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Hip joint centre location: An *ex vivo* study

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ABSTRACT

The human hip joint is normally represented as a spherical hinge and its centre of rotation is used to construct femoral anatomical axes and to calculate hip joint moments. The estimate of the hip joint centre (HJC) position using a functional approach is affected by stereophotogrammetric errors and soft tissue artefacts. The aims of this study were (1) to assess the accuracy with which the HJC position can be located using stereophotogrammetry and (2) to investigate the effects of hip motion amplitude on this accuracy. Experiments were conducted on four adult cadavers. Cortical pins, each equipped with a marker cluster, were implanted in the pelvis and femur, and eight skin markers were attached to the thigh. Recordings were made while an operator rotated the hip joint exploiting the widest possible range of motion. For HJC determination, a proximal and a distal thigh skin marker cluster and two recent analytical methods, the quartic sphere fit (QFS) method and the symmetrical centre of rotation estimation (SCoRE) method, were used. Results showed that, when only stereophotogrammetric errors were taken into account, the analytical methods performed equally well. In presence of soft tissue artefacts, HJC errors highly varied among subjects, methods, and skin marker clusters (between 1.4 and 38.5 mm). As expected, larger errors were found in the subject with larger soft tissue artefacts. The QFS method and the distal cluster performed generally better and showed a mean HJC location accuracy better than 10 mm over all subjects. The analysis on the effect of hip movement amplitude revealed that a reduction of the amplitude does not improve the HJC location accuracy despite a decrease of the artefact amplitude.

1. Introduction

Under normal conditions, the relative movement between the femur and the pelvis is assumed to be a pure rotation about a point named the hip joint centre (HJC) which is used to define the femoral anatomical axes (Cappozzo, 1984). When hip joint kinetics is investigated, again, this joint is represented using an ideal spherical hinge centred in the HJC. External loads are reduced to this point and the relevant intersegmental couple can be interpreted as representing the so-named muscular moment.

Lower limb movement analysis protocols require the determination of the location of the HJC; the high sensitivity of the results of the analysis to the inaccuracy with which this is done is still regarded as a problem seeking a satisfactory solution (Della Croce et al., 1999; Stagni et al., 2000).

The subject-specific location of the HJC can be determined in the laboratory by using a functional approach which entails moving the femur, passively or actively, relative to the pelvis, reconstructing this movement using reflective skin markers in association with stereophotogrammetry, and estimating the relevant centre of rotation using one of the many methods proposed in the literature (Della Croce et al., 2005; Camomilla et al., 2006; Ehrig et al., 2006).

The position of the HJC estimated with the functional method is affected by photogrammetric errors and by the artefacts associated with soft tissue deformation. The soft tissue artefact (STA) is defined as the displacement of the skin where markers are located, relative to the underlying quasi-rigid bone. Normally, this displacement is due to variations of muscular contraction, muscle passive stretching, inertial effects, and skin stretching around the joints involved. However, the low speed characterising the exercise performed for the HJC estimate entails minimal wobbling effects, and the muscular contraction, mainly isometric, entails little superficial movements. The main cause for STA is skin stretching, which may be considered to be related to joint rotations.

In the last decade, a large number of research has tackled, from different perspectives, the problem of the HJC determination based on the functional approach. These studies can be classified

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into three categories depending on the type of data used in the analysis: mathematical simulation studies (Halvorsen et al., 1999; Halvorsen, 2003; Gamage and Lasenby, 2002; Camomilla et al., 2006; Begon et al., 2006; Ehrig et al., 2006), experimental studies that used mechanical analogues (Piazza et al., 2001; Siston and Delp, 2006; Camomilla et al., 2006; MacWilliams, 2008), and experimental studies on human subjects (Cappozzo, 1984; Bell et al., 1990; Shea et al., 1997; Leardini et al., 1999; McDermott and Keane, 2001; Piazza et al., 2004; Schwartz and Rozumalski, 2005; Hicks and Richards, 2005).

In mathematical simulations both bone movement and HJC location are known. The major limitation of this approach is related to the synthetic noise generation. In fact, whereas photogrammetric noise can be effectively modelled as a Gaussian, zero-mean noise (Della Croce and Cappozzo, 2000), the STA components, characterized by complex patterns which vary according to the subject anthropometry and the performed motor task (Cappozzo et al., 1996; Cappello et al., 2005), are difficult to model. This circumstance strongly affects the possibility of translating the relevant findings to reality.

In experimental studies employing mechanical analogues, the HJC location is known, photogrammetric errors are consistent, but STAs still need to be modelled.

Human studies can be further divided into two subgroups: studies where the HCJ location is unknown (Cappozzo, 1984; Shea et al., 1997; McDermott and Keane, 2001; Piazza et al., 2004; Schwartz and Rozumalski, 2005) and studies where the HJC location is known (Bell et al., 1990; Leardini et al., 1999; Hicks and Richards, 2005). In the former subcategory, analyses have to be limited to repeatability evaluation. On the other hand, when the HJC location is known, for example using bio-imaging techniques, information about the method accuracy is made available but the actual bone movement and hence the STAs patterns, which are the major causes of error, are still unknown. For example, the work proposed by Leardini et al. (1999) (11 male volunteers) reported an average HJC error equal to 11.8 (sd = 4.1) mm, whereas in the study of Bell et al. (1990) (7 male volunteers) the average error was equal to 37.9 (sd = 19) mm. The large differences between these studies and the large inter-subject variability in Bell et al. (1990) may be attributed to differences in STA amplitude among subjects. Unfortunately, this hypothesis cannot be verified due to the lack of information regarding the STA patterns.

In the present *ex vivo* study, for the first time to authors' knowledge, both the actual bone movement, the STA amplitudes and the nominal HJC position were known.

Using state-of-the-art equipment, photogrammetric errors propagate to the HJC coordinates and cause inaccuracies in the range 1–5 mm (Piazza et al., 2001; Camomilla et al., 2006). For this specific application, photogrammetric errors are assumed to be negligible with respect to the STAs, but no relevant detailed information has been provided (Siston and Delp, 2006; Camomilla et al., 2006; MacWilliams, 2008).

Given the principles that govern the estimate of a rotation centre, it is reasonable to assume that the larger the hip joint movement, the better the HJC location identification (Piazza et al., 2001); however, on practical grounds, the STA may be expected to increase. Thus, the question arises as to whether the optimal movement amplitude is indeed the largest possible.

In summary, the open questions addressed in this study are the following:

(1) How accurately can the position of the HJC be determined using stereophotogrammetry and skin markers?
(2) What is the relationship between the amplitude of the hip motion and the accuracy with which the HJC location is estimated?

2. Materials and methods

2.1. Experimental protocol

Experiments were carried out on four intact adult cadavers, three males and one female, with no detectable damages to the hip joints. Two pins (transosseous bi-cortical) were implanted into the femur and two (mono-cortical) into the pelvis. Each steel pin (6 mm in diameter) was equipped with a four marker cluster. The minimal distance between two markers of the same cluster was 70 mm. Prior to inserting the pins into the bones, cruciform incisions were made through the skin and soft tissue to reduce forces applied to the pins (Lafortune et al., 1992). In addition, eight markers were glued on the thigh skin along two longitudinal lines in antero-lateral and antero-medial positions avoiding the quadriceps muscle bellies. Using these pins, a proximal and a distal cluster were defined (Fig. 1). The diameters of the proximal and distal section of the thigh (S_p, S_d) were measured for each subject.

For practical reasons, cadavers were made to lie supine on a table. The instantaneous position in a global frame of the markers was reconstructed using a 9-camera stereophotogrammetric system (VICON MX) acquiring at 120 Hz. The measurement volume was a 1.5-m-sided cube. The following anatomical landmarks were calibrated using a pointer equipped with a cluster of four markers: right and left anterior superior spines, right and left posterior superior spines, and right and left femoral epicondyles (Cappozzo et al., 1995). Three trials were recorded for each subject while an operator rotated the right femur with respect to the pelvis as much as allowed by the table. The movements consisted of rotations in the sagittal plane, and in three planes externally rotated about the cranio-caudal axis by about 20°. This was followed by a half circumduction (Fig. 2).

The accuracy of the stereophotogrammetric system (spot check) was determined in terms of the propagation of the instrumental errors to the estimate of the centre of rotation of a mechanical linkage that mimicked the geometry of the pelvis and femur ensemble. The two segments were coupled through a spherical hinge with virtually no play and were equipped with four markers each, located so that their relative distances were similar to those used for the *ex vivo* experiments. Five trials were performed.

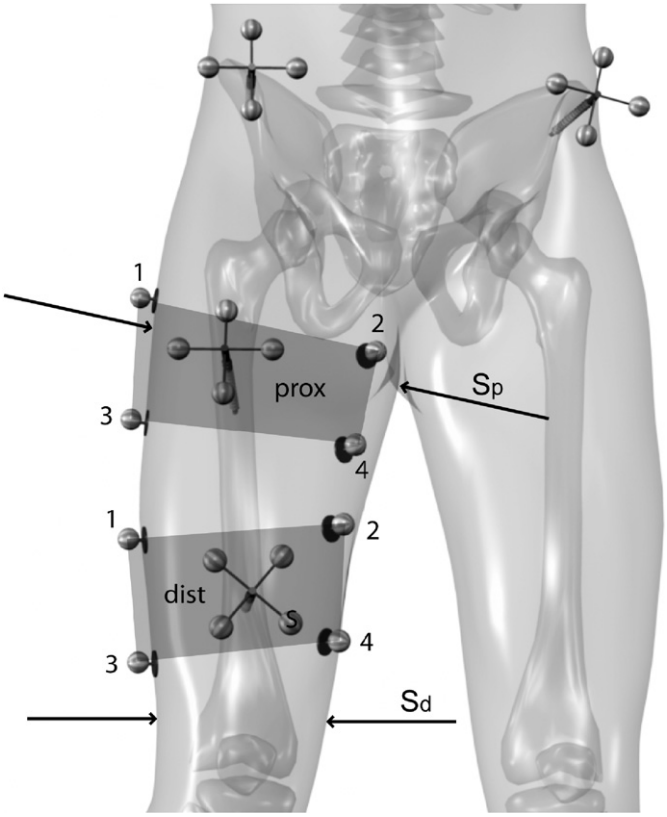

Fig. 1. Pin clusters and skin markers configuration. Two pins were drilled on each bone involved in the analysis: on the right and on the left iliac crest, and at one and two thirds of the femoral diaphysis length. The four proximal skin markers (prox.: 1,2,3,4) and the four distal skin markers (dist.: 1,2,3,4) were used to define the proximal and distal cluster, respectively. S_p, S_d. measured as indicated, represent the diameters of the quasi-circular proximal and distal section of the thigh.