Gait & Posture 40 (2014) 20–25

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

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

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ARTICLE INFO

Article history:
Received 22 July 2013
Received in revised form 22 January 2014
Accepted 23 January 2014

Keywords:
Hip joint centre
Gait analysis

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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http://dx.doi.org/10.1016/j.gaitpost.2014.01.024
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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, $\mathrm{HJC}_{\mathrm{EOS}}$, 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 $\mathrm{HJC}_{\mathrm{EOS}}$.

2.1. Statistical analysis

The linear distance between the functional HJCs and $\mathrm{HJC}_{\mathrm{EOS}}$ 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

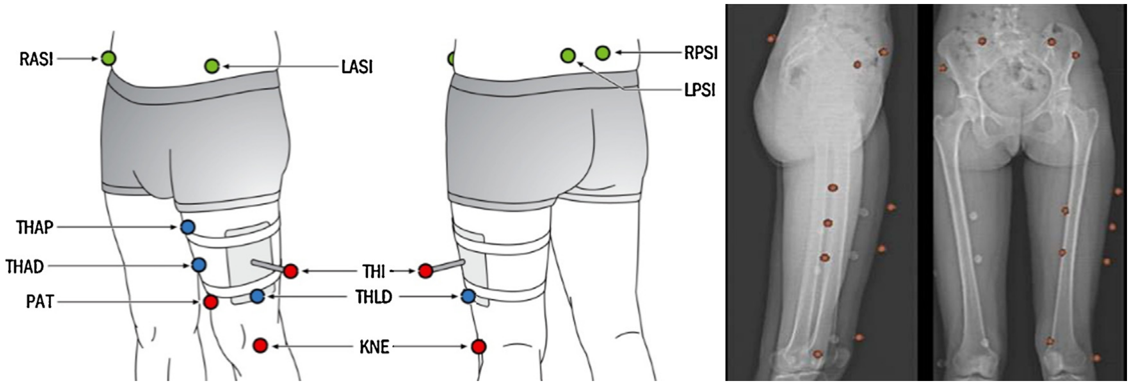

Fig. 1. (a) Marker set definition. Markers displayed in green were attached to the pelvic segment; 3 markers in blue and 3 in red were attached to the femoral segments. (b) Stereographic EOS images of the pelvis and femur displaying the motion capture markers. (For interpretation of the references to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