The effect of pelvic movement on the accuracy of hip centre location acquired using an imageless navigation system

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Abstract

Objective The aim of this study was to assess the accuracy of an imageless navigation system in localising the hip centre and to evaluate the effect of pelvic movement on the accuracy of hip centre acquisition.

Material and methods A phantom leg was constructed to simulate the hip joint and upper femur. A 3D measurement device was used to measure precisely the co-ordinates of hip centre. A limber link simulated hip motion as used when defining the hip centre during computer-assisted surgery. The data generated by the 3D measurement device and the image-free navigation system was compared with increasing amounts of simulated pelvic movement.

Results For moderate pelvic movement (5 mm) the mean error of the hip centre ranged between 1.5 mm and 3.9 mm with a corresponding angular error of between 0.25° and 0.64°. In conditions of excessive pelvic movement (15 mm) the mean error was 11.7 mm corresponding to an angular error of 1.9°.

Conclusion This in vitro study showed accurate acquisition of the centre of hip with a surgical navigation system. These data suggest that during TKA using this computer assisted navigation system, the accuracy of insertion will not be significantly affected by moderate pelvic movement during data acquisition.

Introduction

The number of total knee arthroplasties (TKAs) performed worldwide is growing considerably, and for the past few years new computer-assisted navigation systems have been developed to help orthopaedic surgeons achieve more accurate prosthetic alignment [1–5]. The PLEOS knee system (Tornier®, Saint-Ismier, France) is image-free and creates the mechanical axis of the femur for femoral component positioning using the “rotational method” [6, 7].

The aim of this study was to assess the accuracy of the system in localising the centre of the femoral head. An independent evaluation of the computer-assisted navigation system using a purpose-built mechanical phantom leg in conjunction with a computerised precision coordinate measuring system was used. The influence of pelvic movement on the accuracy of mapping the hip centre was assessed, as well as how much deviation resulted from this movement when calculating the mechanical axis of the femur. Finally, the results were compared to the accuracy needed in total knee arthroplasty.

Material and methods

This was an in vitro laboratory study, which aimed at determining the effect of pelvic movement on the accuracy

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of hip centre location acquired using an imageless navigation system.

Material

An artificial leg (phantom) was constructed to simulate the upper femur and the hip joint (Fig. 1). The femur was a metal ball attached to an aluminium bar. This was articulated as a ball-joint to simulate the hip. This model allowed circumduction, a crucial movement in computer-assisted surgery (CAS), with 30° in the sagittal plane and 40° in the frontal plane. A sensor device was attached to the model at 35 cm from the hip joint anchored via a pin as used in the CAS system. This was chosen to reflect the mean distance for a normal population between the hip centre and the femoral sensor during surgery. A precision coordinate measurement device (3D Zeiss Spectrum Device, Software Calypso) was used to collect coordinate data on the phantom. This multi-axis, articulated digital calliper has a single-point accuracy of SD 0.003 mm. The computer navigation software and hardware used were the Tornier Hardware (Polaris on a foot stand, PC and a flat-screen, one femoral sensor) and the PLEOS Knee system software.

The model was fixed to the working table of the 3D machine to enable simultaneous acquisition of data with the 3D measurement machine and the navigation system (Fig. 2). The PLEOS camera was set at a distance of 2 m from the model, allowing visualisation of the sensor during circumduction and registration of the movements.

Fig. 1 The simulated femur with the perfect articulated ball joint at one end and the femoral sensor fixed at 35 cm of the joint centre. This model allowed circumduction with 30° in the sagittal plane and 40° in the frontal plane

Fig. 2 The model fixed to the working table of the precision coordinate measurement device (3D Zeiss Spectrum Device, Software Calypso) used to collect coordinate data on the phantom. The PLEOS camera was set at a distance of 2 m from the model, allowing visualisation of the sensor during circumduction and registration of the movements. We were able to acquire simultaneously data with the 3D measurement machine and the navigation system

Methods

Acquisition of the data

First the centre of the sphere (C1) was calculated. The coordinates of the joint centre were acquired using the 3D machine as a reference value. On the precision coordinate measurement device the orthonormed system which applies to the femoral sensor (origin 0, X, Y, Z axes) was defined. Then, using the sensor, the 3D precision measurement device recorded 20 points on the ball-joint surface. Out of these points the coordinate of the centre (C1) of the joint (centre of the sphere) was finally calculated.

Four levels of pelvic movement were tested:

- A level: No movement
With the model leg set to produce only pure ball-and-socket movement it was manipulated by careful circumduction while the navigation system (PLEOS Knee) recorded the tracker positions. Then the computer calculated the hip centre coordinates (CA) with respect to the femoral tracker.
- B level: B1 moderate, B2 severe and B3 critical movement

Hip centre coordinates with 5 mm (CB1), 15 mm (CB2) and more than 20 mm (CB3) pelvic movement were simulated using a limber link (Fig. 3) connecting the femur and the ball joint to the 3D machine. Three different limber links, with three different ranges of

Fig. 3 The model with and without the limber link connecting the ball joint to the 3D machine. This limber link allowed severe movement of 15 mm around the initial position of the joint centre simulating pelvic movement during hip centre acquisition by circumduction of the model

mobility (5 mm, 15 mm and more than 20 mm) were used. The first link used moderate movement of 5 mm around the initial position of the joint centre. The second allowed severe movement of 15 mm. The third allowed critical movement of more than 20 mm.

The circumduction and the movement of the hip centre were recorded using the navigation system (PLEOS Knee) (CB1, CB2 and CB3) in comparison to the orthonomed system.

Procedure

To acquire C1 the simulations were repeated ten times. The mean reference value of the coordinates was calculated with an accuracy within 0.02 mm. CB1, CB2 and CB3 were repeated 100 times. Prior analysis determined that this number of times would give a study power superior to 0.9 in order to identify a statistically significant difference between the coordinates calculated with each procedure and the reference value.

Algorithm principles

1. (C1) The 3D measurement device calculated the centre of the sphere according to the 20 points palpated. The computer then gave the coordinates of the centre of the joint in the orthonormed system for each hip centre acquisition, which was defined previously by the 3D measurement device.
2. (CA, CB1, CB2 and CB3) The computer-assisted navigation system recorded one hundred consecutive positions of the femoral tracker during circumduction of the femur. It then defined the coordinates of the origin of cone, which is an invariant point. The coordinates of this invariant point were those of the joint centre (C).

Accuracy assessment

The coordinates C1 were used as the reference. For each acquisition (CA, CB1, CB2 and CB3) the value of the distance between C1 and C was calculated. This was considered as the error x during acquisition of the hip centre with the PLEOS knee navigation system. The criteria used to define the accuracy of the method was the mean error x (in mm).

The angular error analysis corresponding to an error of x mm for the positioning of the centre of the hip was calculated by the equation $y = \sin^{-1}(x/350)$ where y was the angular error and the femoral length was 350 mm and x the error in mm in the acquisition of the hip centre.

Statistics

The statistical analysis used Minitab software (Minitab Inc). ANOVA was used to compare the quantitative values with the three different pelvic movements. Significance was set at $p < 0.05$.

Results

The results are shown in the Tables 1 and 2. The accuracy of the algorithm to localise the hip centre with no pelvic

Table 1 Accuracy for hip centre acquisition (in millimetres) for each pelvic movement condition. With more than 20 mm pelvic movement, the PLEOS knee software was not able to calculate an invariant point

Pelvic movement	None	Moderate (5 mm)	Severe (15 mm)	>20 mm	<i>P</i> value
Mean error	1.51	3.97	11.66	No data	$P < 0.001$
Standard deviation	0.36	1.20	8.07	No data	
Maximum error	2.10	7.80	30.2	No data	$P < 0.001$

Table 2 Corresponding angular error (in degrees) in the mechanical femoral axis for each pelvic movement condition. With more than 20 mm pelvic movement, the PLEOS knee software was not able to calculate an invariant point

Pelvic movement	None	Moderate (5 mm)	Severe (15 mm)	> 20 mm	P value
Means error	0.25	0.65	1.90	No data	$P<0.001$
Standard deviation	0.06	0.19	1.32	No data	
Maximum error	0.34	1.20	4.95	No data	$P<0.001$

movement had a mean error of 1.51 mm and a maximum error of 2.1 mm. The corresponding error for the mechanical femoral axis was 0.25° (maximum error 0.34°). With moderate pelvic movement the mean error was 3.9 mm with a maximum error of 7.3 mm (Fig. 4). The corresponding error for the mechanical femoral axis was 0.64° (maximum error 1.19°). With severe pelvic movement the mean error was 11.7 mm with a maximum of 30.2 mm. The corresponding error for the mechanical femoral axis was 1.9° (maximum error 4.9°). With critical pelvic movement, the PLEOS knee software was not able to calculate an invariant point. There was a significant difference between the three mobility levels ($p<0.001$).

Discussion

Numerous authors have studied the accuracy of CAS in knee arthroplasty, with very large series of patients [8–12], but to our knowledge, only one publication focuses on the influence of pelvic movement during acquisition of the hip centre [13]. Nevertheless this point is fundamental to the procedure, and a mistake in acquisition may lead to an error in the final positioning of the implant. Moreover, the type of acquisition itself, by mobilising the entire lower limb, necessarily leads to some movement of the hip centre.

Fig. 4 Graph showing the positioning error for each acquisition comparing no pelvic movement with moderate and severe pelvic movement

The centre of the hip is undoubtedly the most difficult landmark to acquire during total knee arthroplasty because of its location deep within the groin. Finding a method capable of locating the centre of the hip is valuable, especially when there is a significant femoral deformity or in obese patients [14, 15]. Marin et al. [7] suggested that the algorithm used for computation is fundamental. They showed that, in contrast to the sphere-fitting method, the minimal amplitude point method permits the evaluation of the rotation centre with an error less than 4.1 mm having a range of motion of 5° . This point was confirmed by our study with an accuracy of 1.5 mm in the no pelvic movement test.

In a study on the acquisition of the hip centre, Picard et al. [16] used the navigation system as the algorithm validation tool by directly palpating the centre of the hip after having divided the femoral head into two. To use the same navigation system as its own control is questionable. For this reason a different, independent system (3D measurement device) was used in this study to assess the precision of the navigation system. Pitto et al. [17] used the same method to assess the accuracy of an infrared CAS navigation system in legs with abnormal mechanical axes and to determine accuracy of CAS based on electromagnetic technology [18].

The circumduction amplitudes were chosen as described by Matziolis et al. [19]. They recommended a ROM of 30 degrees in the sagittal plane and 30 to 40 degrees in the frontal plane during pivoting for maximal accuracy in hip centre determination. In this study a minimal movement model was first used to determine the hip centre with the data in order to study the influence of the actual deviation induced by pelvic movement.

Picard et al. [16] presented a study using seven fresh cadaver hips to assess the reliability of the same algorithm for acquisition of the hip centre with the Orthopilot system. They also used hip circumduction motion during manipulation. The authors only presented angle values and did not focus on the precise coordinates of the hip centre. They demonstrated a satisfactory level of accuracy of the CAS without an iliac tracker giving a maximum error of 0.92° . Our results are similar to this. Our “perfect” model (without movement) showed a maximum error of 2.1 mm (0.34°). This confirms that the algorithm of the system tested has

satisfactory precision in the absence of movement of the centre of rotation during acquisition.

This study assessed the effect of pelvic movement during the determination of the hip centre using a typical knee arthroplasty computer-assisted system. During an operation the pelvis is not fixed to the operating table. It was estimated that movements of the pelvis of 5 mm would be realistic. The results of this study show that in a typical surgical scenario an accuracy of 3.9 mm for the hip centre is likely and corresponds to a mechanical femoral angle error of 1° . With severe pelvic movement (15 mm) where the accuracy for the hip centre was 11.6 mm, the predicted mean error in the femoral mechanical axis was 1.9° with a maximum of 4.95° . The movement of the pelvis and therefore of the hip during the acquisition of the hip centre therefore does influence the measurement accuracy. However, if the movement was less than 5 mm, the angular error was under 1° . This corresponds to the same precision as shown in a fresh cadaver study [14]. Severe pelvic movements on the other hand increase the consequent error and support the robustness of the algorithm. These results are similar to those of Stindel et al. [13]. Using the PRAXIM system they showed an important variation in the precision of acquisition of the hip centre if hip movement varied between 0 and 15 mm; however, the calculated error in the mechanical axis was less than 1° .

To reduce the actual deviation caused by pelvic movement, some authors have assessed the effect of using a pelvic tracker. Mihalko et al. [20] evaluated the use of this algorithm in a comparative study. He showed that measurements with or without a pelvic tracker attached to the iliac crest resulted in statistically significant differences in the sagittal plane measurements. On the other hand, Picard et al. [16] showed that the Orthopilot System, without an iliac tracker, gave accurate and precise determination of the centre of the hip. This study had similar results with acceptable accuracy even in the presence of moderate pelvic movement. This supports the view that a pelvic tracker is not needed with the algorithm used by the PLEOS knee system.

Many studies focus on the precision of the knee arthroplasty with system of surgical navigation [8, 10, 21]. Mason et al. [9], in a meta-analysis of articles published between 2000 and 2006, found 91% of good positioning with a maximum error of 3° , the femoral component being well positioned in 95.1% of the cases with the same criteria. The precision of the positioning of the centre of hip found in our study, even with a moderate movement of the pelvis, had a maximum error of 1.3° which fits well into the margins of error for the radiological measurements quoted in the literature [9].

This in vitro study showed accurate acquisition of the centre of hip with a modern surgical navigation system. The

algorithm used localised the centre of the hip to within 1.5 mm. However, when simulating the necessary pelvic movement that occurs in an operation the true precision was about 4 mm. This amount of deviation is acceptable as it reflects an error in calculating the mechanical femoral angle of less than 1° . These data suggest that during TKA using this CAS system, the accuracy of insertion will not be affected by moderate pelvic movement, but in order to prevent critical pelvic movement, circumduction movement should be limited during acquisition.

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