Title: Pelvic Orientation for Total Hip Arthroplasty in lateral decubitus: Can it be accurately measured?

Short Title: Pelvic Orientation for Hip Arthroplasty

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Development and validation of the algorithms was carried out at Queen’s University Belfast and the BOTNAR Research Centre. Laboratory work with participants was conducted in the Gait Laboratory in Musgrave Park Hospital.

Pelvic Orientation for Total Hip Arthroplasty in Lateral Decubitus: Can it be Accurately Measured?

Abstract

Introduction

During total hip arthroplasty, accurately predicting acetabular cup orientation remains a key challenge, in great part because of uncertainty about pelvic orientation. This pilot study aimed to develop and validate a technique to measure pelvic orientation; establish its accuracy in the location of anatomical landmarks and subsequently; investigate if limb movement during a simulated surgical procedure alters pelvic orientation.

Method

The developed technique measured 3D orientation of an isolated Sawbone pelvis, it was then implemented to measure pelvic orientation in lateral decubitus with post-THA patients (n=20) using a motion capture system.

Results

Orientation of the isolated Sawbone pelvis was accurately measured, demonstrated by high correlations with angular data from a coordinate measurement machine; R-squared values close to 1 for all pelvic axes. When applied to volunteer subjects, largest movements occurred about the longitudinal pelvic axis; internal and external pelvic rotation. Rotations about the antero-posterior axis, which directly affect inclination angles, showed >75% of participants had movement within ±5° of neutral, 0°.

Conclusion

The technique accurately measured orientation of the isolated bony pelvis. This was not the case in a simulated theatre environment. Soft tissue landmarks were difficult to palpate repeatedly. These findings have direct clinical relevance, landmark registration in lateral decubitus is a potential source of error, contributing here to large ranges in measured movement. Surgeons must be aware that present techniques using bony landmarks to reference pelvic orientation for cup implantation, both computer-based and mechanical, may not be sufficiently accurate.

Pelvic Orientation for Total Hip Arthroplasty in Lateral Decubitus:
Can it be Accurately Measured?

Introduction

Acetabular orientation in Total Hip Arthroplasty (THA) plays a vital role in the success of the operation [Ref]. When malpositioned, adverse effects can significantly compromise patient outcomes [Ref]. Pelvic orientation during surgery is considered to be an important factor in component malposition[1],[2],[3]. Knowing the 3D pelvic orientation and accurately determining cup orientation remains a key challenge. Most cup navigation techniques (both mechanical and computer assisted) are designed for use with patients in lateral decubitus and measure cup inclination angles in relation to a horizontal reference and the use of anatomical pelvic landmarks [Ref]. Large errors may exist in palpation of landmarks due to the surrounding soft tissue. It is difficult to know if the pelvis has been secured by supports in a neutral position prior to surgery, and during surgery further inaccuracies exist due to potential pelvic movement resulting from movement within the lumbar spine rotations or movement relative to the supports.

Movement occurring about the Antero-Posterior (AP) axis of the pelvis has a direct impact on the cup inclination angle achieved[4],[5]. This may leave the implanted component in an unsatisfactory orientation, potentially leading to accelerated component wear, impingement, joint instability and poor patient outcomes[6],[7],[8].

The aims of this pilot study were to assess: 1) If the precise location of an anatomical landmark is known, how accurately can orientation be measured? 2) How accurate is the locating of these anatomical landmarks? and 3) Once the location and orientation of the pelvis has been determined, what effect does limb movement have on the pelvic orientation.

Materials and Methods

The measurement technique was based on the principles of rigid body motion, commonly used for motion analysis. The orientation of the rigid body (pelvis) was represented by an orthogonal right hand system[9]. A rotation matrix represented the pelvis' angular position[10],[11]. This matrix was decomposed to extract and quantify the corresponding Euler angles (α, β and γ), representing the angles of rotation completed by each axis of the rigid body (x, y and z, respectively)[12]. The computations were performed using custom programs written in Matlab (www.mathworks.com, version R2010a, MathWorks Inc., Natick, MA, USA). The 2D rotation angles were calculated about the AP and Longitudinal (L) axis. These 2D angles are projections of the angle onto the plane of rotation.

Anatomical bony landmarks, commonly used for pelvic representation[13], defined the rigid body: Right and Left Anterior Superior Iliac Spines (ASIS; R_{asis} and L_{asis}) and the Pubic Symphysis (Pub_{sym}) together forming the Anterior Pelvic Plane (APP)[6].

A 6 camera video-based motion analysis system (Vicon 612 System, Vicon Motion Systems Ltd., UK), was used to capture the 3D coordinates of the above defined anatomical landmarks using a specially designed pointer[14](manufactured from carbon fibre) with 38mm diameter retro-reflective markers balls (Precision Plastic Ball Company Ltd, UK).

To validate the technique's ability to accurately measure the orientation of the pelvis, 3D coordinates of a Sawbone pelvis (using the same anatomical landmarks), mounted in lateral decubitus, were recorded using a Brown and Sharpe MXCEL PFX 454 Coordinate Measuring Machine (CMM), (Brown and Sharpe Manufacturing Company, USA). Coordinates were used to quantify the orientation of the pelvis in various positions using the routines written in Matlab which were then compared to those angles measured by the CMM's software. Sawbone pelvic orientation was recorded in controlled rotations (2 - 10° in 2° increments) about each pelvic axis; AP, L and Medio-Lateral (ML).

CMM coordinates of the anatomical Sawbone landmarks were input to the custom Matlab routines from which the rotation matrices were computed. Euler angles corresponding to rotations about each pelvic axis were extracted from the matrix. These angles were validated by angles measured within the CMM software. These controlled rotations were again imposed using the Sawbone pelvis in a gait analysis laboratory to establish the accuracy of the pointer using the Vicon 3D motion capture system.

This pelvic measurement technique was further applied in a live subject trial to analyse angular orientations of participants' pelves in three lateral decubitus positions, simulating the different positions patients' limbs are manipulated into during surgery. Full ethical approval was sought and granted from ORECNI (Study Reference: 11/NI/0178).

Subjects consisted of THA patients, (>1year post-operative, n=20). Height, weight, and inter-ASIS distance were recorded. A standard operating table with hip supports was used to simulate an intra-operative setup. Participants were manipulated (as if anesthesised) into three positions: Legs-Extended, Legs-Flexed and Legs-Flexed with upper leg-Adducted with the latter reflecting our usual intra-operative position at the time of cup insertion. At each position, the previously described anatomical landmarks were palpated and measured using the pointer and the motion analysis system. All palpations were performed by an experienced physiotherapist, supervised and trained in the positioning and palpation technique by the consultant orthopaedic surgeon (DEB). Landmark measurement was repeated three times in each position. For the final measurement, participants were asked to lie supine. During initial trials, the Pub_{sym} was not easily palpated in Legs-Flexed and Legs-Flexed with upper leg-Adducted. Attempting to palpate in each position, three times, increased procedure time (45 minutes), beyond what was ethically approved or comfortable for participants. The protocol was changed to exclude Pub_{sym} in lateral decubitus positions. The Pub_{sym} was recorded for each individual whilst supine and then reestablished with respect to the L_{asis} and R_{asis} in lateral decubitus positions. This assumes a minimal change in pelvic flexion/extension which previous intra-operative studies have shown [Ref 3,17]. Statistical tests (PASW Statistics 18, SPSS Inc., USA) involved Pearsons and Spearman's correlation tests. Need to check and then add in which statistical tests were used to look at repeatability.

To relate AP pelvic orientation to the cup's angular position, rotational angles were added (in cases of adduction) or subtracted (for abduction) to a set optimum cup inclination angle. An operative inclination of 40° was selected based on target angles used during intra-operative analysis of cup inclination by Hill et al.[15]. Rotations were also compared to a radiographic inclination of 46°, based on studies demonstrating increased radiographic inclination resulting from cup anteversion[16], which creates an average increase of 6° to the operative inclination[15].

Results

Sawbone Pelvis: Angles measured using CMM (x axis) versus Matlab (y axis) were plotted. Rotations about each axis demonstrated high correlation between the two techniques, $R^2 \geq 0.998$. Comparison of CMM measurements with those made using the motion analysis system and the pointer also yielded high correlations, $R^2=0.996$.

Table 1 Summary of Participant Information

Post-THA Patient Participants: Figures 1 and 2 highlight distribution of participants' pelves about zero rotation (neutral) for pelvic axes (L and AP) at each position (Legs Extended, Legs Flexed and Legs flexed with upper leg Adducted). Analysis of ML Axis movement was not included due to the assumption of the Pub_{sym} location in lateral decubitus.

Figure 1 Distribution of Rotations about the Longitudinal Axis

Figure 2 Distribution of Rotations about the Antero-Posterior Axis

Landmarks measurement was repeated in each position to assess repeatability in the angles measured. Repeated pelvic angles about the L axis were significantly different in both Legs-Extended ($p=0.012$) and Legs-Flexed ($p=0.047$). Repeated angles about the AP axis was not significantly different but still demonstrated variability. Mean range between repeats were calculated for each position about L and AP axes to examine variability. L axis mean ranges; 4.8°±2.5, 4.8°±4.6 and 5.7°±3.6 for Legs-Extended, Legs-Flexed and Leg-Adducted respectively, AP ranges; 5.3°±3.6, 5.5°±3.7 and 8.8°±6.4.

Within this pilot study, the most important rotations to consider were those occurring about the AP axis, since component inclination may be affected by rotations about this axis during surgery.

Table 2 Mean and Ranges of Movement about the AP Axis for all 20 participants

Table 2 highlights absolute angles of AP rotation. On average 40%, 50% and 65% of patients' pelves were adducted; Legs Extended, Legs Flexed and Legs flexed and upper leg Adducted respectively. No trends existed between magnitude and direction of AP rotation and patient BMI or inter-ASIS distance.

The measured relationship between 2D and 3D angles yielded R^2 values of 0.9317 and 1.0000, AP and L axes respectively, demonstrating reliable abstraction of 2D data, relevant to clinical imaging and component placement for surgeons. Clinical measurements defining acetabular and pelvic orientation are often projected angles[16], such as 2D AP radiographs.

Table 3 Effect of Measured Pelvic Movement on an Operative Inclination of 40° and Radiographic Inclination of 46°

Table 3 highlights mean operative and radiographic inclination based on the incorporation of AP rotations. The overall mean operative inclinations are similar to the set value of 40°, large deviations (min and max) are observed at each position.

Discussion

Pelvic orientation intra-operatively has a direct effect on acetabular component orientation when techniques implemented to position the cup rely on external references[4],[5]. The technique presented here, commonly utilised in gait and motion analysis, was applied and validated for the measurement of pelvic orientation in a simulated setting, clinically relevant to THA.

Validation using a Sawbone pelvis yielded high correlations (R^2~1), demonstrating reliability as a very accurate method of determining landmark position and subsequent pelvic orientation. Validation of the pointer using video-based motion analysis also demonstrated high correlations and reliability (R^2=0.996).

Imposed rotations about one pelvic axis did not effect the angular position of the other two axes. A finding in agreement with Zhu et al [17], where changes in pelvic flexion/extension (ML axis) had minimal effect on inclination angles (AP axis). The measurement technique was applied to post-THA patients to assess its accuracy and repeatability when using anatomical landmarks covered by soft tissues. Pelvic orientation in lateral decubitus was measured and the effect of lower limb movement on this orientation was investigated.

In this study, with the same experienced physiotherapist (trained by the operating consultant) palpating the same points, a high degree of intra-position variability existed; mean range between repeats across all positions and axes was 4.4°±4.2. Some participants were more repeatable than others, yet no correlation was found between rotations and patient related factors.

Deviation in pointer position during measurement can be a source of error. A 10mm linear deviation between real ASIS versus registered landmark generates a mean angular error of

2.4°±0.2° (based on mean participant inter-ASIS distance, 242mm±1.7mm within this study). This linear relationship corresponds to measurement errors in the same direction as the L axis of the pelvis. Deviations along the ML axis of 10mm, combined with 10mm palpation error along the L axis, increased angular deviation by 0.1° to 2.5°±0.2° compared to a deviation of 10mm along the L axis alone (2.4°±0.2°).

Large ranges of orientations existed between participants, with no trend identified between pelvic orientation and lower limb position. These ranges are in agreement with previous work[2] [18],[19],[20], but in this study are thought to be compromised by the inaccuracy of repeated measurements at each limb position.

Large orientations about the L axis were observed across all positions, potentially impacting acetabular anatomical anteversion and radiographic inclination[2],[18]. ML axis rotations, effecting operative anteversion, were excluded to avoid inaccuracies based on assumed Pubsym location in lateral decubitus positions. For the AP axis, (influencing cup inclination)[4], ≥75% of participants were within ± 5° of rotation in all positions. Although outliers did exist with larger rotations, which if occurring undetected intra-operatively, could result in dangerously high or low angles of inclination. DiGioia et al.[20] measured AP pelvic movements using computed tomography based CAOS, reporting a range of -9°- +19° before dislocation and -11°- +11° during cup insertion (AP axis). Timperley[19], measured pelvic position using intra-operative radiographs, reported AP ranges of -10°- +5° prior to patients draping (legs flexed) and -2°- +5° after acetabular exposure. Murphy et al.[2] found movements - 11°- +6° post-acetabular implantation, with patients in ‘neutral position’; the authors did not state what this limb position this represented (extended/flexed).

Correlations of 2D/3D angles (AP axis) were used to relate resultant cup inclination angles as clinical measurements, which are often projections onto 2D planes. AP movements generated an apparent mean radiographic inclination of 46.5° (31.2°-62.6°). This compares with Hill et al.[15] reporting 46.9° mean post-operative radiographic inclination (29.0°-59.0°). Hill et al. concluded the pelvis appeared to adduct intra-operatively (mean, 6.9°) with no evidence of abduction. In this study, mean AP movement was 1.2° and 52% of patients were abducted. Some deviations in AP movements are likely to source from landmark registration.

This study performed laboratory simulations of a surgical setup. Factors such as; effect of anaesthetic and movements due to retractors during surgery[18],[19] could not be accounted for. Acquiring sufficient capture of the pointer's marker coordinates was difficult in cases where a camera's field of view was obscured[21]. The rigid body assumption of the pelvis may cause errors through participants moving between measurements, although every effort was made to reduce this. I THINK MENTIONED ENOUGH As this research represents a pilot study with low patient numbers, caution is needed when drawing conclusions from statistical analysis and the presence, or lack of, significant correlation.

The technique using a pointer and a motion analysis system is very accurate in tracking and quantifying orientations of the isolated saw bone pelvis; if the pointer is placed on the same anatomic point, it will reproduce the 3D position with very small error. This relies on knowing and registering the exact position of the anatomical landmark. Applying this technique to post-operative THA patients demonstrated that assuming a neutral pelvic position in lateral decubitus is not valid nor is the registration of anatomical landmarks reliable. This leads to the question: How well can any clinician repeatedly locate a given set of landmarks? In theatre, clinicians position patients on the table using hip supports, relative to where they believe pelvic landmarks to be, thereby creating the pelvic reference plane based on their perception of landmarks' location. This study shows a 'best case' scenario for palpation and registration of landmarks, using the same trained and highly experienced physiotherapist throughout, along with participants at the lower end of the BMI scale typically seen in THA. Even with these favorable conditions, repeatable registration of landmarks in the same position was difficult.

The findings of this pilot study question the accuracy of cup implantation techniques involving palpation and registration of bony landmarks, which may be compromised in cases with excessive soft tissue and where registration is completed in lateral decubitus. Intra-operative techniques dependent on identification of bony landmarks may have considerable error. Computer assisted methods reliant on landmark registration need further risk/benefit analysis as the increased risk, operation time and cost may outweigh the potential gains from a system that may not increase accuracy, but contribute to mal-positioned components. Caution is needed when interpreting any data generated using these landmark palpation techniques.

As registration of patients' pelves was not found to be repeatable, uncertainty remains as to the pelvic orientation when patients are lying in lateral decubitus, and the associated effect of intra-operative limb manipulation on this orientation. The findings of this pilot study have led to the design and development of a Randomized Clinical Trial (RCT) to assess pre- and intra-operative movement of patients' pelves on the operating table and the associated effect on acetabular cup inclination. This pilot study and upcoming RCT aim to contribute to the overall goal of understanding pelvic movement and orientation during cup implantation, which remains crucial to ensuring greater accuracy with respect to cup angles.

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Table 1 Summary of Participant Information

		Age (years)				BMI			
Gender	**N (%)**	**Mean**	**StdDev**	**Min**	**Max**	**Mean**	**StdDev**	**Min**	**Max**
Female	16 (85)	68.9	5.4	58.0	78.0	29.3	4.4	21.3	37.1
Male	4 (25)	72.0	7.0	64.0	80.0	27.7	3.4	23.6	30.6
Total	20 (100)	69.6	5.7	58.0	80.0	28.9	4.2	21.3	37.1

Table 2 Mean and Ranges of Movement about the AP Axis for all 20 participants

	Repeat	Mean (°)	Abduction (°) (Minimum)	Adduction (°) (Maximum)
Legs Extended	**1**	0.1	10.9	13.4
	2	1.4	14.8	4.4
	3	1.0	12.8	9.6
Legs Flexed	**1**	0.9	6.0	5.9
	2	0.3	10.8	15.2
	3	0.8	14.1	7.9
Leg Adducted	**1**	0.2	12.6	11
	2	2.2	5.9	16.6
	3	4.1	3.8	15.6

Table 3 Effect of Measured Pelvic Movement on an Operative Inclination of 40° and Radiographic Inclination of 46°

	Operative Inclination 40°			**Radiographic Inclination 46°**		
	Mean (°)	**Min (°)**	**Max (°)**	**Mean (°)**	**Min (°)**	**Max (°)**
Legs Extended	39.2	25.2	53.4	45.2	31.2	59.4
Legs Flexed	40.1	25.9	55.2	46.1	31.9	61.2
Leg Adducted	42.1	27.4	56.6	48.1	33.4	62.6
Overall	40.5	25.2	56.6	46.5	31.2	62.6

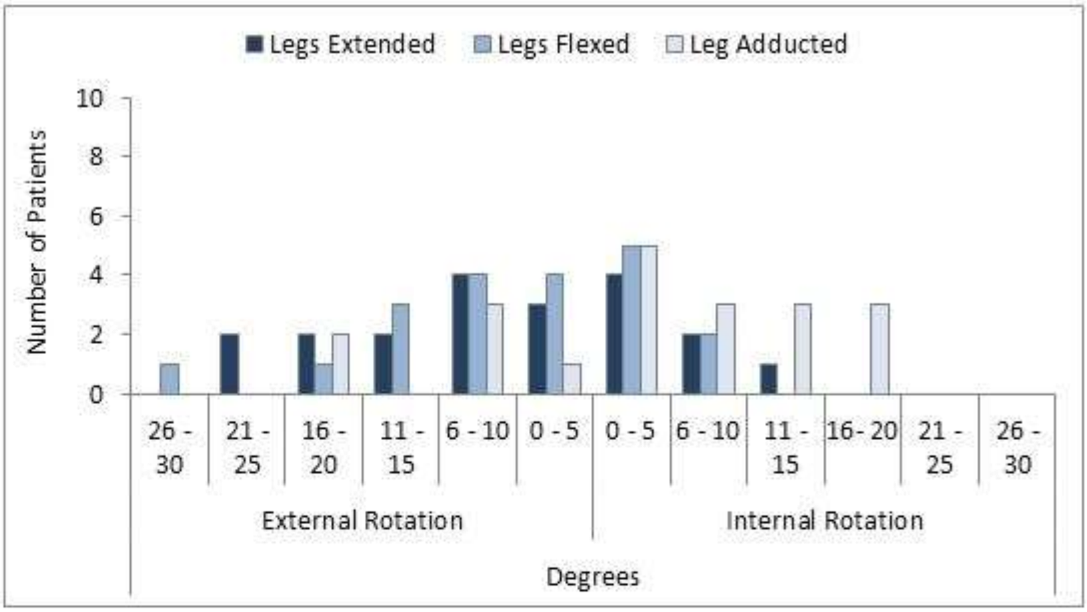

Figure 1

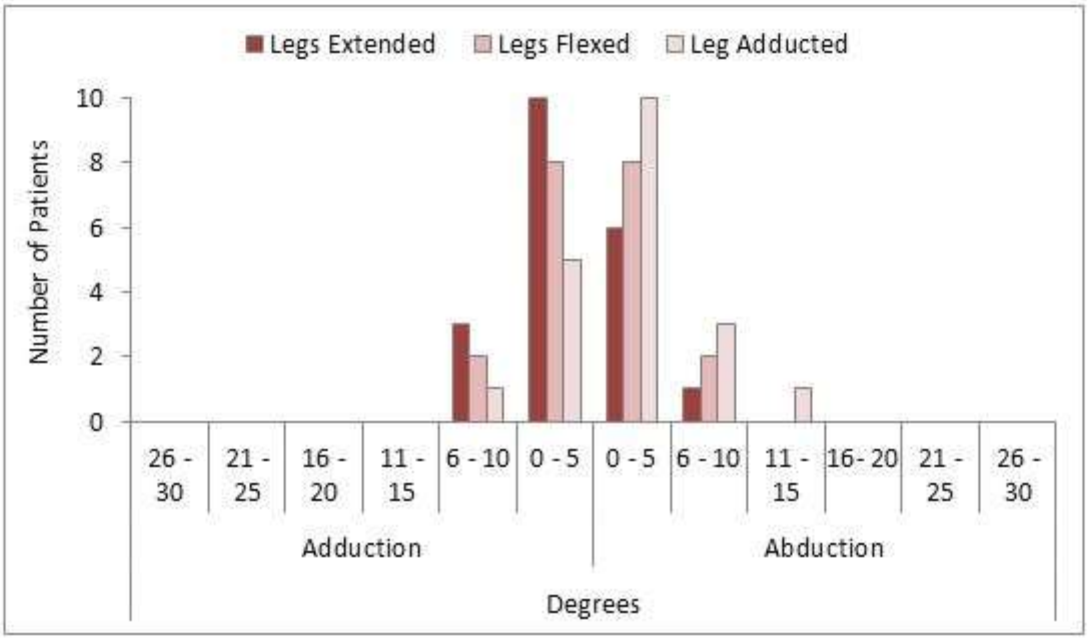
Legs Extended
Legs Flexed
Leg Adducted
Number of Patients
10
8
6
4
2
0
26 - 30
21 - 25
16 - 20
11 - 15
6 - 10
0 - 5
0 - 5
6 - 10
11 - 15
16- 20
21 - 25
26 - 30
Adduction
Abduction
Degrees

Figure 2