Which method of hip joint centre localisation should be used in gait analysis?

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ABSTRACT

Accurate localisation of the hip joint centre is required to obtain accurate kinematics, kinetics and musculoskeletal modelling results. Literature data showed that conclusions drawn from synthetic data, adult normal subjects and cerebral palsy children may vary markedly. This study investigated the localisation accuracy of the hip joint centre against EOS. The EOS system allowed us to register the hip joint centres with respect to the skin markers on standing subjects. A comprehensive set of predictive and functional calibration techniques were tested. For the functional calibration techniques, our results showed that algorithm, range of motion and self-performance of the movement were factors significantly affecting the results. Best results were obtained for comfortable range and self-performance of the movement. The best method in this scenario was the functional geometrical sphere fitting method which localised the hips 1.1 cm from the EOS reference in average and 100% of the time within 3 cm. Worst results for functional calibration methods occurred when the movement was assisted with a reduced range of movement. The best method in this scenario was the Harrington et al. regression equations since it does not rely on a functional calibration movement. Harrington et al. equations put the hips 1.7 cm from the EOS reference in average and 97% of the time within 3 cm. We conclude that accurate localisation of the hip joint centre is possible in gait analysis providing that method to localise the hip joint centres are adapted to the population studied: functional geometrical sphere fitting when hip calibration movements are not a problem and Harrington et al. predictive equations otherwise.

1. Introduction

Movement analysis based results depend on one critical step, calibration of the model to the external markers or sensors used to track the movement. The hip joint centre (HJC) is a major feature to localise precisely because of its influence on both kinematics [1] and kinetics [2]. It will also have a major influence on any subsequent musculoskeletal computations [3].

The hip is a ball and socket joint with the centre of the femoral head coinciding with the centre of the acetabulum. This leads to two possible approaches to define the HJC; the predictive method uses anthropometric based regression equations to estimate the position of the HJC, the functional calibration method infer the HJC position from the movement of the thigh with respect to the pelvis during calibration trials. Although extensive research has been conducted in this area, it is still unclear which approach should be preferred in which situation.

Many studies on functional calibration implementations were based on synthetic data [4], or cadaveric based simulation [5]. Only a small number of studies have validated their results against a medical imaging reference [6–8]. Results from these studies often contradicted those from synthetic data [9].

Two recent studies [9,10], found different results although the same sets of predictive equations and functional algorithms were compared. The only differences between those studies were the population assessed and the conditions of the functional calibration trials. In the first study, an asymptomatic population was assessed and the functional movement was performed by the subject with comfortable range of movement amplitude (ROM). In the second study, patients with cerebral palsy were assessed. Due

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to the inability of all patients to perform the functional movement, the patients were supported by a bike frame for stability, the movement was assisted by a third person and it was performed with smaller ROM.

The goal of this study was to compare the accuracy of a range of HJC localisation approaches against a medical imaging reference. Various experimental conditions for the functional calibration trials were implemented and compared in order to generalise the conclusions for different uses of gait analysis.

2. Material and methods

Approval from the appropriate ethics committee was received and 17 subjects study gave their informed consent to participate in this study. Demographics included 12 males and 5 females with an average height of 1.74 m (range: 1.55–1.84 m), weight of 74.8 kg (range: 54.3–101.8) and BMI of 25 (range: 17–33).

The subjects' lower limbs were equipped with 31 light reflective markers on the pelvis, thighs and shanks according to the schematics in Fig. 1a.

The medical imaging reference for this study was obtained from EOS [11,12]. Bi-plane EOS images of the lower limbs (pelvis to feet) were taken while the subject stood still with feet slightly shifted [13] (Fig. 1b). Full EOS acquisition required about 12 s to complete. For localisation of the HJC, a sphere was fitted in the least square sense to the contour of the femoral head region thus allowing location of the head centre in the EOS coordinate system. Positions of the markers were determined by manual retro-projection and adjustments on both images of a 14 mm marker model. The pelvic and thigh markers were localised on both images by an experienced operator. A three-dimensional (3D) model of the femur was fitted to the EOS images in order to obtain co-ordinates of the femoral head. The femoral head was defined as the HJC. The pelvic markers (i.e. left and right ASIS and PSIS) were used to define a pelvic co-ordinate system following the convention in [14] and co-ordinates of the HJC within the pelvic co-ordinate system were obtained. These co-ordinates, HJC_{EOS}, served as a benchmark to compare all subsequent estimates of the HJCs.

The static calibration and functional calibration movements were performed immediately after the EOS acquisitions, without removing external markers. The functional calibration consisted of a star-arc movement [15]. To study the effect of reduced range of movement (ROM); the movement was performed with a comfortable ($>30^{\circ}$) or reduced amplitude ($<30^{\circ}$). To study the effect of the inability to perform the calibration movement; it was performed with and without the assistance of a third person. To avoid occlusion of the markers and skin artefact, a stalk was strapped to the subjects' ankle and the operator used the stalk to manoeuvre the leg. Combinations of the two above variations led to four different calibration movements: assisted or self-performed and comfortable or reduced amplitude.

Data from the functional calibration movements were processed according to 4 published methods [4,9] and using a subset of three or the full set of six markers to track the thigh segment. Two methods belonged to the sphere fitting family, Geometrical [16] and Algebraic [17] and two belonged to the transformation family, CTT [Centre Transformation Technique, [18]] and SCORE [4]. All were processed in Matlab (MathWorks, Natick, MA, USA) according to the procedure detailed in [9].

Two predictive methods of locating the HJC were also compared to the EOS reference positions. The first (subsequently denoted *PIG*) is derived from the work of Davis et al. [14]. The anthropometric measurements used included the distance between the left and right anterior superior illiac spines (L/R ASIS) and leg length. The second method (reported by Harrington et al. [[19], using full equations on p. 599] and denoted as *HAR*) is the most recent, and uses measures of pelvic width, depth and leg length.

Co-ordinates of the HJCs from all functional and predictive methods were expressed in the same pelvic co-ordinate system, i.e. based on the four external pelvic markers, as for HJC_{EOS}.

2.1. Statistical analysis

The linear distance between the functional HJCs and HJC_{EOS} were calculated. These results were analysed through a general linear model ANOVA with the following fixed effects: number of thigh markers (3, blue or 6, red and blue in Fig. 1a), functional method (geometrical, algebraic, CTT and SCORE), movement amplitude (comfortable or reduced), movement performance (self-performed or assisted) and subject ID as the only random effect.

Bonferroni simultaneous tests and grouping analysis were performed post hoc in order to determine the differences between methods at $\alpha < 0.05$. All statistical analyses were performed in Minitab® (State College, USA).

3. Results

Functional calibration ranges of movements (ROM) were greater for self-performed than for assisted movements. Flexion-extension, ab-adduction and rotation range were 43(SD: 10), 32(5) and 24(5) respectively for the self-performed comfortable amplitude movement down to 27(7), 21(4) and 17(5) for the self-performed reduced amplitude. Assisted movements flexion-extension, ab-adduction and rotation range were 30(5), 25(4) and 16(4) for the comfortable amplitude and 20(3), 18(3) and 13(3) for the reduced amplitude.

Results from the general linear model ANOVA (Fig. 2) regarding functional models linear distance to EOS showed that number of markers had no significant

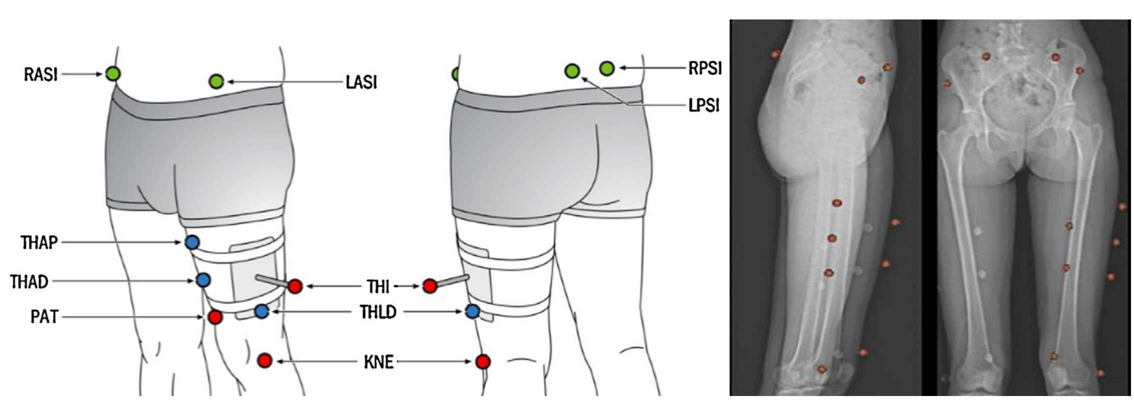

Fig. 1. (a) Marker set definition. Markers displayed in green were attached to the pelvic segment; 3 markers in blue and 3 in red were attached to the femoral segments. (b) Stereographic EOS images of the pelvis and femur displaying the motion capture markers. (For interpretation of the references to color in this legend, the reader is referred to the web version of the article.)

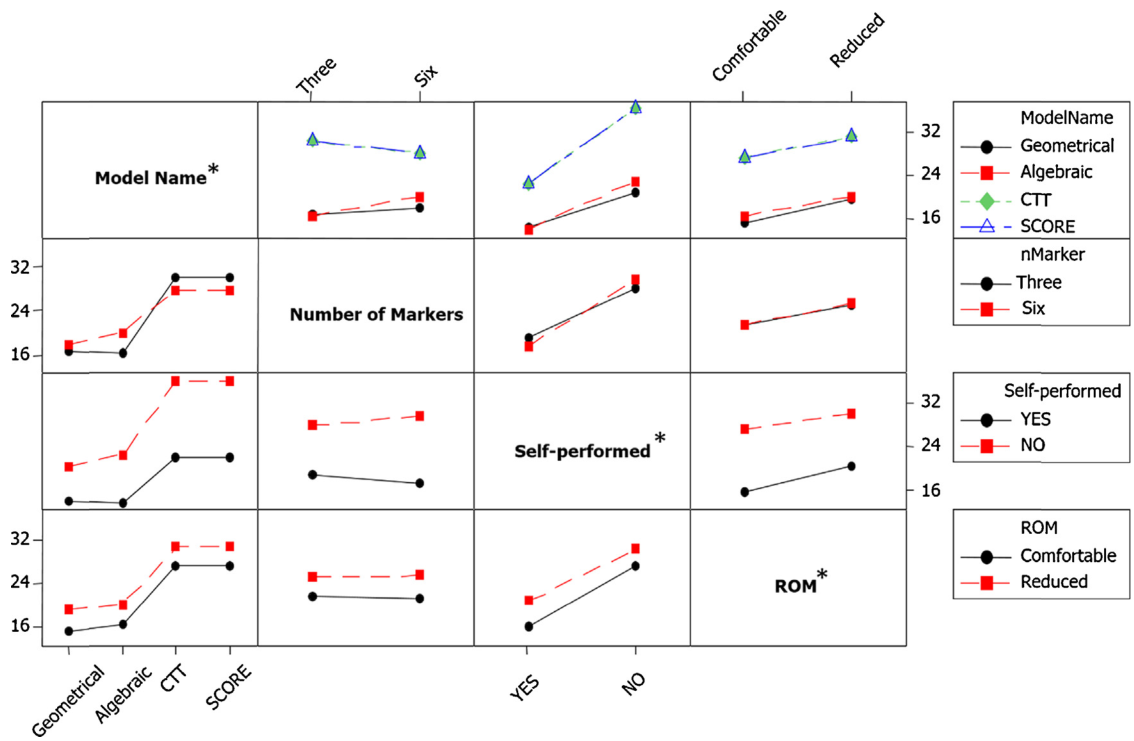

Fig. 2. General linear model ANOVA effect matrix applied to the linear distance between the functional methods HJC to the EOS benchmark. Significant effects at $\alpha < 0.05$ are specified with *.

influence on the results whereas the method, the movement amplitude and assistance of the movement were all significant effects. Sphere fit methods (geometrical, algebraic) were significantly closer to the EOS reference than transformation techniques (CTT, SCORE). Self-performed movements were significantly closer to the EOS reference than assisted movements and comfortable amplitude calibration movements were significantly closer to the EOS reference than reduced amplitude ones.

Since assisted movements tend to have smaller ROM and in order to isolate the movement assistance factor, the reduced amplitude self-performed movements and comfortable amplitude assisted movements results were tested against each other. Those two conditions had ROMs that were not significantly different but the linear distances to the EOS reference was significantly greater for the assisted movements ($p < 0.001$).

Results for two extreme case scenarios, derived from the statistical analysis, are presented below. It is important to note that these case scenarios only apply to functional calibration methods since PIG and HAR methods do not rely on functional calibration movements. Results from non-significant effects (i.e. number of markers) were averaged. Best results (i.e. closest to the EOS reference) were obtained for the large amplitude and self-performed calibration movements (Fig. 3) whereas worse results were obtained for small amplitude and assisted movements (Fig. 4). On both Figs. 3 and 4, the same PIG and HAR results are displayed to allow easier comparison between methods. In clinical studies the proportion of cases falling within a given threshold is an important measure of reliability. In Figs. 3 and 4, the threshold was set to 30 mm [20]. In the most favourable case scenario, 68% per cent of results were below 30 mm for PIG, 97% for HAR, 100% for sphere fitting techniques (both geometric and algebraic) and 85% for transformational techniques. In the least favourable case scenario, results for functional calibration methods dropped to 88% and 72% for sphere fitting techniques (respectively geometric and algebraic) and only 25% for transformational techniques.

Bonferroni grouping in the best case scenario led to both functional sphere fitting techniques performing significantly better than the HAR predictive method. CTT/SCORE functional methods were in the third group and PIG in the last group. In the worst case scenario, HAR predictive and Geometrical functional sphere fit were the leading methods and all other methods were grouped together after.

4. Discussion

This study investigated the accuracy of a comprehensive set of methods for the localisation of the HJC against a medical imaging reference, EOS. From the literature, it was expected that the experimental conditions of the functional calibration trials would impact the accuracy results. Methods type and implementation as well as assistance of the movement and ROM amplitude were tested. All had significant effects except the number of thigh markers used by the functional calibration algorithms. We also found that self-performing the calibration movement improved the results of the functional calibration methods independently of the ROM amplitude ($p < 0.001$). Soft tissue artefact may affect the marker sets differently when the movement is self-performed or assisted. Muscle tone may be absent when the movement is assisted whereas increased when self-performed. Our results indicate that soft tissue artefact has a lesser effect on marker sets when there is some muscle tone. We speculate this relates to the marker sets static calibration during which the subjects were actively standing.

Two extreme case scenarios, i.e. self-performed at comfortable amplitude and assisted with reduced amplitude were analysed. These scenarios correspond well to different uses of gait analysis. The first case applies to sport's research or clinical research where patients do not present hip problems or pain and do not have motor control impairments. Examples of such cohorts are athletes, patients with knee osteoarthritis, patients following knee reconstruction surgery and patients with knee prostheses. Some of the results for this case scenario can be compared with data found in the literature and Table 1 presents results describing the linear distance to the medical image reference. Apart the first study of Bell et al. [6], results were consistent with the accuracy of functional sphere fitting techniques between 1 and 1.3 cm, and predictive methods around 3 cm or 1.7 cm depending on the equations, respectively Davis et al. [14], and Harrington et al. [19]. These consistent results demonstrate that the functional sphere fitting hip calibration method performs better than any other method and provides good estimation of the HJC location when participants can comfortably self-perform the hip functional movement.

Comparison of the difference in co-ordinates between the localisation methods and the reference is also possible with Leardini et al. [7] and Sangeux et al. [9]. Such a comparison remains

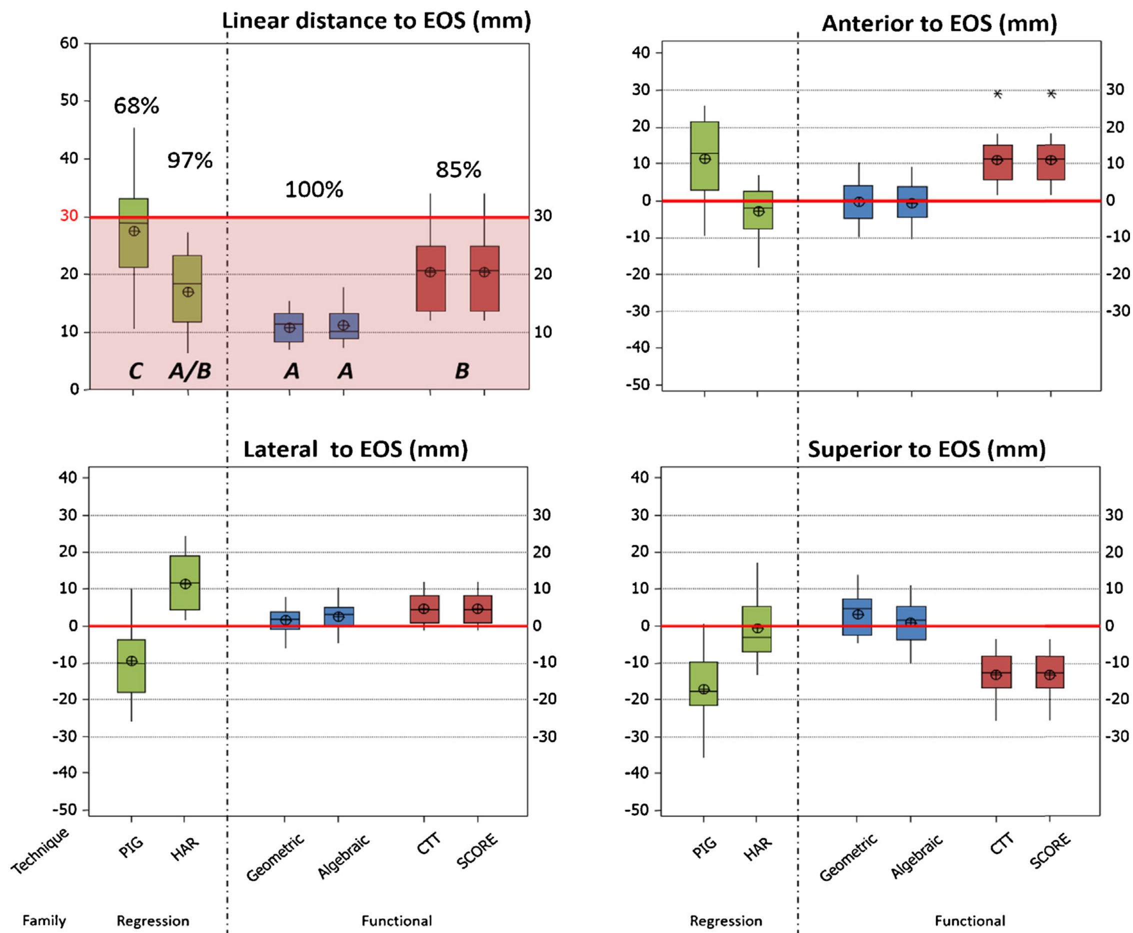

Fig. 3. Linear distance and co-ordinates difference (x, anterior; y, lateral and z, superior) results for the best case scenario (i.e. no assistance and comfortable ROM). Proportion of data below a 30 mm threshold is specified at the top of the linear graph. Bonferroni grouping results ($\alpha < 0.05$) are specified at the bottom of the linear graph. Each letter specifies a statistically separate group.

difficult since the results are expressed in a pelvic co-ordinate system which is directly dependent upon pelvic marker placement. Since the compared data were collected from different centres with different operators, marker placement difference may affect the comparison of results. Comparison with Leardini et al. should also take into account the difference in the name of axes and direction. However, all three studies were in overall agreement for PIG (too anterior, medial and inferior to the medical imaging references) and sphere fitting functional technique (slightly too posterior, lateral and inferior to the medical imaging reference). The second case scenario, assisted with reduced amplitude, mainly applies to patients with motor control impairments such as patients with cerebral palsy or hip problems such as hip pain, hip osteoarthritis or femoral acetabular impingement. In this second case, we found that Harrington et al. equations perform better than any other method. The accuracy, about 1.7 cm on average, remains close to the best functional method in the ideal condition, 1 cm. Comparison with the literature in this case is only possible with Peters et al. study [10], although the authors measured the accuracy directly on young cerebral palsy patients whereas this study only simulated equivalent difficulties (assistance and reduced ROM) for the calibration trials on adult subjects. Peters et al. found the average accuracy of Harrington et al. equations of 14(8) mm. Both the average and standard deviation is comparable to the current study. Peters et al. also found similar results for the functional methods. In particular, they found that the functional geometrical sphere fitting technique was the most accurate among functional techniques with an average accuracy of 2 cm, similar to the current study.

The comparison of co-ordinates error data between Figs. 3 and 4 outlines that inferior–superior and antero-posterior positions of the HJCs are the most affected by assistance of movement and reduced ROM. Errors for the geometrical sphere fit functional technique increased from 3 mm superior to 8 mm inferior and increased to 5 mm anterior.

This study presented for the first time HJC localisation results against an EOS based medical imaging reference. Previous studies used either bi-plane X-rays or three-dimensional freehand ultrasound (3DUS). EOS acquisitions presented advantages against these previous methods. Compared to the X-ray based methods [6,21], it did not require the use of additional and specific markers (tantalum balls). Compared to 3DUS it allowed the simultaneous visualisation of both full lower limbs together with standard external markers in one acquisition. However, EOS did expose subjects to low dose ionising radiations. In the context of clinical use of gait analysis, especially if EOS acquisitions can be used in place of required X-rays of the hips, spine or foot, these radiations may be considered acceptable. In this case, direct calibration of the full skeleton of the subjects with reference to the motion capture markers would be possible prior to the gait analysis assessment.

A limitation of our work is that our study cohort consisted of adults with normal to high BMI: 25(4). This was comparable with previous studies but did not include adults who were considered to be obese. Our results may therefore not apply to this population.

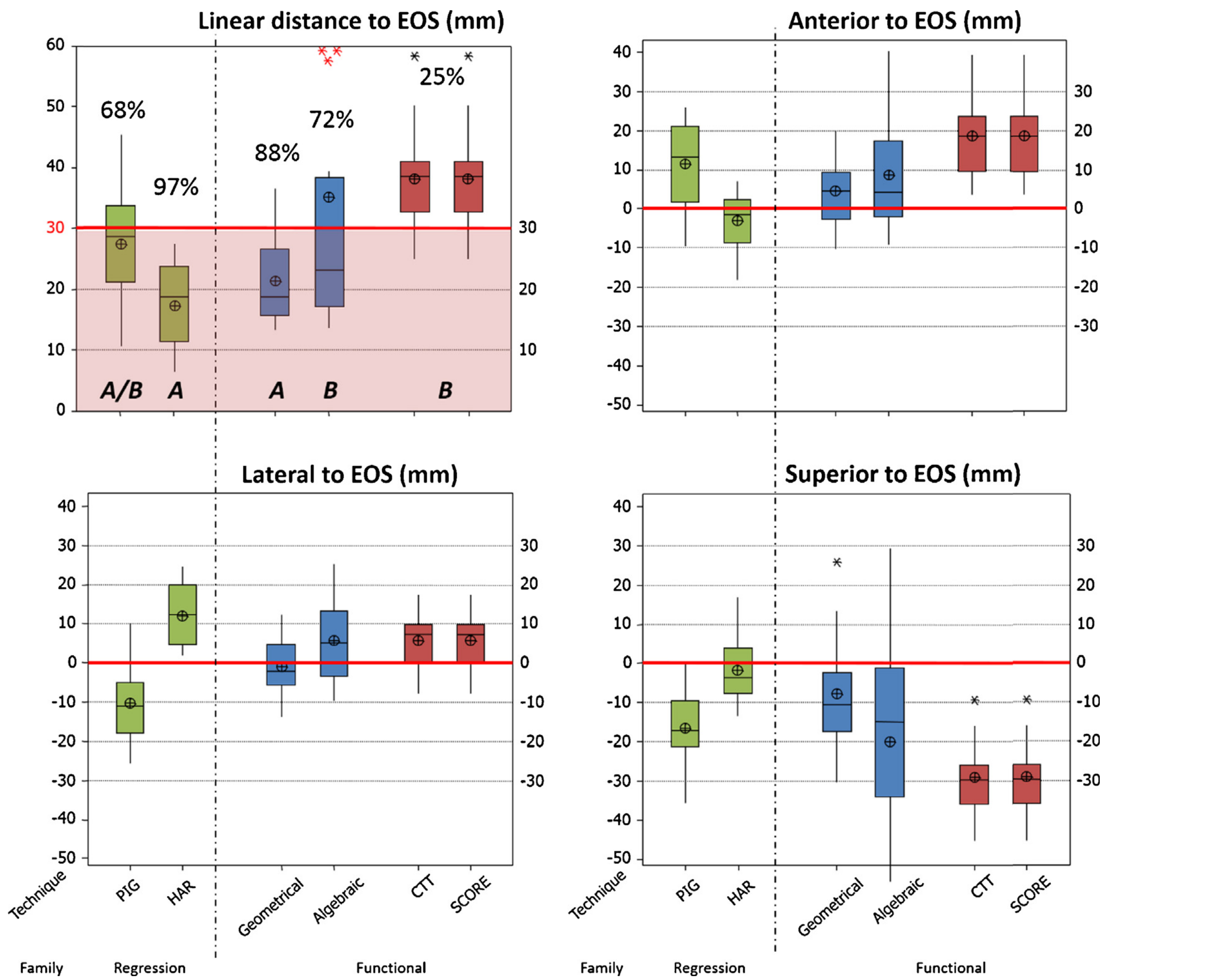

Fig. 4. Linear distance and co-ordinates difference (*x*, anterior; *y*, lateral and *z*, superior) results for the worst case scenario (i.e. assistance and reduced ROM). Proportion of data below a 30 mm threshold is specified at the top of the linear graph. Bonferroni grouping results ($\alpha < 0.05$) are specified at the bottom of the linear graph. Each letter specifies a statistically separate group.

Table 1
Comparison of the average linear distance (mm) of the HJC location against a medical image based reference in previous literature compared to the current study.

Reference		*N* subject	BMI (kg/m^2)	Functional, sphere fit (mm)	Davis [14] (mm)	Harrington [19] (mm)
Bell et al. [6]	X-ray	7	26.2[a]	38 (19)		
Leardini et al. [7]	X-ray	11	23.7 (2.8)	12 (4)	29 (8)	
Hicks and Richards [8]	3-DUS	9	NS	13 (4)		
Sangeux et al. [9]	3-DUS	19	23.0 (3.6)	13 (5)	30 (10)	17 (7)
Current	EOS	17	25 (4)	11 (4)	27 (9)	17 (8)

[a] The average BMI has been estimated from the mean height and mean weight provided in the study; NS, not specified, subjects were described as 'normal weight'.

5. Conclusion

This study showed that the choice of method to localise the HJC depends on the context. For subjects without hip pathologies or motor impairments, functional sphere fitting techniques are best suited. These techniques are not dependent on accurate pelvic marker placement and provide the most accurate results, on average 1 cm away from the EOS benchmark. For subjects who cannot perform the movement without assistance and/or have a reduced ROM, Harrington et al. [19], regression equations are best suited, on average 1.7 cm from the EOS benchmark. These rely on accurate marker placement and therefore require well trained professionals.

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Conflict of interest

There is no conflict of interest to declare.

References

[1] Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints

for the reporting of human joint motion – Part I: ankle, hip, and spine. Journal of Biomechanics 2002;35(4):543–8.
[2] Stagni R, Leardini A, Cappozzo A, Grazia Benedetti M, Cappello A. Effects of hip joint centre mislocation on gait analysis results. Journal of Biomechanics 2000;33(11):1479–87.
[3] Scheys L, Spaepen A, Suetens P, Jonkers I. Calculated moment-arm and muscle-tendon lengths during gait differ substantially using MR based versus rescaled generic lower-limb musculoskeletal models. Gait & Posture 2008;28(4): 640–8.
[4] Ehrig RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for determining the centre of rotation of ball joints. Journal of Biomechanics 2006;39:2798–809.
[5] Cereatti A, Donati M, Camomilla V, Margheritini F, Cappozzo A. Hip joint centre location: an ex vivo study. Journal of Biomechanics 2009;42(7):818–23.
[6] Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. Journal of Biomechanics 1990;23(6): 617–21.
[7] Leardini A, Cappozzo A, Catani F, Toksvig-Larsen S, Petitto A, Sforza V, et al. Validation of a functional method for the estimation of hip joint center location. Journal of Biomechanics 1999;32:99–103.
[8] Hicks JL, Richards JG. Clinical applicability of using sphere fitting to find a hip joint centers. Gait & Posture 2005;22:138–45.
[9] Sangeux M, Peters A, Baker R. Hip joint centre localization: evaluation on normal subjects in the context of gait analysis. Gait & Posture 2011;34(3):324–8.
[10] Peters A, Baker R, Morris ME, Sangeux M. A comparison of hip joint centre localisation techniques with 3-DUS for clinical gait analysis in children with cerebral palsy. Gait & Posture 2012;36(2):282–6.
[11] Dubousset J, Charpak G, Skalli W, Deguise J, Kalifa G. EOS: a new imaging system with low dose radiation in standing position for spine and bone & joint disorders. Journal of Musculoskeletal Research 2010;13(01):1–12.
[12] Pillet H, Sangeux M, Hausselle J, El Rachkidi R, Skalli W. A reference method for the evaluation of femoral head joint center location technique based on external markers. Gait & Posture 2014;39(1):655–8.
[13] Chaibi Y, Cresson T, Aubert B, Hausselle J, Neyret P, Hauger O, et al. Fast 3D reconstruction of the lower limb using a parametric model and statistical inferences and clinical measurements calculation from biplanar X-rays. Computer Methods in Biomechanics and Biomedical Engineering 2012;15(5): 457–66.
[14] Davis RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. Human Movement Science 1991;10(5):575–87.
[15] Camomilla V, Cereatti A, Vannozzi G, Cappozzo A. An optimized protocol for hip joint centre determination using the functional method. Journal of Biomechanics 2006;39(6):1096–106.
[16] Cappozzo A. Gait analysis methodology. Human Movement Science 1984;3:27–51.
[17] Chang LY, Pollard NS. Constrained least-squares optimization for robust estimation of center of rotation. Journal of Biomechanics 2007;40:1392–400.
[18] Piazza SJ, Erdemir A, Okita N, Cavanagh PR. Assessment of the functional method of hip joint center location subject to reduced range of hip motion. Journal of Biomechanics 2004;37:349–56.
[19] Harrington ME, Zavatsky AB, Lawson SEM, Yuan Z, Theologis TN. Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. Journal of Biomechanics 2007;40(3): 595–602.
[20] Stagni R, Leardini A, Cappozzo A, Benedetti MG, Cappello A. Effects of hip joint centre mislocation on gait analysis results. Journal of Biomechanics 2000;33(11):1479–87.
[21] Leardini A, Chiari L, Croce UD, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 3: soft tissue artifact assessment and compensation. Gait & Posture 2005;21:212–25.