Nm/kg in the transverse plane.

Conclusions. Locating the hip center based on the distance between the antero-superior iliac spine and the symphysis pubis is a valid technique for estimating the hip center in routine gait analysis.

Relevance

Utilization of a non-invasive method of hip center location eliminates the need for X-rays, lowering costs and time in gait analysis studies as well as unnecessary exposure of subjects to radiation.

Keywords: Biomechanics; Gait; Joint moments of force; Hip joint; Hip joint center; Bone prominence; Radiology

1. Introduction

Estimating the location of the hip center (HC) from the position of external markers is important in the accurate calculation of the moments of force at the hip joint during gait. The lever arm of the force or the distance from the axis of rotation or joint center to the segments center of mass must be determined in three dimensions. Inaccurate estimation of the location of the HC will result in inaccurate calculation of this distance and hence moments of force at the hip joint.

Previous researchers have estimated the location of the HC based on external non-invasive measurements of points on the pelvis [1–3]. Andriacchi and Strickland [4] and Andriacchi et al. [1] estimated that in the frontal plane the HC would lie 1.5–2 cm directly distal to the midpoint of a line connecting the antero-superior iliac spine (ASIS) and the pubic symphysis (PS). Bell et al. [3,5] estimated the location of the HC in all three planes using a fixed percentage of the pelvic width (PW), defined as the distance between the right and left ASIS. Seidel et al. [2] stated that estimating the HC location using fixed proportions of three pelvic parameters, pelvic width (PW), pelvic depth (PD) and pelvic height (PH), optimized hip center location. All of these non-invasive methods rely on accurate palpation of bony landmarks and the distance between them to estimate the hip joint center. Cappozzo [6] and Persson et al. [7] described a rotational method of estimating the hip

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center based on premise that the thigh is like a pendulum rotating with a fixed center (hip center). However, this type of approach to hip center location is not applicable when limitations of joint range of motion are present.

Radiographic techniques have also been used to determine the location of the HC [8–10]. However, planar films are prone to errors of parallax and poor control of subject positioning [9]. The QUESTOR Precision Radiography (QPR) system was developed to control these sources of error [8,9,11]. The QPR provides frontal views of the hip and knee joints and sagittal views of the knee corrected for parallax errors. The hip correction vectors in the medial/lateral and vertical directions relative to the marker over the greater trochanter are computed from the radiographs. Although costly and involving X-ray exposure, the QPR is accurate in estimating the hip joint center of rotation.

The objective of this study was to compare the moments of force at the hip in level walking obtained using four non-invasive methods of adjusting the location of the external marker to the hip center of rotation, to those obtained using the QPR, which is considered the gold standard [8,9,11]. The QPR technique includes radiographic exposure combined with manual digitization and software analysis to mathematically move the external marker from the skin into the body. If any agreement between the non-invasive methods of determining the hip center location and the QPR are found, X-rays would be not required, lowering costs, time and unnecessary exposure to radiation.

2. Methods

2.1. Subjects

Data from a group of 10 healthy subjects, 55 years of age or older, with no history of lower limb problems were collected.

2.2. Measurement system

Hip moments during level walking were obtained using the Queen's Gait Analysis in Three Dimensions or QGAIT system [8,12,13]. The QGAIT system is a software package designed to compute moments of force and angles at the hip and knee. Validation of the system for measurement of kinematic and kinetic parameters at the lower limb has been documented in detail in previously published work [8,12,13]. The QGAIT system computes hip moments using kinematic information obtained using an Optotrak (Northern Digital, Waterloo, Ontario, Canada), force plate data (AMTI – Advanced Mechanical Technology, Boston, MA, USA), anthropometric and joint center information using the QPR.

Infrared emitting diodes (IREDs) were placed over the greater trochanter, the lateral femoral epicondyle, the head of the fibula and the lateral malleolus. In addition, two projecting probes were attached to the subject's thigh and shank, and an IRED was attached to these endpoints. This resulted in three markers on each segment needed to track the orientation of the limb in space. A footswitch, placed under the right heel, provided information regarding foot contact during gait.

Vertical and shear ground reaction forces were obtained using an AMTI force platform. A 16-channel analogue to digital (A/D) board integrated with the Optotrak allowed simultaneous collection of the force plate and foot switch data.

Anthropometric data were collected and included the subject's weight, height, length of lower limb from greater trochanter and tibial plateau to floor, thigh and calf circumferences and shoe weight. These measurements are important for the calculation of the thigh, shank and foot center of mass locations, segment mass and inertial properties.

Optotrak, anthropometric, force plate and joint center measures are integrated to calculate net moments in Newton meters (Nm) at the hip. In the QGAIT system, the conventions for hip moments are as follows: all external moments are positive using the right hand rule with respect to the axis about which it is defined. At the hip, a frontal moment is about the antero-posterior axis (AP), or x-axis, resulting in adduction as positive. A sagittal moment is about the lateral–medial axis (LM), or y-axis, therefore extension is positive. In the transverse plane, movement occurs about a distal–proximal (DP), or z-axis, and internal rotation is positive. However, every external moment is resisted or counter balanced by an internal moment [4,14]. Thus, for the most part an external extensor moment at the hip would represent internal flexor muscle and soft tissue forces. Internal moments are reported in this paper and they represent the net effect of all internal forces produced by muscles, ligaments, bones and friction. The diagrams presented in this paper show the internal positive moment on the top of the graph. The moments are normalized by body weight resulting in measures of Nm/kg.

3. Hip joint center estimation

3.1. Invasive method: QPR

The standardized X-ray (QPR) incorporates an aluminum frame mounted in castors. Two Plexiglas panels are attached to the side of the frame. The outer panel has a repeating pattern of four radiopaque markers in a circular cluster and the inner panel has a radiopaque grid. These two plates are aligned so that a horizontal X-ray beam shows clusters centered about the grid nodes on the radiographic image. In case of X-ray divergence, geometric distortions (grids and clusters out of alignment) are visualized on the radiograph. These parallax errors are then corrected using a program designed for this purpose [9].

Radiographs were obtained with the subject standing on a calibrated turntable inside a frame that is fixed relative to the X-ray source. The pelvis is supported by adjustable pads and a hand rest is provided for extra support. The feet are centered over marks set 9 cm on either side of the mid line of the turntable. The feet are aligned in a way that the knee's flexion axis is perpendicular to the sagittal view and parallel to the frontal view. The angle of the foot measured on a protractor scale on the turntable is recorded. Anteroposterior and lateral radiographs are obtained by simply rotating the turntable through 90°.

The hip correction vector was computed from the frontal view radiograph of the hip. A small lead bead was taped over the most lateral point of the greater trochanter. The lead bead is visible on the X-ray, and used to calculate the relationship between the surface marker on the greater trochanter and the hip internal structure. Both the external marker and center of the femoral head are digitized from the X-ray and the distance between the points is calculated using a correction factor to adjust for size. The position of the external marker was corrected in the lateral/medial and distal/proximal directions. No correction was performed in the antero/posterior direction, as the greater trochanter is assumed to accurately represent the hip center.

Hip moments in level walking were obtained using inverse dynamics with a link segment model. The QGAIT system solves the problem at the proximal end of the shank and then the analysis proceeds to the proximal end of the thigh. Therefore, the joint center of rotation of the ankle and knee as well as the hip are needed in the analysis. The QPRs provide the location of the knee center in the frontal, sagittal and transverse planes. The ankle cannot be seen in the QPRs; therefore, the ankle joint center in the frontal plane is defined as the midpoint between the medial and lateral malleolus. A caliper is used to determine the distance between the malleoli. In the sagittal plane, the ankle correction vector is determined based on the foot rotation angle obtained with the subject standing in a standard reference position.

4. Non-invasive methods

4.1. Method 1

Method 1 used the technique developed by Seidel et al. [2] in which the HC location was estimated in the frontal, sagittal and transverse planes based on three pelvic measurements, pelvic width (PW), pelvic height (PH) and pelvic depth (PD). PW was represented by the distance in centimeters (cm) between the right (P1) and left (P2) antero-superior iliac spine (ASIS) (Fig. 1). PH was the perpendicular distance (cm) from the pubic symphysis (P4) to a midpoint of a line connecting the ASISs (P3). PD was represented by the distance in centimeters between the right ASIS (P1) and the respective postero-superior iliac spine (PSIS) (P5) (Fig. 1).

The right leg was the test leg in this study. Three-dimensional coordinates of the five bony landmarks (right ASIS, left ASIS, right PSIS, symphysis pubis, and the right greater trochanter) were obtained using a pen-like digitizing probe of the Optotrak which provides the three-dimensional coordinates of any point touched by the probe tip. These bony landmarks were palpated and marked with a piece of tape that contained an X in the center. Once all five landmarks were identified and marked in a static position, the three-dimensional coordinates of the points were collected with the subject standing and facing the Optotrak camera. Three trials were collected and the average location used in data analyses.

Pelvic width (PW) was calculated using the distance formula:

$$\sqrt{\partial x^2 + \partial y^2 + \partial z^2}$$

where ∂x^2 is equal to $(\mathrm{P2}x - \mathrm{P1}x)^2$; thus:

$$\mathrm{PW} = \sqrt{(\mathrm{P2}x - \mathrm{P1}x)^2 + (\mathrm{P2}y - \mathrm{P1}y)^2 + (\mathrm{P2}z - \mathrm{P1}z)^2}.$$

The same formula was used to estimate PD using the coordinates from points P1 and P5. In order to obtain

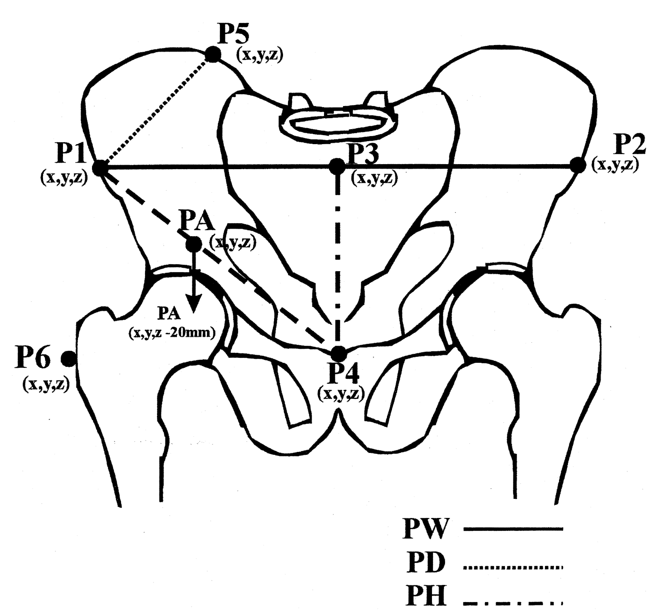

Fig. 1. Schematic representation of the pelvic parameters used to estimate the hip joint center of rotation using the techniques described by Seidel et al. [2], Bell et al. [3,5] and Andriacchi and Strickland [4].

PH, the three-dimensional coordinates of the midpoint (P3) between P1 and P2 had to be calculated. The three-dimensional coordinates of P3 were obtained by averaging the x, y and z coordinates of P1 and P2 as follows.

$$\frac{P1x + P2x}{2} \; \frac{P1y + P2y}{2} \; \frac{P1z + P2z}{2}$$

where $P1x$, $P1y$ and $P1z$ are the frontal, sagittal and transverse coordinates of the right ASIS and $P2x$, $P2y$ and $P2z$ are the frontal, sagittal and transverse coordinates of the left ASIS.

The distance between P4 and P3 was obtained by using the distance formula as previously explained. Once the distances were determined, the predicted location of the right HC in each plane was found by multiplying each distance by the percentage factor determined by Seidel et al. [2]. The right HC was located at 14% of PW medial to the right ASIS, 34% of PD posterior to the right ASIS and 79% of PH distal to the midpoint between the right and left ASIS. The correction vector was then obtained by subtracting the three-dimensional coordinates of the greater trochanter marker from the coordinate of the estimated hip center in each plane.

4.2. Method 2

Method 2 used the technique described by Bell et al. [3,5] that predicted the right HC in every plane as a function of the PW only (Fig. 1). The distance between the right (P1) and left ASIS (P2) and the correction vectors were obtained as explained previously. The HC was located at 14% of PW medial to the right ASIS, 30% of PW distal to the right ASIS and 22% of PW posterior to the right ASIS.

4.3. Method 3

Andriacchi and Strickland [4] stated that the location of the hip center was 1.5–2 cm distal to the midpoint (PA) of a line between the right ASIS and the pubic symphysis in the frontal plane. However, in their study the marker was only corrected in the frontal plane, i.e. corrected medially from the greater trochanter to the point PA. In this study, Method 3 was divided in two parts. Method 3A corrected the hip center in the medial/lateral direction only as reported by Andriacchi et al. [1] and Method 3B corrected the hip center in both medial/lateral and distal/proximal or vertical directions.

4.3.1. Method 3A

Point A was located at the midpoint of a line connecting the right ASIS (P1) and the symphysis pubis (P4) (Fig. 1). The three-dimensional coordinates of the Point A were obtained by averaging the x, y and z coordinates of P1 and of P4 using the formula as explained previously. The external marker on the greater trochanter was also digitized and the three-dimensional coordinates obtained. The distance between the y coordinate of the external marker to the y coordinate of the Point A was obtained by subtracting one from the other.

4.3.2. Method 3B

Method 3B is the same as Method 3A except that the HC location was also corrected in the vertical direction. This technique was accomplished by subtracting 20 mm from the transverse coordinate (z coordinate) of Point A ($PAz = PAz - 20$ mm) to move the HC location inferiorly. The correction vector was then obtained by subtracting the external marker coordinates at the greater trochanter ($P6z$) from the Point A coordinate ($PAz-$ 20 mm).

The knee and ankle center location estimation, when the non-invasive methods were used to calculate the hip moments, was based on the approach described by Andriacchi and Strickland [4]. The knee center correction vector in the medial direction was estimated using a caliper to measure the distance between the medial and lateral margins of the tibial plateaus and identifying its midpoint. The knee correction vector in the vertical direction was determined as the distance from the lateral femoral epicondyle inferiorly to the level of the tibial plateau and the distance between the fibula head marker superiorly to the tibial plateau. The ankle center correction vector was obtained using a caliper to measure the distance between the medial and lateral malleolus and recording the midpoint.

5. Procedure

This study was approved by the Human Research Ethics Board, Queen's University, and 10 subjects signed a consent form prior to participating. The radiographs were obtained first according to procedures previously described. Lead beads were placed over three anatomical landmarks (greater trochanter, lateral femoral epicondyle and head of the fibula) and standardized X-rays were taken with the subjects standing on the turntable.

After the QPRs were taken, the subjects were accompanied to the Motion Laboratory. IREDs were placed over the same anatomical landmarks (greater trochanter, lateral femoral epicondyle and head of the fibula) identified prior to the X-ray. In addition, an IRED was placed over the lateral malleolus, and on the thigh and shank probes. A belt with a strober attached to it was placed around the subject's waist. The strober enables the Optotrak system to automatically identify each marker in real time. A footswitch was then attached to the posterior aspect of the subject's footwear and was used to determine the beginning and end of the gait cycle.

Five trails were collected with the subject walking along a raised walkway that has a force plate embedded into it. The trials were then checked for missing markers and saved.

Once data were collected, static marker location was obtained with subjects standing in a standard reference position. Subjects stood on a turntable identical to the one in the radiology department with their feet at the same angle recorded during the X-ray and the knee flexion axis parallel to the global x-axis. Data were then collected for 1 s.

Once all the equipment was removed from the subject, the five anatomical bony landmarks on the pelvis were identified and digitized using the Optotrak. At the knee and ankle, the distances between the lateral and medial margins of the tibial plateus and the lateral and medial malleolus, respectively, were measured using a caliper. The results were then divided by half and recorded. A tape measure was used to obtain the distance between the lateral femoral epicondyle and the level of the tibial plateau to permit correction of the knee center in the vertical direction. Finally, the anthropometric measurements were obtained.

The correction vectors obtained at the hip, knee and ankle were then added to the database together with the information collected during gait. During processing of the hip moments of force, the appropriate correction vectors are requested and used automatically by the programs.

6. Data analysis

The hip moment profiles in three planes obtained using the four non-invasive methods of HC location were first compared descriptively with the profiles obtained using the QPR correction vectors. The average deviation curve of the difference between each method and the QPR curve was also obtained. This curve quantifies the error of each of the methods relative to the QPR curves.

A 95% confidence interval of the point with maximum difference in the curve between each method and the QPR was also calculated. Statistical software SPSS was used to analyze the data.

7. Results

7.1. Subject characteristics

Data from six male and four female subjects were analyzed in total. The mean age of the subjects was 65.5 years (range = 57–73 years) and the mean weight was 73 kg (range = 51–99 kg). The average distance between the ASISs (PW) was 28.3 cm. The mean distance between the right ASIS and the right PSIS (PD) was 10.7 cm and the average distance between the symphysis pubis and the midpoint of a line between the ASISs (PH) was 15.8 cm. Table 1 shows the average correction vectors at the hip joint using the QPR and the non-invasive methods.

7.2. Descriptive analysis

Fig. 2 shows the hip moment profiles during level walking obtained with the QPR and Methods 1, 2 and 3A and B of estimating the HC. In the frontal plane, Methods 1 and 2 showed greater hip moments of force during the stance phase compared to those obtained using the QPR technique. A maximum difference in peak internal abductor moments of 0.22 and 0.26 Nm/kg between Methods 1 and 2, respectively, and the QPR occurred in the frontal plane at 47% of the gait cycle. Methods 1 and 2 resulted in a small difference in the internal adductor moment of approximately 0.07 and 0.06 Nm/kg, respectively, during the swing phase.

The hip moment profiles obtained using Methods 3A and B showed very small peak moment differences in the frontal plane compared with those obtained using the QPR. Method 3A underestimated the hip moment by a maximum of 0.08 Nm/kg and Method 3B by 0.05 Nm/kg during the stance phase. For both curves, the maximal discrepancy occurred at 46% of the cycle.

In the sagittal plane, all three methods were in close agreement with the QPR. Method 1 underestimated the internal extensor moment by a maximum of 0.08 Nm/kg at 5% of the cycle. The location of the peak internal extensor moment differed between Method 2 and the QPR, occurring at 13% and 5% of the gait cycle, respectively. Method 2 slightly overestimated the internal extensor moment by 0.03 Nm/kg compared to the QPR.

Table 1
Average correction vector (cm) at the hip joint using the QPR and the non-invasive methods

Planes	QPR	Method 1	Method 2	Method 3A	Method 3B
Frontal (y)	9.0	6.4	6.4	9.7	9.7
Sagittal (x)		1.0	−0.5		
Transverse (z)	2.1	−0.007	3.1		2.9

Frontal plane: medial/lateral (medial = $+y$);
sagittal plane: anterior/posterior (anterior = $+x$);
transerse plane: superior/interior (superior = $+z$).

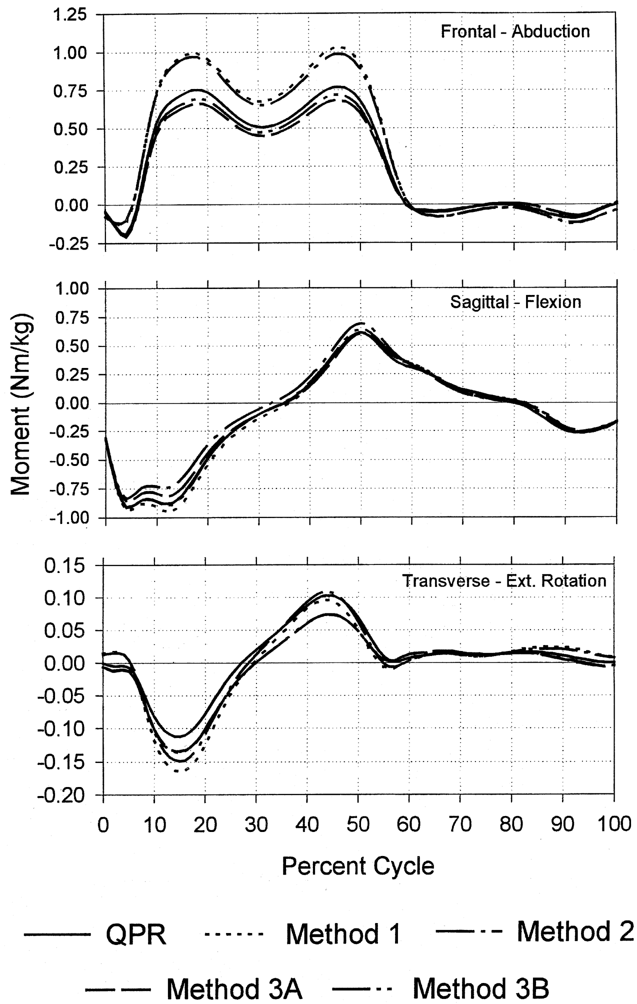

Fig. 2. Graphic representation of the hip movements during level walking obtained with the QPR and Methods 1, 2, 3A and 3B of estimating the hip center.

The peak internal flexor moment comparison showed a slight overestimation of 0.08 Nm/kg during the double support phase (50–60% of the cycle) using Method 1.

The sagittal plane curves for Methods 3A and B nearly overlap each other. Compared to the QPR, Method 3A underestimated the hip internal extensor moment (−0.05 Nm/kg at 5% of the cycle) between heel contact and beginning of the midstance phase. Method 3B slightly overestimates the internal flexor moment (0.03 Nm/kg at 51% of the cycle) at terminal stance.

In the transverse plane, Methods 1 and 2 overestimated the peak internal rotation moments during midstance. The greatest differences in amplitude were observed between Method 2 and the QPR at 16% of the cycle and did not exceed 0.05 Nm/kg. The maximum differences in amplitudes in the transverse plane for Methods 3A and B occurred at 16% and 45% of the cycle, respectively, and did not exceed 0.03 Nm/kg. Table 2 shows the maximal amplitude and location of hip peak moments in the gait cycle obtained using the different methods of estimating the hip center.

7.3. Average error curve and confidence intervals

Figure 3 was obtained by subtracting the average moment curve of the 10 subjects obtained using Methods 1 to 3 from the average moment curve from the same 10 subjects obtained using the QPR. The result is an average error moment curve that quantifies the error of each of the methods relative to the QPR.

In every plane, Methods 1 and 2 display the greatest deviation from the QPR, with marked variability particularly in the frontal plane during the stance phase. Methods 3A and B of estimating the hip center produced the least deviation in moments when compared to the QPR method. In the frontal plane, Method 3B showed the closest agreement with the QPR. In the sagittal and transverse plane, Methods 3A and B showed similar deviations from the QPR.

Table 3 shows the 95% confidence interval for the maximum error difference ($n = 10$) between each method of estimating the HC and the QPR. The differences obtained between Method 3A and the QPR resulted in a

Table 2
Mean maximum hip peak moments comparison between the QPR and the non-invasive methods (Nm/kg, % gait cycle)

Peaks	QPR	Method 1	Method 2	Method 3A	Method 3B
MxAbd	0.76, 47	0.98, 47	1.02, 47	0.68, 46	0.71, 46
MxAdd	−0.19, 5	−0.12, 4	−0.13, 4	−0.20, 5	−0.21, 5
MxFlx	0.61, 51	0.69, 51	0.61, 51	0.60, 51	0.64, 51
MxExt	−0.91, 5	−0.83, 5	−0.94, 13	−0.86, 5	−0.91, 5
MxExtRot	0.10, 45	0.10, 45	0.09, 45	0.07, 45	0.07, 45
MxExtRot	−0.11, 16	−0.14, 16	−0.16, 16	−0.13, 16	−0.13, 16

MxAbd = maximum internal abductor moment;
MxAdd = maximum internal adductor moment;
MxFlx = maximum internal flexor moment;
MxExt = maximum internal extensor moment;
MxExtRot = maximum internal external rotation moment;
MxIntRot = maximum internal internal rotation moment.

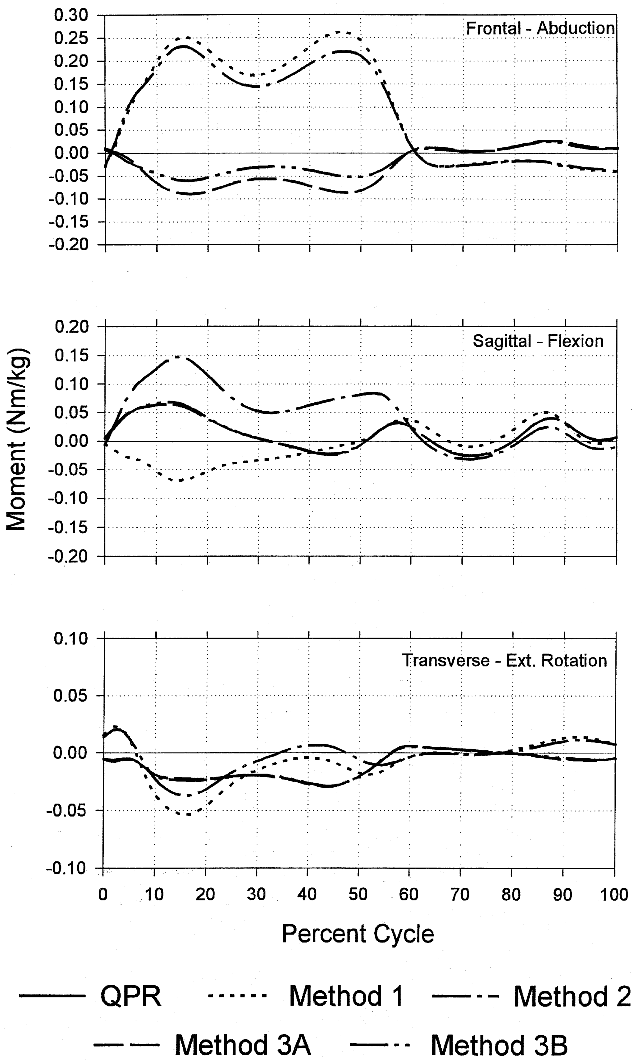

Fig. 3. Graphic representation of the average error moment curve that quantifies the error of each of the methods (1, 2, 3A and 3B) of estimating the hip center relative to the PQPR (X-ray) method.

95% confidence interval that ranged from −0.19 to −0.001 Nm/kg in the frontal plane, 0.03–0.11 Nm/kg in the sagittal plane and −0.05 to −0.03 Nm/kg in the transverse plane. Method 3B and the QPR differences resulted in interval estimations that ranged from −0.15 to 0.04 Nm/kg in the frontal plane, −0.03 to 0.07 in the sagittal plane and −0.05 to −0.03 Nm/kg in the transverse plane.

8. Discussion

Of the non-invasive methods of HC estimation examined in this study, Method 3B appears to be most in agreement with the QPR gold standard technique. Method 3B used the technique described by Andriacchi and Strickland [4] which predicts that the HC would lie 1.5–2 cm directly below the midpoint of a line connecting the ASIS to the symphysis pubis. Method 3A also used the technique by Andriacchi and Strickland [4] but only corrected the HC medially. Correcting the HC medially resulted in greater lack of agreement between the non-invasive methods and the QPR curves in the frontal and sagittal planes and no difference in the transverse plane.

The average medial correction of the external marker on the greater trochanter using Methods 3A and B was 9.7 cm compared to 9.0 cm using the QPR. Thus, Methods 3A and B displaced the HC 0.7 cm on average medial to the true location of the HC. Although, displacing the hip center medial to its true location resulted in lower moments measured in the frontal and transverse planes, the discrepancies were minimal.

The average superior displacement of the marker on the greater trochanter using Method 3B was 2.9 cm compared to 2.1 cm using the QPR. Two errors in palpation were identified using the QPR. The external landmark in one of the X-rays was placed at the same level as the center of the femoral head and in the other it was located well above the greater trochanter. This resulted in inferior correction of the greater trochanter marker by −0.05 cm and −2.05 cm in these two subjects. Displacing the HC superior to its true location had no effect on the moments measured in the transverse plane, but probably contributed to the small discrepancies recorded in the frontal and sagittal planes. Method 3B corrected the hip center medially and superiorly and the overall results were better than Method 3A when compared to the QPR. Therefore, although correction of the hip center in the vertical direction does

Table 3
95% confidence interval of the maximum error difference in moments (Nm/kg) between the QPR and the non-invasive methods (lower limit/mean difference/upper limit) (standard deviation)

Methods	Frontal			Sagittal			Transverse		
	Lower	Mean	Upper	Lower	Mean	Upper	Lower	Mean	Upper
1	0.08	0.24 (±0.21)	0.39	0.02	0.15 (±0.18)	0.29	−0.05	−0.01 (±0.05)	−0.01
2	0.13	0.27 (±0.19)	0.41	−0.21	−0.05 (±0.22)	0.10	−0.07	−0.04 (±0.05)	−0.02
3A	−0.19	−0.09 (±0.13)	−0.001	0.03	0.07 (±0.06)	0.11	−0.05	−0.04 (±0.01)	−0.03
3B	−0.15	−0.05 (±0.13)	0.04	−0.03	0.02 (±0.07)	0.07	−0.05	−0.04 (±0.01)	−0.03

not improve the accuracy of the moments measured in the transverse plane it appears that it results in improvement in the moments obtained in the frontal and sagittal planes.

The 95% confidence interval of the maximum difference between Method 3B and the QPR crossed zero in the frontal and sagittal planes, suggesting that the true differences could be zero. In the transverse plane, although the confidence interval did not cross zero, the interval was small, suggesting that the results were due to the small variability of the individual observations or to a low standard deviation.

Andriacchi and Strickland [4] determined that the error between the surface measurement on the greater trochanter and the actual location of the hip center in the frontal plane using their technique compared to X-rays was ±0.79 cm. Conversely, Bell et al. [3] based on pelvic radiographs and digitization of bony landmarks, determined that the estimated hip center location would be 4.6 cm distal and 1.7 cm lateral to the true HC location using Andriacchi and Strickland approach. Our results do not agree with this finding, as the HC was located only 0.7 cm medial to and 0.8 cm proximal to the true location of the hip center using Andriacchi and Strickland [4] approach.

Discrepancies in moments obtained using Methods 1 and 2 compared to the QPR method are present in all three planes. Methods 1(2) and 2(3) used a fixed percentage of pelvic parameters to estimate the location of the HC in all three planes. The percentages were estimated based on distances between external markers [2,3,5]. The average medial correction of the marker on the greater trochanter by Methods 1 and 2 was 6.4 cm compared to 9.0 cm using the QPR. Thus, 14% of PW placed the HC 2.6 cm an average too far laterally compared to the true location estimated using the QPR method. Displacing the hip center too far laterally affected both the measures in the frontal and transverse planes, with the internal abductor moments being most affected. Methods 1 and 2 generated peak internal abductor moments 16–34% higher than those generated using the QPR, respectively, suggesting that these techniques are not appropriate for locating the HC in gait analysis studies.

Method 1 corrected the external marker slightly inferiorly −0.007 cm on average. Thus, the use of 79% of pelvis height to adjust the marker in the vertical direction did not have a great effect on the position of the external marker in this direction. Method 2, however, resulted in correction of the external marker over the greater trochanter superiorly an average of 3.1 cm compared to 2.1 cm using the QPR. Thus, the 30% of PW used by Method 2 displaced the external marker too far superiorly. Displacing the hip center too far superiorly had no effect on the transverse plane moments measured but affected the frontal and sagittal plane moments, explaining the discrepancies in the internal abductor and extensor moments generated by Method 2.

Bell et al. [3] reported that the error in estimating the HC location using their approach's (Method 2) was probably due to the inaccuracy of estimating the exact location of the bony ASISs from skin markers. Considering that Method 3B also relies on accurate palpation of the ASIS to estimate the location of the HC and results in curve profiles similar in shape and magnitude to those obtained using the QPR, we believe that inaccuracy in palpation does not explain the discrepancies found between Methods 1 and 2 and the QPR. The discrepancies are more likely to be a result of error in the percentages estimated in the studies by Seidel et al. [2] The differences in average marker correction, particularly in the frontal plane between Methods 1 and 2 and the QPR would support this conclusion.

The overall results of this study suggest that Method 3B or Andriacchi and Strickland's [4] approach is a valid technique for estimating the hip joint center of rotation in routine gait analysis. Although Method 3B underestimated the hip internal abductor moment during the stance phase, the magnitude of the error was small. On average, the HC was located 0.7 cm too far medially and 0.8 cm too far superiorly resulting in small discrepancies when compared to the QPR. The technique is non-invasive, low cost, and the overall results are quite comparable to those obtained using the QPR method.

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