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Hip joint centre localization: Evaluation on normal subjects in the context of gait analysis

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ABSTRACT

Locating the position of the hip joint centre (HJC) is an important part of lower limb modeling for gait analysis. Regression equations have been used in the past but a range of functional calibration methods are now available. This study compared the accuracy of HJC localization from two sets of regression equations and five different functional calibration methods against three dimensional ultrasound (3-DUS) on a population of 19 able bodied subjects. Results show that the *geometric* sphere fitting technique was the best performer with mean absolute distance error of 15 mm and 85% of measurements being within 20 mm. The results also show that widely used regression equations perform particularly badly whereas the most recent equations performed very closely to the best functional method with a mean absolute error of 16 mm and 88% of measurements being within 20 mm. *In vivo* results are more than an order of magnitude worse than predictions using synthetic data suggesting that additional work is required before soft tissue artifact can be effectively modelled.

1. Introduction

In lower limb movement analysis accurate location of the hip joint centre (HJC) is important as it influences both kinematics [1] and kinetics [2]. The hip joint is universally assumed to be a ball and socket joint with the centre of the femoral head being coincident with that of the acetabulum. This leads to two approaches to define the HJC, the predictive method which uses anthropometry based regression equations to estimate the local position of the HJC within the pelvis, and functional calibration in which the position of the HJC is inferred from movement during calibration trials.

In gait analysis the predictive method is by far the most widely used through commercial software (e.g. Plug In Gait [PIG], Vicon, Oxford, UK) which implements well established models [3,4]. Accuracy is limited however by the examiner's ability to place markers and make anthropometric measurements which can be exacerbated in subjects with substantial soft tissue over pelvic landmarks. The accuracy of the regression equations is also unknown with several sets of equations available for use [4–6]. Functional methods, based only on the relative movement of the segments, should be insensitive to both these sources of inaccuracy. They may, however, be affected by measurement artifacts as well as the quality and range of movement during calibration trials [7–11]. In modern measurement systems soft tissue artifact (STA) is likely to dominate [12], but errors in 3-D marker reconstruction are also possible.

There have been many simulation based comparative studies of functional methods [13–15] and a recent comprehensive overview of available algorithms outlined their respective strengths and weaknesses [16]. The authors identified two different families of algorithms which they named sphere fitting techniques and transformation techniques and focused on the mathematical implementation of the methods and their robustness to artificial noise simulating STA. It concluded that transformation techniques gave the best results. More recently, Cereatti et al. [17] compared the accuracy of functional algorithms from both families on cadavers and suggested that the sphere fitting techniques performed better. The contrasting results and the inherent limitations of synthetic or cadaveric data studies leave the question of the most appropriate choice for gait analysis unresolved.

Another functional method, global calibration [18,19], aims to calibrate the full skeleton in a single step in order to provide the best fit to marker data from the calibration trial. An inner optimization loop finds the best kinematic fit of the model to the

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Table 1
Comparison of the average distance (mm) of the HJC localization against a medical image based reference in previous literature compared to the current study. NS, not specified, subjects were described as 'normal weight'.

Reference		N subject	BMI (kg/m^2)	Functional (mm)	Davis et al. [4] (mm)	Harrington et al. [6] (mm)
Bell et al. [5]	X-Ray	7	26.2[a]	38 ± 19		
Leardini et al. [20]	X-Ray	11	23.7 ± 2.8	12 ± 4	29 ± 8	
Hicks and Richards [21]	3-DUS	9	NS	13 ± 4		
Current	3-DUS	19	23.0 ± 3.6	15 ± 5	30 ± 6	16 ± 6

[a] The average BMI has been estimated from the mean height and mean weight provided in the study.

medical image based reference (bi-plane X-ray or RSA [5,20] and 3-DUS [21]). All these studies used only the *geometric* functional calibration technique. The current study was the first to compare transformation techniques localization of the HJC to the reference position in medical images. Table 1 presents a comparison of previous study's results with the current study for the geometrical sphere fitting technique. Errors are substantially higher than the agreement of 3-DUS with MRI (4 ± 2 mm) as suggested by the previously published study [28]. This suggests that 3-DUS is of sufficient accuracy as a basis for this type of work.

Errors were found to be an order of magnitude worse than simulations performed with synthetic data covering a similar range of movement [16]. Cereatti et al. [17] found mean errors of between 1.4 and 39 mm for locating the HJC in cadavers, identifying STA as the principle source of this error. The current work confirms that modeling STA as Gaussian noise, as in previous simulations, does not give an adequate representation of the limitations of functional calibration techniques. Cereatti et al. [17] were able to limit errors to less than 10 mm by only using a distal thigh cluster. They used bone pins to determine the pelvic co-ordinate system thus eliminating STA of the pelvic markers as a source of error which may explain the larger errors reported in this study. The simulation study [16] suggested that transformational techniques performed better than sphere fitting techniques. Yet, the opposite is observed in this study with the transformational techniques showing a significant bias to place the hips too inferiorly. It is possible therefore that sphere fitting techniques may be more robust in relation to STA. Global calibration on the other hand, appears to perform similarly to the other transformational techniques.

All functional techniques perform less well in the vertical direction than in the other two directions. This may suggest that STA in the proximal-distal direction is particularly important. In clinical gait analysis the primary concern is of how errors in determining the HJC will affect joint kinematics and kinetics. Both are likely to be more susceptible to errors in the transverse plane than those perpendicular to it and from this perspective, the absolute errors may over-estimate the impact of errors on gait analysis data.

Using 3 or 6 markers had little effect on the results of functional calibration with the ANOM results showing a non-significant effect. Use of 6 markers reduced the spread of the results for the *geometric* method but did not change the average whereas it increased both spread and average for the *algebraic* method. 6 markers gave marginal improvement in the transformational techniques.

As expected (and predicted by the work of Leardini et al. [20]) PIG performed particularly badly despite being implemented in almost all commercially available gait analysis software. HAR, by contrast, performed particularly well with overall results very similar to those of the best functional calibration technique. Many patients may find performing functional calibration exercises difficult and Harrington's equations would appear to be particularly useful in this case. On the other hand the predictive approach is still dependent on accurate palpation of pelvis landmarks and functional calibration provides the solution when accurate palpation is difficult.

5. Conclusion

This study shows that functional calibrations can provide good HJC localization in a population of healthy adults with an average error of 15 mm and 85% of hips being within 20 mm of the 3-DUS measurement. Of the various methods tested, the *geometric* sphere fitting technique determined from 6 markers on the thigh is the one that provided the best results. The regression equations results were mixed with one method, *PIG*, leading to obvious inaccurate results whereas the latest regression equations found in the literature, [6], provided almost as good results as the best functional calibration technique. The study also highlights that Gaussian noise does not model STA well and that conclusions based upon its use can be highly mis-leading.

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Conflict of interest

Morgan Sangeux and Richard Baker received research support from Vicon Motion System to conduct this study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2011.05.019.

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