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In-vitro experimental assessment of a new robust algorithm for hip joint centre estimation

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ABSTRACT

Hip joint centre (HJC) localization is used in several biomedical applications, such as movement analysis and computer-assisted orthopaedic surgery.

The purpose of this study was to validate in vitro a new algorithm (MC-pivoting) for HJC computation and to compare its performances with the state-of-the-art (least square approach–LSA). The MC-pivoting algorithm iteratively searches for the 3D coordinates of the point belonging to the femoral bone that, during the circumduction of the femur around the hip joint (pivoting), runs the minimum length trajectory. The algorithm was initialized with a point distribution that can be considered close to a Monte Carlo simulation sampling all around the LSA estimate.

The performances of the MC-pivoting algorithm, compared with LSA, were evaluated with tests on cadavers. Dynamic reference frames were applied on both the femur and the pelvis and were tracked by an optical localizer.

Results proved the algorithm accuracy (1.7 mm ± 1.6, 2.3—median value ± quartiles), reliability (smaller upper quartiles of the errors distribution with respect to LSA) and robustness (reduction of the errors also in case of large pelvis displacements).

1. Introduction

Hip joint centre (HJC), which is assumed to be the centre of rotation of the femur with respect to the pelvis (*ball-and-socket* model), must be computed in several biomedical applications. In gait analysis (Cappozzo et al., 1995; Corazza et al., 2007), HJC computation allows determining the functional reference frame of the femur, so moments acting on the hip joint can be estimated, allowing the assessment of muscles action (Stagni et al., 2006). HJC localization is also a basic step in computer-assisted orthopaedic surgery (CAOS): in total knee replacement (TKA) in order to correctly align the knee prosthetic component in the sagittal plane (Haaker et al., 2006; De Momi et al., 2008; Martelli et al., 2007), in total hip replacement (THA) for positioning the acetabular cup (Jaramaz et al., 1998) and in hip resurfacing for aligning the cap peg to the femoral neck (Barrett et al., 2007).

Different approaches have been so far proposed in literature for the accurate determination of the HJC. In image-based systems, it is manually located in the 3D dataset (Kirkwood et al., 1999). Despite this method represents the gold standard, other less invasive, less time consuming and cheaper procedures are preferred.

Other approaches used regression equations applied to data collected by the palpation of accessible physical landmarks or on medical images. Regression parameters were obtained by specimens of pelvis (Seidel et al., 1995). The mean error in the HJC computation was in the range 25–30 mm when computed on able-bodied adult male subjects (Bell et al., 1990).

Functional methods (kinematic approach) are currently applied for computing the HJC with respect to a pre-defined reference frame. The femur is moved around the pelvis (pivoting) while tracked by a localization system that measures the coordinates of markers (tracker) attached to the limb. Several algorithms have been so far proposed in literature to estimate the HJC from the obtained dataset and are referred as "sphere fitting algorithms". One of these methods is based on a quadratic best fitting procedure (Cappozzo, 1984; Piazza et al., 2001), a second one uses a quartic best sphere fitting procedure (Gamage and Lasenby, 2002) and a third method determines the HJC using the planes perpendicular to the markers trajectories (Halvorsen et al., 1999). All those methods showed to be very noise sensitive for small ranges of motion. In order to decrease such sensitivity to

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noise, an improvement of the sphere fitting approach based on evolutionary computation was proposed (Cerveri et al., 2005). All these approaches require an initial guess followed by an optimization procedure in order to compute the mobile centre of the sphere described by the femur around the hip joint. Despite they proved to be computationally efficient, matching the operative procedures requirements, they still lack any in vitro or clinical validation. Recently, almost all these sphere fitting methods were tested on the same laboratory conditions, showing great repeatability and accuracy around 1 mm (Camomilla et al., 2006; Ehrig et al., 2006).

A source of systematic error in HJC localization is represented by the pelvis motion during pivoting. To reduce the effect of such errors, a least square approach was proposed (Piazza et al., 2004) and was experimentally validated in laboratory, simulating the hip joint with a mechanical link (Siston and Delp, 2006). Although results indicated better performances with respect to previous methods and synthetic noise was added to data in order to simulate the operating room conditions, the actual pelvis motion during the surgical procedure was not taken into account.

In their work, Milhalko et al. (2006) demonstrated that the insertion of a pelvic tracker did not significantly improve the TKR prosthesis alignment. Even if a pelvic tracker may increase surgical morbidity, they suggested using it for checking the motion of the pelvis and repeating the pivoting when large standard deviations were detected.

Although Krackow et al. (1999) assumed that a normal range of motion (ROM) of the hip joint is required for assessing HJC, it was recently demonstrated (Schwarz et al., 2005) that limitations in the hip joint ROM has no influence on the accuracy of its localization as long as the pelvis is still.

In this frame, this paper proposes and assesses a new functional algorithm using a Monte Carlo-inspired optimization strategy for the HJC computation (MC-pivoting). During pivoting, the HJC, seen as the femoral point around which the femur rotates, does not (ideally) move with respect to the femur reference frame (Marin et al., 2003; Stindel et al., 2005; Picard et al., 2007). Noise and pelvis displacement make it move, but, reasonably, with the smallest trajectory length with respect to the any other point. The algorithm, exploiting this latter constraint, was validated through cadaveric tests where trackers were fixed both on the femur and on the pelvis. The data were acquired during kinematic tests.

2. Materials and methods

2.1. The algorithm

MC-pivoting searches for the point of the femoral bone running the minimum trajectory length during pivoting. This point is computed by minimizing the following cost function (f):

$$f = \sum_{i=1}^{N} \| TR_{Femur_{i+1}} \cdot cl_{i+1} - TR_{Femur_i} \cdot cl_i \| \tag{1}$$

where cl_i is the vector of the coordinates of the HJC in the femoral reference frame at time sample i and matrix TR_{Femur_i}(Fig. 1) is the orthonormal transformation describing the position of the femur in the absolute reference frame at ith time sample (from 1 to N) during pivoting.

The initial guess, cl_0, was computed using the algorithm proposed by Siston and Delp (2006) (called Siston&Delp, hereafter):

$$\begin{bmatrix} L \\ S \end{bmatrix} = \begin{bmatrix} -L_x \\ -L_y \\ -L_z \\ S_x \\ S_y \\ S_z \end{bmatrix} = \begin{bmatrix} M_{Rotation_1} \\ \vdots \\ M_{Rotation_{N1}} \end{bmatrix}^{-1} \times \begin{bmatrix} Translation_1 \\ \vdots \\ Translation_N \end{bmatrix} \tag{2}$$

where L and S represent the HJC, in the femoral and the absolute reference frame respectively, $M_{Rotation\_\_i}$ is the rotation part of the femoral reference frame and $Translation_i$ is its translation part, both with respect to the absolute reference frame. Three spheres of different radii (10–30 and 50 mm) were built around the starting guess and those points were used as different starting points for the optimization procedure (these points can be considered close to samples of a Monte Carlo simulation in which each point is the result of a different noise vector superimposed on the correct model) (Fig. 2).

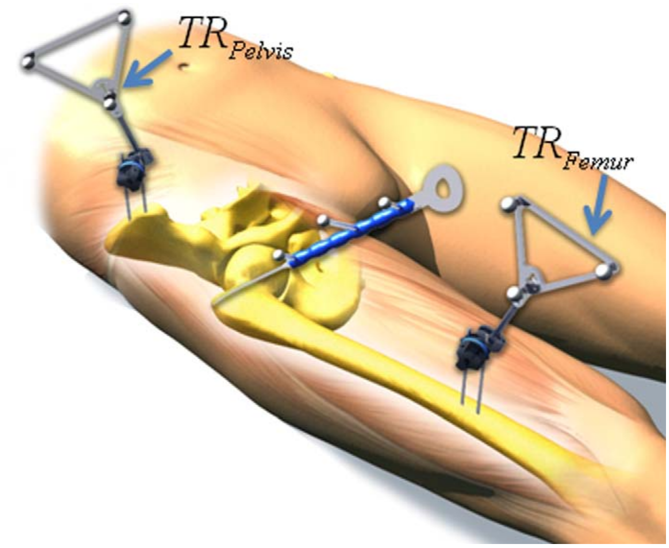

Fig. 1. Reference frames, tracked by the optical localization system, were attached on both the pelvis and the femur (TR_{Pelvis} and TR_{Femur}, respectively).

MC-pivoting was coded in Matlab 7.6.0 (The MathWorks, Inc. Natick, MA, USA). The minimum of the cost function was searched by the Levenberg Marquardt algorithm stopped after 50 iterations. The minimum of obtained minima was considered the HJC best estimate.

2.2. The experimental protocol

Four fresh-frozen normal cadaveric hemi-corpse specimens (3 males and 1 female, aged 72 ± 21 years) were provided by the Stanford University Medical Center (Stanford, CA, USA). The four pelvis bones, complete with both lower limbs, were used for eight hip analyses.

All hips underwent magnetic resonance imaging to assure the absence of arthritis, significant soft tissue pathology or previous surgery. The limbs were sectioned at the level of the knee joint, thus having complete specimens from the upper iliac crest (entire pelvis) to the distal part of the femur (femoral condyles). Thus, ranges of motion at hip level were independent of tibial position. All specimens were thawed 24 h prior to testing. Each specimen was placed on and fixed to a wooden support with eight threaded Steinmann pins passing through both iliac bones in order to stabilize the pelvis structure. The wooden support was fixed to a sturdy table by adopting heavy duty “C” clamps. The wooden support and pelvis were affixed to the end of the table, stabilizing the pelvis, but allowing unrestricted motion of the hip and femur. Residual movements of the pelvis were allowed in order to mimic real operating room situation, i.e. possible pelvis displacements due to the manoeuvres, as it was seen from the tracker trajectories. Left and right hips were alternatively analyzed for each specimen before changing the setup.

A system for intra-operative kinematic assessment (BluIGS/KLEE, Orthokey, Delaware), based on an optical localizer (Polaris, NDI, Waterloo, Ontario, Canada) with stated accuracy of 0.3 mm, was used to acquire the kinematic and anatomical data (Martelli et al., 2007). In order to track the relative motion between femur and pelvis, a tracker with passive optical markers was mounted on the iliac crest (TR_{Pelvis}), on the side of the analyzed hip, and another tracker was fixed on the femoral diaphysis (TR_{Femur}), about 10 cm distal to the lesser trochanter toward the anterolateral femur (Fig. 3).

The femur was passively circumducted around the hip by a trained orthopaedic surgeon experienced with surgical navigation systems. Repeated acquisition trials were performed, those with less than two-third of valid data were discarded (Table 1). During such movements, the 4 × 4 transformation matrices of the two trackers were collected at 60 Hz frame rate for 3 s.

2.3. Data analysis

In order to compute the gold standard position of the HJC in the femoral reference frame, the movement of the femur (TR_{Femur_i}) was corrected for the

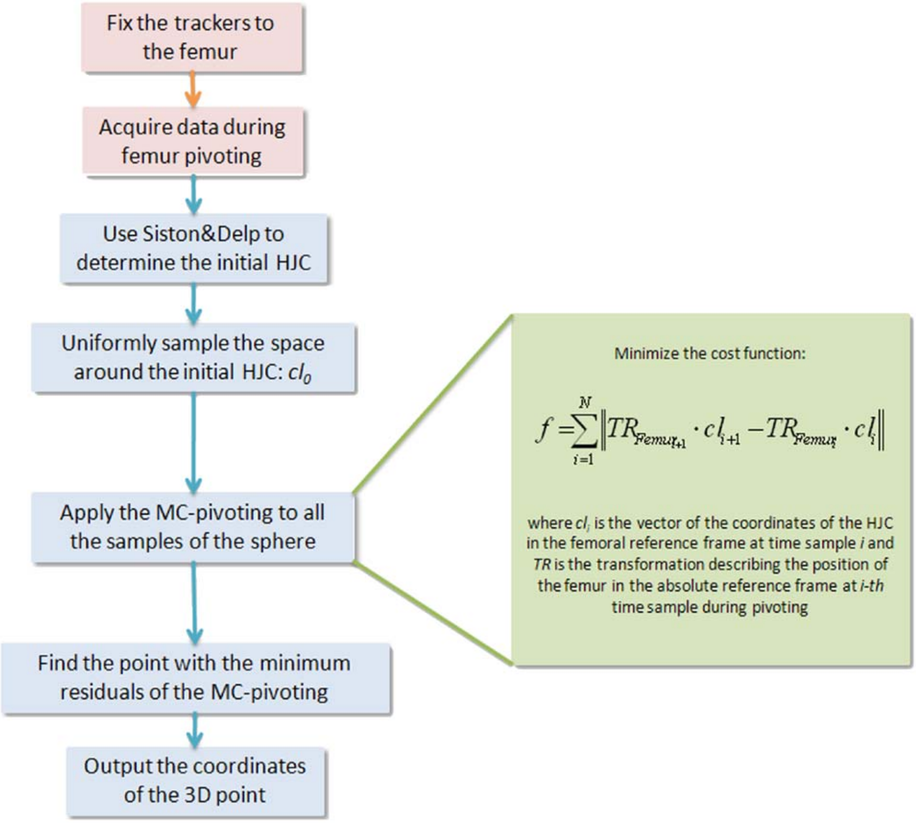

Fig. 2. Workflow of the proposed algorithm.

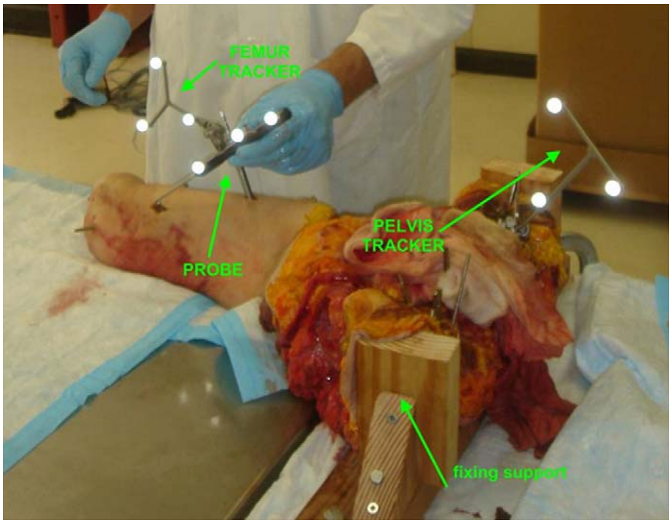

Fig. 3. Experimental setup. The trackers and a digitizing probe are visible, together with the cadavers fixation device.

movement of the pelvis (TR_{Pelvis_i}) for each frame i ($i = 1 \ldots N$)

$$TR_{Femur-Pelvis_i} = TR^{-1}_{Pelvis_i} TR_{Femur} \tag{3}$$

The obtained dataset $TR_{Femur-Pelvis_i}$ represents the better estimate of the movement of the femur as if the pelvis was kept fixed during the pivoting. The estimate HJC position for each trial (21 trials, Table 1) was computed by applying the MC-pivoting and Siston&Delp algorithms to the obtained dataset. HJC positions computed with the MC-pivoting algorithm were used as reference since it produced better results for both algorithms, when applied a posteriori to acquired data with moving pelvis, thus demonstrating higher signal to noise ratio.

Errors ($e_j j = 1 \ldots M$) were computed as Euclidean distances between the gold standard and the computed centres

$$e_j = \sqrt{(x_j - x_T) + (y_j - y_T) + (z_j - z_T)} \tag{4}$$

where $[x_j \; y_j \; z_j]$ are the HJC coordinates computed with each algorithm (Siston&Delp and the MC-pivoting algorithm) in each repetition and $[x_T \; y_T \; z_T]$ are the coordinates of the gold standard HJC for each trial.

Statistical analysis of the results was performed with a non-parametric test (Mann–Whitney U Test—Statistica 7.0, StatSoft Inc., Tulsa, OK, US) since data distribution was not normal being it a distribution of Euclidean distances. A statistically significant result was given a $p \leqslant 0.05$.

In order to analyze the relationship between the femoral movement and the pelvis movement and possible dependencies of the algorithms performances with them, the femur movement range was expressed as the spatial angle between the two furthest positions reached by the femoral tracker during the pivoting, while the pelvis movement was computed as three times the standard deviation of the displacement (98th percentile of the samples) of the coordinates of the centre of mass of the pelvis tracker.

Linear regression was computed between the femur and the pelvis movement.

Pearson correlation coefficient was computed between:

- errors computed with the Siston&Delp algorithm and the pelvis movement;
- errors computed with the MC-pivoting algorithm and the pelvis movement;
- errors computed with the Siston&Delp algorithm and the femur movement; and
- errors computed with the MC-pivoting algorithm and the femur movement.

p-Values were computed for testing the hypothesis of no correlation against a non-nil correlation. If the value of p is less than 0.05, then the correlation is significantly different from zero.

3. Results

Fig. 4 shows the median (±25th and 75th percentile) values of the errors for each one of the two algorithms. MC-pivoting allows estimating the HJC with an accuracy of 1.7 mm as median value

Table 1
describes how the data were grouped: pivoting repetitions are reported for each cadaver.

Cadaver	1			2		3		4			5		6			7			8		
Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Number of repetitions	52	26	31	39	39	40	39	44	24	45	40	93	40	47	47	39	48	41	38	44	41

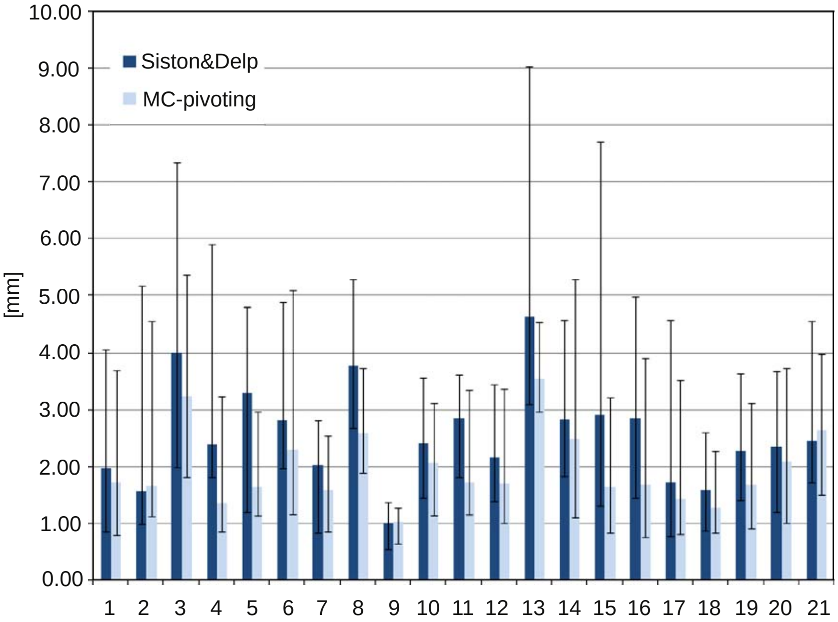

Fig. 4. Median (±25° and 75° percentile) values of the errors for each one of the two algorithms analyzed (Siston&Delp and MC-pivoting) for each one of the 21 trials. Stars (*) indicate that the statistical difference is significant.

(±1.6, 2.3 mm) in all the repetition of the 21 trials, while Siston&Delp accuracy is 2.41 mm as median value (±2.03, 2.85 mm).

As shown in Fig. 4, in 6 out of 21 trials MC-pivoting proved (statistical significance highlighted by ‘*’) to have better performances with respect to Siston&Delp, with a reduction of the median error value of 1.13 mm (median of the 6 trials). Although the performances of MC-pivoting are worse in 3 trials, these differences are not statistically significant ($p > 0.73$), so Siston&Delp never encompassed MC-pivoting. MC-pivoting lower quartiles are indeed smaller, except in 4 trials, and the upper quartiles are lower in all the trials but three.

The measured mean pelvis movement range was around 5 mm and reached up to 20 mm as maximum value. The measured femoral movement range was around 30° and reached up to 60° as maximum value.

Fig. 5 shows the pelvis t (y-axis) versus the femur ranges (x-axis): the line slope is negative (−0.059) and the fitting was not significant in 10 cases out of 21 (95% confidence level).

Fig. 6 shows the PC index computed between the pelvis range and the median values of the HJC computation errors:

(1) *Siston&Delp/Pelvis* is the PC index between the range of the displacement of the pelvis and the errors of the Siston&Delp algorithm;
(2) *MC-pivoting/Pelvis* is the PC index between the range of the displacement of the pelvis and the errors of the MC-pivoting algorithm.

In Fig. 6, one can see that in case of the Siston&Delp algorithm, there is a positive correlation between the range of movement of the pelvis and the median errors in the computation of the HJC. This indicates that unwanted displacements of the pelvis worsened the algorithm performances (the correlation is significantly different from zero in 8 cases out of 21).

In contrast, MC-pivoting is less significantly affected by the pelvis movements indicating that larger movement affects lesser the results. In 5 cases out of 21, the correlation coefficient was significantly different from zero and negative, indicating the larger the pelvis movement, the smaller the error.

Fig. 7 shows the PC index computed between the femur range of movement and the median values of the HJC computation errors:

(1) *Siston&Delp/Femur* is the PC index between the range of the femur and the errors of the Siston&Delp algorithm;
(2) *MC-pivoting/Femur* is the PC index between the range of the femur and the errors of the MC-pivoting algorithm.

In Fig. 7, one can see that there is a significant negative correlation between the range of the femur and the errors in the median of the HJC computation, indicating that large ranges decrease the error in general. That index is lower comparing the Siston&Delp algorithm with respect to MC-pivoting, indicating that, in our case, larger movements improve the results.

4. Discussion

In this paper we introduced a new algorithm for determining the HJC using kinematic data. This new iterative algorithm

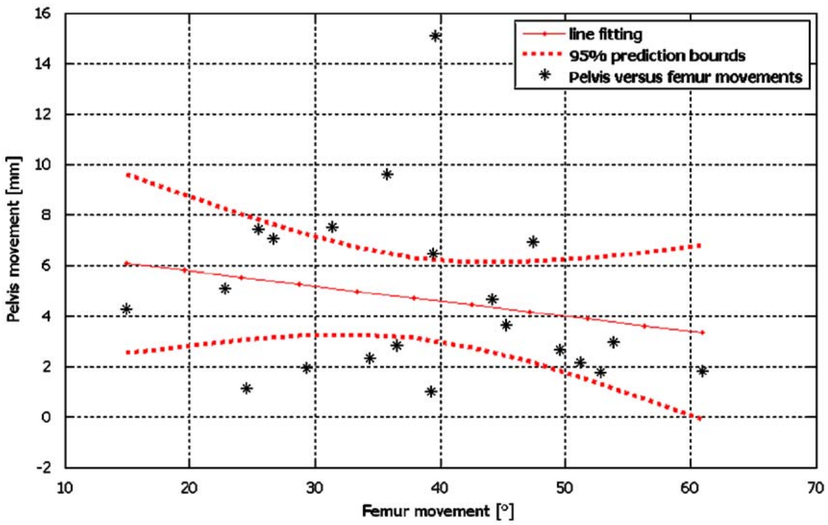

Fig. 5. Pelvis movement (*y*-axis) versus femur movement (*x*-axis). The black line indicates the linear regression, dotted lines the confidence interval at 95%.

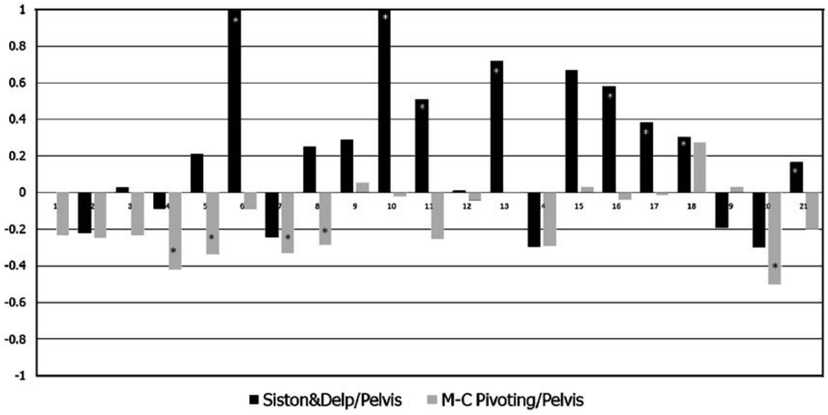

Fig. 6. Bar chart of the Pearson correlation index between the pelvis range and the median values of the HJC estimation errors computed with the two algorithms (Siston&Delp and MC-pivoting), (*) indicates the correlation is significantly different from zero.

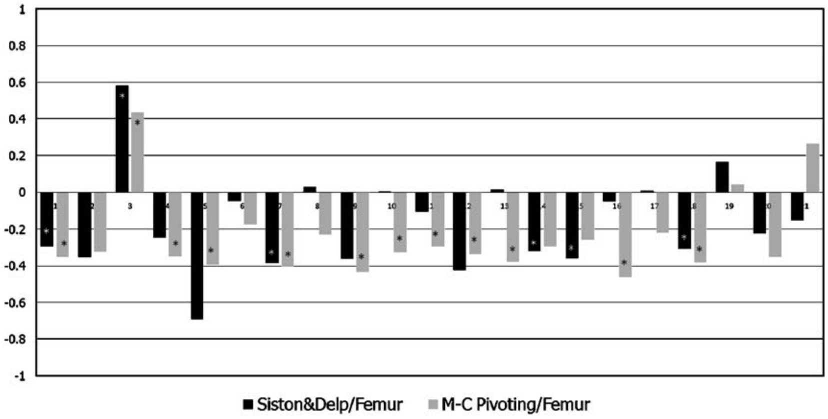

Fig. 7. Bar chart of the Pearson correlation index computed between the femur range and the median values of the HJC estimation errors computed with the two algorithms (Siston&Delp and MC-pivoting), (*) indicates the correlation is significantly different from zero.

searches for the point of the femur with the shortest trajectory in space during pivoting. Data input are the (4×4) transformation matrices of the femoral reference frame computed by the localization system with respect to absolute reference.

Errors computed by MC-pivoting algorithm have the same order of magnitude of the ones reported by Picard et al. (2007), but the authors, who used a sort of "minimal amplitude" method, complained the algorithm was not stable when the pivoting angle was large, this did not happen here. Compared to the algorithm of Siston and Delp (2006), MC-pivoting proved to perform significantly better in six out of the 21 experiments performed, while in the others there was not any statistical difference, even if

MC-pivoting performances were qualitatively better (except 4 non-significant cases). Apart from three cases (out of 21), the upper quartiles are always smaller, indicating the MC-pivoting algorithm is more reliable, presenting less outliers.

The errors observed with both algorithms, were one order of magnitude greater than the localization errors of the optical system used (0.3 mm), which therefore could be considered negligible.

Apart from Picard et al. (2007), the literature only reports evaluation studies performed on mechanical linkages. Those studies, despite providing the exact location of the HJC (computed with the accuracy allowed by the optical localization system), do not allow for simulating the real operator environment since the simulated motion of the pelvis is far away from being real. Indeed, in order to evaluate the algorithm's sensitivity to noisy data, Siston and Delp (2006) added random errors (amplitude ranges between 5 and 30 mm) to the measured position of the femoral reference frame, but the actual noise is not additive, since the movement of the pelvis can also strongly depend on the movement of the femur, as asserted by (Picard et al., 2007). Our analysis showed there is not any linear dependence among the ranges of the two movements: in 10 out of 21 cases the relationship was out of the boundary of 95% of the linear model (Fig. 5) showing that the surgeon imposed a great movement of the femur, without perturbing significantly the position of the pelvis. Further analysis is therefore required in order to deepen the knowledge of the relationship between femoral and pelvis displacements during pivoting.

Other works proved their algorithms accuracy in laboratory tests only, with ad hoc developed mechanical linkage (Camomilla et al., 2006). Even if it allows one to establish the "true HJC", provided the accuracy of the measurement technique, this situation does not definitely mimic the actual pelvis movement during the pivoting of the femur. Least square approaches accuracy is overestimated in such cases, because they do not simulate realistic surgical conditions.

Differently, using cadavers, as in this work, allows simulating surgical conditions, performing different trials on the same subject and positioning a reference frame also on the pelvis, which is currently avoided in clinical practice. The performed experiments showed that the larger the femur movement (larger angles of movement), the smaller the error in the HJC computation. The MC-pivoting algorithm is more sensitive to the femur movement, but being the median value of the pivoting range in our experiments less than 30°, it can be applied also to pathological limbs, where the range of motion could be restricted.

As demonstrated by Milhalko et al. (2006), without tracking the pelvis movement, although errors increased of 4 mm, differences resulted in sagittal misalignment of the mechanical axis by only 0.3° in extension, with no statistically significant difference in the coronal plane alignment. However, while such errors minimally affect measurements in orthopaedic surgery, the impact on biomechanical modelling of the hip joint is clearly evident. As expected, large displacements of the pelvis affect significantly the result of Siston&Delp algorithm. On the contrary, the correlation coefficient for the MC-pivoting algorithm is close to zero, or slightly negative (Fig. 6), indicating that the method is more insensitive to pelvis motion during the acquisitions.

Unwanted displacements between the actual HJC and the pelvis (e.g. due to the ball being levered out of the socket) were not monitored, therefore the computed gold standard could have been affected even if cadavers used did not present hip pathologies. Nonetheless, this source of noise cannot be reproduced with synthetic added noise. The motion of the pelvis on the table was not controlled, but it mimics the actual OR conditions.

Results were affected by the cadavers treatment: the absence of the leg may have affected the femur movement due to the absence of the bi-articular musculature. Also, the way the pelvis was fixed (inside the wooden support, since the torso was missing) does not simulate the true physiological conditions. Anyway both tested algorithms were put in the same testing conditions.

Further research will be directed towards the analysis of the motion of the pelvis in the 1000 trials constituting our dataset. Future work will be addressed to build a model of the hip joint in order to allow compensating the pelvis motion with Kalman filters (non-linear extended) with the aim of overcoming the statement of Stindel et al. (2005) that the displacement of the centre of rotation during the acquisition motion cannot be modelled.

Conflict of interest statement

All authors disclaim any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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