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Original
Is the acetabulofemoral joint a spherical joint? / Cereatti, Andrea; Donati, M; Margheritini, F; Cappozzo, A.. - In: JOURNAL OF BONE AND JOINT SURGERY-BRITISH VOLUME. - ISSN 0301-620X. - 92:(2010), pp. 311-314. [10.1302/0301-620X.92B2.22625]

Publisher:
British Editorial Society of Bone and Joint Surgery

Published
DOI:10.1302/0301-620X.92B2.22625

Is the human acetabulofemoral joint spherical?

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The human acetabulofemoral joint is commonly modelled as a pure ball-and-socket joint, but there has been no quantitative assessment of this assumption in the literature. Our aim was to test the limits and validity of this hypothesis. We performed experiments on four adult cadavers. Cortical pins, each equipped with a marker cluster, were implanted in the pelvis and the femur. Movements were recorded using stereophotogrammetry while an operator rotated the cadaver's acetabulofemoral joint, exploiting the widest possible range of movement. The functional consistency of the acetabulofemoral joint as a pure spherical joint was assessed by comparing the magnitude of the translations of the hip joint centre as obtained on cadavers, with the centre of rotation of two metal segments linked through a perfectly spherical hinge. The results showed that the radii of the spheres containing 95% of the positions of the estimated centres of rotation were separated by less than 1 mm for both the acetabulofemoral joint and the mechanical spherical hinge.

Therefore, the acetabulofemoral joint can be modelled as a spherical joint within the considered range of movement (flexion/extension 20° to 70°; abduction/adduction 0° to 45°; internal/external rotation 0° to 30°).

The convex femoral head and concave acetabular surface, and the different supporting structures (the capsule, labrum, and ligamentum teres), constrain the relative movement between the femur and the pelvis. Under normal conditions and range of movement, this is assumed to be a pure rotation around a point, named the hip joint centre, resembling an ideal ball-and-socket joint.

Although several authors[1,2] have shown that the shape of the bone within the femoral head deviates from being spherical, a morphology-based point, represented by the centre of a sphere which fits the femoral head, is defined and assumed to coincide with the hip joint centre.[1,2] The latter can be determined by using a functional approach which entails moving, passively or actively, the femoral head relative to the acetabulum, reconstructing this movement using a tracking system and identifying a point which approximates to a centre of rotation using one of the analytical methods proposed in the literature.[3-7]

The hip joint centre is used in analysis of movement of the lower limb to define the anatomical axes of the femur with respect to which hip and knee kinematics are described. It is also used as the point of application of external loads while estimating the muscular moment of the hip.[7-9] Moreover, it is used in alignment of the implant during total knee replacement, in primary and revision hip replacement and for computer-assisted hip and knee surgery.[10-14]

Despite the extensive use of the hypothesis that there is a hip joint centre which is static and around which rotation of the acetabulum and femoral head occurs, we are unaware that there has been a quantitative assessment of this hypothesis in the literature. Our aim was to quantify the hip joint centre using contemporary techniques and identifying translatory component of the relative movement between the femur and the pelvis.

Materials and Methods

Experimental protocol. Experiments were carried out using four intact adult cadavers, three males and one female, with no detectable damage to the acetabulofemoral joints. Two transosseous bicortical pins were implanted in each femur and two monocortical pins placed in each iliac crest. Each steel pin, 6 mm in diameter, was equipped with a cluster made up of four markers 14 mm in diameter (Fig. 1). The minimal distance between two markers of the same cluster was 70 mm. Before inserting the pins into the bones, incisions were made through the skin and soft tissue to reduce the forces applied to the pins.[13]

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doi:10.1302/0301-620X.92B2.22625 $2.00

J Bone Joint Surg [Br]
2010;92-B:311-14.
Received 23 March 2009; Accepted after revision 17 September 2009

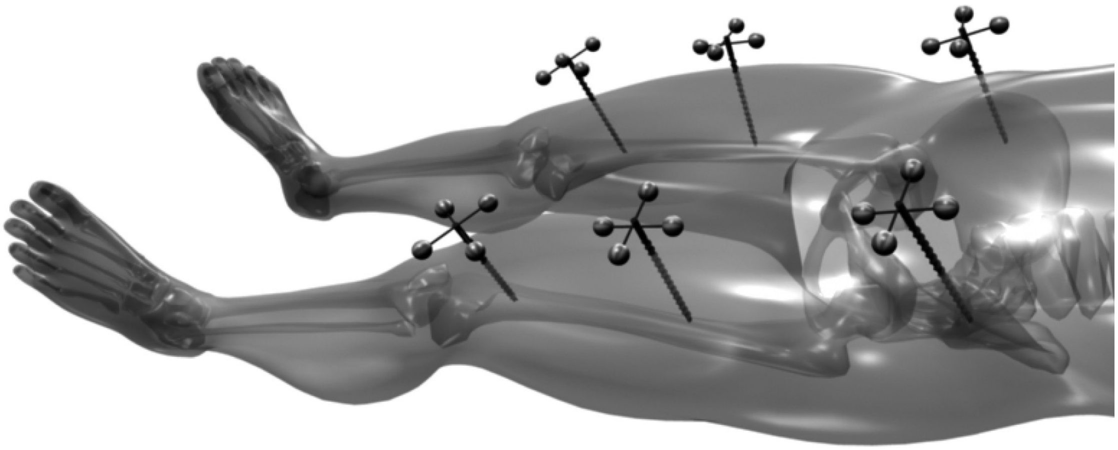

Fig. 1

Diagram showing the configuration of the marker clusters. Two pins were drilled into each bone involved in an analysis, on the iliac crests, and at one- and two-thirds of the length of the femoral diaphysis.

For practical reasons, the cadavers were positioned supine. The instantaneous positions of the markers in a global system of reference were reconstructed using a nine-camera stereophotogrammetric system (VICON MX, resolution 1.3 Mpixels, Vicon Motion System, Oxford, United Kingdom) at a sampling rate of 120 samples per second. The measurement volume was a 1.5 m-sided cube. Recordings were made while an operator (FM) rotated the femur with respect to the pelvis as much as was allowed by the cadaver's position on an examination table. The movements consisted of rotations in the sagittal plane, in a quasi-frontal plane, and in two planes located within the last two planes. This was followed by a half circumduction (Fig. 2). Three trials for each cadaver were recorded.

The effects of the propagation of the stereophotogrammetric errors on the estimates of the centre of rotation were evaluated using a mechanical analogue of the acetabulofemoral joint, which consisted of two metal segments, representing the pelvis and the femur, respectively, coupled through a spherical hinge with virtually no observable play. Each segment was equipped with four markers, located so that their relative distances and their distances from the centre of rotation were similar to those used for the cadaver experiments (Fig. 3). Recordings were obtained from ten trials in which the metal rod was moved with respect to the metal plate, mimicking the hip movement performed on the cadavers.

Analysis. The three-dimensional co-ordinate data were smoothed through approximately third degree polynomials used in a piecewise fashion (cubic splines).[15] The positional vector and orientation matrix of the systems of reference fixed by each marker cluster, and therefore by each bone of interest, relative to the global system of reference, were estimated using a singular-value decomposition technique.[16]

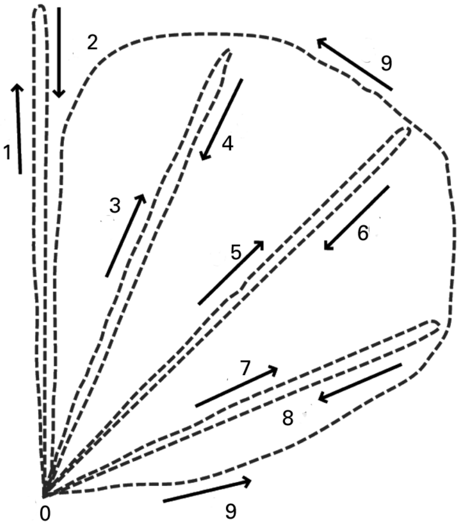

Fig. 2

Diagram showing the trajectory of the lateral epicondyle during movement of the acetabulofemoral joint projected on to the pelvic transverse plane quasiorthogonal to the table. The starting position is indicated by 0 and the direction of progression is shown by the arrows (1 to 9).

The rigidity of the marker cluster-bone coupling was assessed by measuring the relative displacement between marker cluster systems of reference attached to the same bone during the movement. The rest of the analysis was carried out using one marker cluster per bone.[17] The centre of rotation was estimated using the quartic-sphere fit method, proposed by Gamage and Lasenby[4] with the

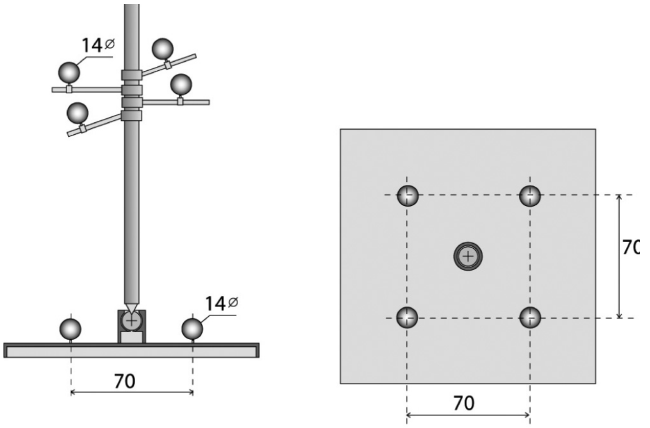

Fig. 3

Diagram showing the mechanical analogue of the acetabulofemoral joint, which consists of a metal rod representing the femur, and a metal plate representing the pelvis, coupled through a spherical hinge. Each segment was equipped with a four-marker cluster. Measurements are in mm.

correction term introduced by Halvorsen.[18] The method was chosen following the suggestions reported in previous studies.[5,19] The algorithm, in principle, determines the hip joint centre as the point belonging to the femur endowed with the minimal displacement with respect to the pelvis during movement.

For each trial, the position vector of the hip joint centre was determined in the system of reference embedded with the pelvis using both marker clusters of the proximal femur (Fig. 1). Each estimate hip joint centre was rapidly associated with the femur when the subject was in the supine position. The position of the latter point, as reconstructed in the system of reference embedded in the hip bone, varied during movement and was described by a set of vectors named c_i ($i = i, .. N$), where $\mathbf{N}$ represented the number of sampled instants of time. The radius r_b of the confidence sphere, containing the 95% of the hip joint centre positions described by $\mathbf{c}_i$, was calculated. The same analysis was carried out for the experiments involving the mechanical linkage, and the radius of the relevant confidence sphere named ($\mathbf{r}_m$).

In a spherical joint endowed with a non-observable play and in the absence of errors, the radius of the aforementioned 95% sphere is virtually zero. Therefore, in the case of the experiments carried out using the mechanical analogue of the acetabulofemoral joint, the magnitude of the radius of the 95% sphere differs from zero exclusively because of the stereophotogrammetric errors affecting reconstruction of the marker position. Thus, the difference between the amplitudes of the radii of the 95% spheres computed on cadavers and on the mechanical analogue, respectively, can be taken as an indicator of the discrepancy of the movement of the reconstructed acetabulofemoral joint from a pure rotation.

Table I. Radius $\mathbf{r}_b$ (mm) of the sphere containing 95% of the positions $\mathbf{c}_i$, for the right and left sides of the four cadavers

		Cadaver			
Side	**Trials**	**A**	**B**	**C**	**D**
Right	1	0.9	0.8	0.8	1.2
	2	0.9	0.6	0.6	1.1
	3	0.8	0.6	0.6	1.1
Left	1	1.0	0.8	1.4	1.5
	2	0.8	0.6	1.2	1.2
	3	0.7	0.6	1.5	1.3

Statistical analysis. Descriptive statistics and SD of the quantites $\mathbf{r}_b$ and $\mathbf{r}_m$ were calculated using Matlab 6.5 software (Mathworks, Natick, Massachusetts).

Results

Assessment of the photogrammetric error. The results relative to the mechanical linkage showed that the mean $\mathbf{r}_m$, computed over ten trial repetitions, was equal to 0.9 mm (SD 0.1). This information indicated that, within the experimental set-up adopted for our study (number and type of cameras, dimension of the measurement volume, marker size, range of movement, distance between markers and centre of rotation), any joint displaying translations not statistically different from those found for the mechanical linkage was perceivably similar to a spherical joint.

Cadaver experimental results. The rotational and the translational components describing the relative movement between marker clusters attached to the same bone (femur and pelvis) had a root mean square value lower than 0.2° and 0.1 mm, respectively.[17]

The values of $\mathbf{r}_b$ for each cadaver and trial are given in Table I. The mean $\mathbf{r}_b$ of the radii of the 95% spheres computed over all subjects and movement repetitions was equal to 1.0 mm (SD 0.1; Fig. 4).

Discussion

In the last two decades, many studies have dealt with the problem of the experimental determination of the hip joint centre.[3,5-7,9,17-29] Others have studied the effect of malpositioning of the hip joint centre both in biomechanical analyses of the joints of the lower limb and in clinical applications.[11,12,14,30-32] Particularly interesting is a study by Karachalios et al[33] which showed that differences as little as 2 mm in the placement of the acetabular component in a total hip replacement could be responsible for long-term, unfavourable, radiological signs.

The basic assumption of all of these studies was that the acetabulofemoral joint behaves, from a kinematic perspective, as a pure ball-and-socket joint. In our study, the limits of validity of the latter assumption have been tested.

The relative movement between pins computed on the selected data set was shown to be negligible, thus assuring the firmness of the pin-bone construct.

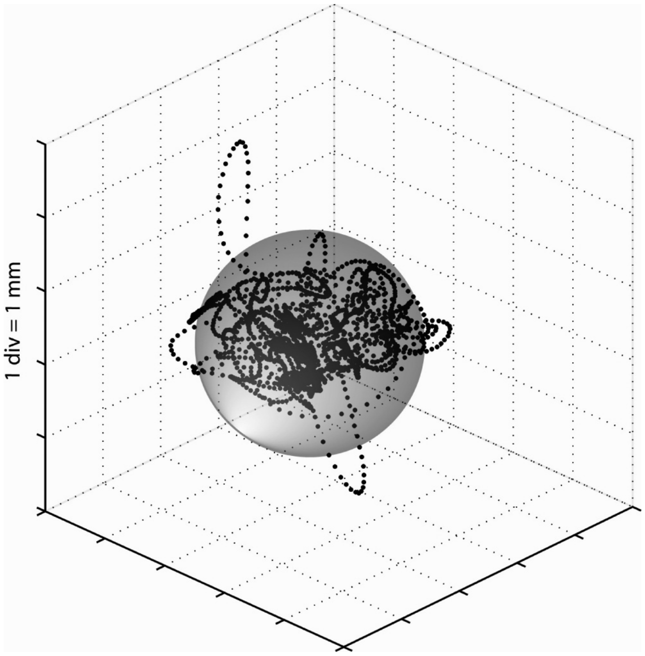

Fig. 4

Diagram of trajectory of point $\mathbf{c}_i$, (black dots) expressd in the system of reference embedded in the pelvis, relative to a trial on cadaver D. The sphere with radius $\mathbf{r}_h$ containing 95% of the positions $\mathbf{c}_i$ is represented in grey.

Our analysis showed that the radius of 95% of the sphere $\mathbf{r}_h$ computed on the human acetabulofemoral joints was, on average, of the same order of magnitude as the radius of the sphere $\mathbf{r}_m$ computed on the mechanical spherical joint (Fig. 4). It is important to reiterate that for a perfectly spherical joint, and in the absence of errors, the radius of the 95% sphere would be zero. The erroneous translational degrees of freedom determined with the mechanical device (virtually pure spherical joint) had the same order of magnitude as that of the acetabulofemoral joints of the cadavers. This implied that the magnitude of the hip joint centre translation, associated with the non-sphericity of the acetabulofemoral joint, was below the resolution of the measurement technique used to observe the phenomenon. We conclude that the acetabulofemoral joint can be modelled as a perfectly spherical joint within the considered range of movement (flexion/extension 20° to 70°; abduction/adduction 0° to 45°; internal/external rotation 0° to 30°), despite the fact that, taking into account the cartilaginous and osseous anatomy, its shape is better described as conchoid.[1]

This work was funded by the University of Rome 'Fore Italico'. We thank Professor P. Paolo Mariani for his advice.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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