Validation of hip joint center localization methods during gait analysis using 3D EOS imaging in typically developing and cerebral palsy children

Ayman Assi [a,b,c,*], Christophe Sauret [b], Abir Massaad [a,c], Ziad Bakouny [a], Hélène Pillet [b], Wafa Skalli [b], Ismat Ghanem [a,c,d]

[a] Laboratory of Biomechanics and Medical Imaging, Faculty of Medicine, University of Saint-Joseph, Beirut, Lebanon
[b] Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris, France
[c] Gait Laboratory, SESOBEL, Beirut, Lebanon
[d] Hôtel-Dieu de France Hospital, Beirut, Lebanon

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ABSTRACT

Localization of the hip joint center (HJC) is essential in computation of gait data. EOS low dose biplanar X-rays have been shown to be a good reference in evaluating various methods of HJC localization in adults. The aim is to evaluate predictive and functional techniques for HJC localization in typically developing (TD) and cerebral palsy (CP) children, using EOS as an image based reference. Eleven TD and 17 CP children underwent 3D gait analysis. Six HJC localization methods were evaluated in each group bilaterally: 3 predictive (Plugin Gait, Bell and Harrington) and 3 functional methods based on the star arc technique (symmetrical center of rotation estimate, center transformation technique and geometrical sphere fitting). All children then underwent EOS low dose biplanar radiographs. Pelvis, lower limbs and their corresponding external markers were reconstructed in 3D. The center of the femoral head was considered as the reference (HJC_{EOS}). Euclidean distances between HJCs estimated by each of the 6 methods and the HJC_{EOS} were calculated; distances were shown to be lower in predictive compared to functional methods ($p < 0.0001$). Contrarily to findings in adults, functional methods were shown to be less accurate than predictive methods in TD and CP children, which could be mainly due to the shorter thigh segment in children. Harrington method was shown to be the most accurate in the prediction of HJC (mean error $\approx$ 18 mm, SD = 9 mm) and quasi-equivalent to the Bell method. The bias for each method was quantified, allowing its correction for an improved HJC estimation.

1. Introduction

Motion analysis has become an important asset during decision making for the treatment of musculoskeletal disorders, such as cerebral palsy [1,2]. Gait analysis is based on biomechanical models that use external skin markers in order to calculate joint kinematics and kinetics [3,4]. These external markers are used to associate a local coordinate system to each skeletal segment. The hip joint center (HJC) is an essential landmark for the creation of the local coordinate system of the thigh segment [5]. While this anatomical landmark is not directly accessible externally, a virtual marker is associated to this point. Two possible approaches exist in the localization of the HJC: either predictive techniques based on regression equations using anthropometric measurements [6–8] or functional calibration methods based on the movement of the thigh relative to the pelvis, where the center of rotation is determined [9–13].

The validation of these hip joint center localization techniques has been mainly based on cadaveric experiments or simulations [11,14]. Medical imaging techniques could be used in order to validate the HJC localization methods in vivo. Fluoroscopy has been previously used in some of the validation studies [9,15]. However, this method is known to deliver a considerable dose of radiation to the patient. Other studies have used three-dimensional (3D) ultrasound and have shown it to be effective [16,17]. However, this method cannot allow simultaneous acquisitions of both HJC and external markers. Magnetic Resonance Imaging could be an alternative [8], but is costly and time consuming.

* Corresponding author at: Faculty of Medicine, University of Saint-Joseph, Damascus Street, Campus of Innovation and Sport, Beirut, Lebanon.
Tel: +9611421676; fax: +9611421681.
E-mail addresses: ayman.assi@gmail.com, ayman.assi@usj.edu.lb (A. Assi).

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More recently, the EOS® system, which is a low dose biplanar radiographic system [18], has been shown to be accurate and reliable in both the detection of the reference HJC and the external markers [19]. The advantage of this technique is that it allows 3D reconstructions of the skeletal segments based on simultaneous biplanar radiographs taken from head to feet while the subject is in a standing position. The EOS® technique was recently used in order to validate hip joint center localization in healthy adults [20]. However, there are no studies on the validation of the hip joint center localization methods in children using this imaging technique. Thus, the aim was to validate hip joint center localization techniques using the EOS® system as a 3D image based reference, both in typically developing children and in children with cerebral palsy.

2. Methods

2.1. Population

After approval from the ethics committee of our institution, seventeen children with cerebral palsy (6F, 11M) and eleven typically developing children (6F, 5M) were enrolled in this study. The demographics of both groups were reported in Table 1. All participants and their parents were previously informed of the protocol and signed a written informed consent form prior to their participation in this study, allowing both collection and use of the data reported in this manuscript.

2.2. Motion capture

Subjects were equipped with 24 reflective skin markers on their lower limbs, based on the Helen Hayes protocol [7], with additional markers located on the posterior and anterior area of the thigh and the medial femoral condyle. Three-dimensional motion analysis was obtained using seven MX3 cameras (Vicon®, Oxford Metrics, UK) and the Workstation® software. First, a static calibration was performed for each subject. The thigh marker was adjusted in order to avoid cross-talk from the knee flexion/extension curve to the knee varus/valgus curve, often observed during gait: a qualitative assessment of the alignment of the knee joint center (obtained by the Plug in Gait model) with the lateral and medial condyles was performed. When the knee joint center was found to be anterior (posterior) to the inter-condylar line, the lateral marker of the thigh was shifted anteriorly (posteriorly, respectively). The static calibration was repeated in order to verify the alignment of the knee joint center with the inter-condylar line. Subsequently, the final trial, with the adjusted thigh marker positioning, was used for the study.

Then, the star arc acquisition was performed for each hip using the method previously developed by Camomilla et al. [21]. Each subject had been accustomed to the protocol prior to the acquisitions and a cane was used for stability when necessary. Hip calibration was performed with a maximal comfortable range of motion for the subject. The range of motion (ROM) performed during the star arc acquisition was collected for each subject.

Three predictive methods were used in order to calculate the hip joint center in each subject bilaterally: Plug in Gait (PiG) [7], Bell [6] and Harrington (HAR) [8]. These methods used anthropometric measures such as pelvic measurements and leg length. Moreover, three functional methods were used in order to calculate the hip joint center bilaterally based on the star arc acquisition: symmetrical center of rotation estimate (SCoRE) [11], center transformation technique (CTT) [12] and geometrical sphere fitting (GSF) [13]. The coordinates of the HJCs obtained from the 3 predictive and 3 functional methods were expressed in the local coordinate system of the pelvis based on the external reflective markers [7].

2.3. Imaging technique

All subjects underwent an EOS® (EOS Imaging, Paris, France) biplanar X-ray [18] examination of their lower limbs (pelvis to feet) following the motion capture acquisitions, with the external reflective markers still in place. Three-dimensional positions of the markers were determined by manual positioning and fitting on frontal and lateral radiographs of a 14 mm marker model. Subject-specific 3D reconstructions of the lower limbs were obtained by a method based on simultaneous adjustment of parametric models on frontal and lateral radiographs [22,23]. An example of EOS® biplanar X-rays with 3D reconstruction of the lower limbs and of the reflective markers is shown in Fig. 1. Three-dimensional reconstructions of the femurs were then processed using Stereos research software (Arts et Métiers ParisTech, Paris, France) allowing the acquisition of the femur mesh and embedded regions, including the femoral head. Then, a sphere was fitted to the femoral head region and its center was considered as the reference hip joint center (HJC_{EOS}). HJC_{EOS} of the right and left lower limbs were expressed in the pelvic coordinate system based on the external markers of the pelvis seen on the radiographs. This method was previously validated [19] and was shown to be reliable for the detection of external reflective markers (within 0.15 mm) and accurate for the detection of the hip joint center (mean errors: 2.9 mm, SD: 1.3 mm).

Subsequently, all hip joint centers obtained from predictive and functional methods, as well as the reference HJC_{EOS}, were all expressed in the same coordinate system.

2.4. Statistics

The error on each hip joint center localization technique was evaluated by calculating the Euclidean distance between the evaluated HJC and the reference HJC_{EOS}. The proportion of hips falling within the threshold of 30 mm [20,24] was counted for each localization method. The deviation from the reference in each direction was also calculated: antero-posteriorly, medio-laterally and vertically.

The distribution of all variables was tested for normality using the Shapiro–Wilk test.

First, between-group comparisons (CP vs. TD) of errors on hip joint centers were performed in order to test if the precision of the method differed between groups. The equality of variances was evaluated using Levene's test. Distances to the HJC_{EOS} obtained for CP and TD groups were compared using Student, Mann–Whitney or Welch tests.

Second, between-method comparisons of errors on hip joint centers were performed in order to determine which method is

Table 1
Demographic table of children with cerebral palsy and typically developing children.

Groups	*N*	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m^2)	GMFCS levels
CP	17	11.9 ± 3.5	41.5 ± 16.8	145.0 ± 16.3	19.0 ± 5.0	I: *N* = 11; II: *N* = 5; III: *N* = 1
TD	11	10.7 ± 2.3	43.7 ± 14	143.2 ± 11.0	20.9 ± 4.1	

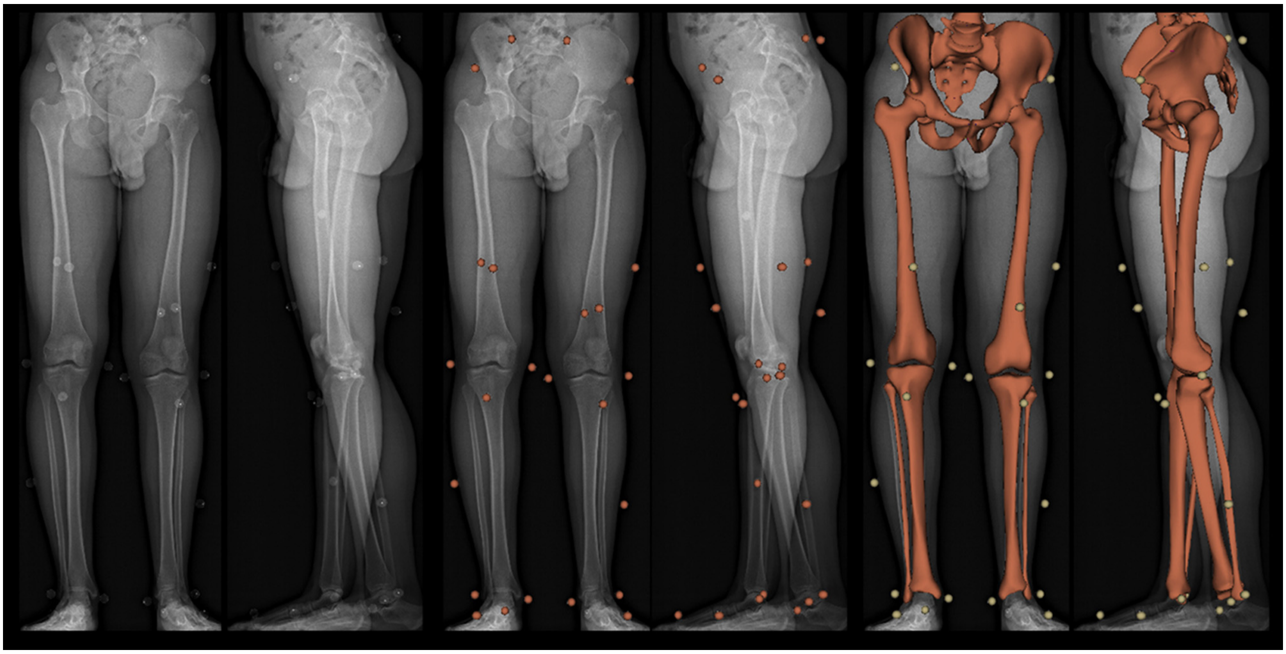

Fig. 1. Frontal and lateral EOS radiographs (left) with 3D reconstruction of the external markers (middle) and of the lower limbs and pelvis (right).

best for HJC estimation in each group. Data sphericity was evaluated using Mauchly's test. Between-method comparisons (3 predictive and 3 functional) of distances to the reference were performed using repeated measures ANOVA with Greenhouse–Geisser correction or Friedman's test, with multiple pairwise comparisons using Bonferroni or Nemenyi methods, respectively.

The ROM performed during the star arc acquisition were compared between CP and TD groups using unpaired *t*-test. A one-way analysis of covariance was performed in order to detect if the ROM was a confounding factor on the errors on hip joint centers calculated by the functional methods.

Level of significance was set at 0.05. Statistical analysis was performed using Xlstat® (version 2015.5.01.22537; Addinsoft, Paris, France) and SPSS Statistics (version 20.0; IBM Corporation, New York, USA) and data were processed using Matlab® (version R2011a; The Mathworks Inc., Natick, MA, USA).

3. Results

In total, both hips of all the enrolled children were processed for the predictive methods: 34 hips of children with cerebral palsy (CP) and 22 hips of typically developing (TD) children. Nine CP and 1 TD children were not able to perform the star arc acquisition and were excluded from the database of functional methods; consequently, 16 hips of children with CP and 20 hips of TD children were evaluated for the functional methods.

The distances between the hip joint centers (HJCs) and the HJC_{EOS} reference were grouped in Fig. 2.

Comparison of errors on HJC localization techniques between CP and TD groups showed a significant difference for the Bell ($p < 0.001$) and geometrical sphere fitting ($p = 0.031$) methods. Thus, each group was considered separately when comparing the HJC localization methods.

In the TD group (Fig. 3a), a significant difference was found between predictive and functional methods ($p < 0.001$) with lower error for predictive methods. Comparisons between functional methods did not show a significant difference ($p = 0.086$). However, comparisons between predictive methods showed that the Harrington method had significantly lower errors (19 ± 9 mm) compared to the Plug in Gait (25 ± 10 mm, $p = 0.048$) and Bell (23 ± 8 mm, $p = 0.03$) methods.

In the CP group (Fig. 3b), a significant difference was found between the predictive and the functional methods ($p < 0.001$), where the predictive methods showed lower mean errors compared to the functional methods. Comparisons between functional methods did not show a significant difference ($p = 0.611$). However, comparisons between predictive methods showed that the Bell method had significantly lower errors (16 ± 8.5 mm) compared to the Plug in Gait method (21 ± 10 mm, $p = 0.005$). There was no significant difference between the Bell and Harrington methods ($p = 0.127$).

The proportions of estimated hip localization errors that were higher than the threshold of 30 mm ranged between 21% and 26% for the predictive methods and between 94% and 100% for the functional methods.

The deviations of HJCs to HJC_{EOS} in each direction of the pelvis coordinate system were reported in Fig. 4. While the medio-lateral deviation did not show a specific trend, it was noted that the PiG method tended to shift the HJC posteriorly to the reference (-17 ± 10 mm). The functional methods tended to place the HJC anteriorly (SCoRE: $+30 \pm 25$ mm, CTT: $+22 \pm 30$ mm, GSF: $+35 \pm 30$ mm) and superiorly (SCoRE: $+38 \pm 29$ mm, CTT: $+38 \pm 30$ mm, GSF: $+44 \pm 18$ mm) to the reference.

The range of motion (ROM) performed during the star arc acquisition was significantly lower ($p = 0.02$) in the CP group compared to the TD group ($35 \pm 9°$ vs. $42 \pm 8°$, respectively). The ANCOVA showed that ROM was not a confounding factor for the errors on HJC localization techniques obtained by the functional methods (SCoRE: $p = 0.41$, CTT: $p = 0.26$, GSF: $p = 0.47$).

4. Discussion

Three predictive and 3 functional hip joint center localization techniques, used in gait analysis, were compared to the hip joint center obtained by 3D EOS® imaging in children with cerebral palsy and typically developing children. All predictive methods were shown to be more accurate than the functional methods. Among the predictive methods, the Harrington method was found

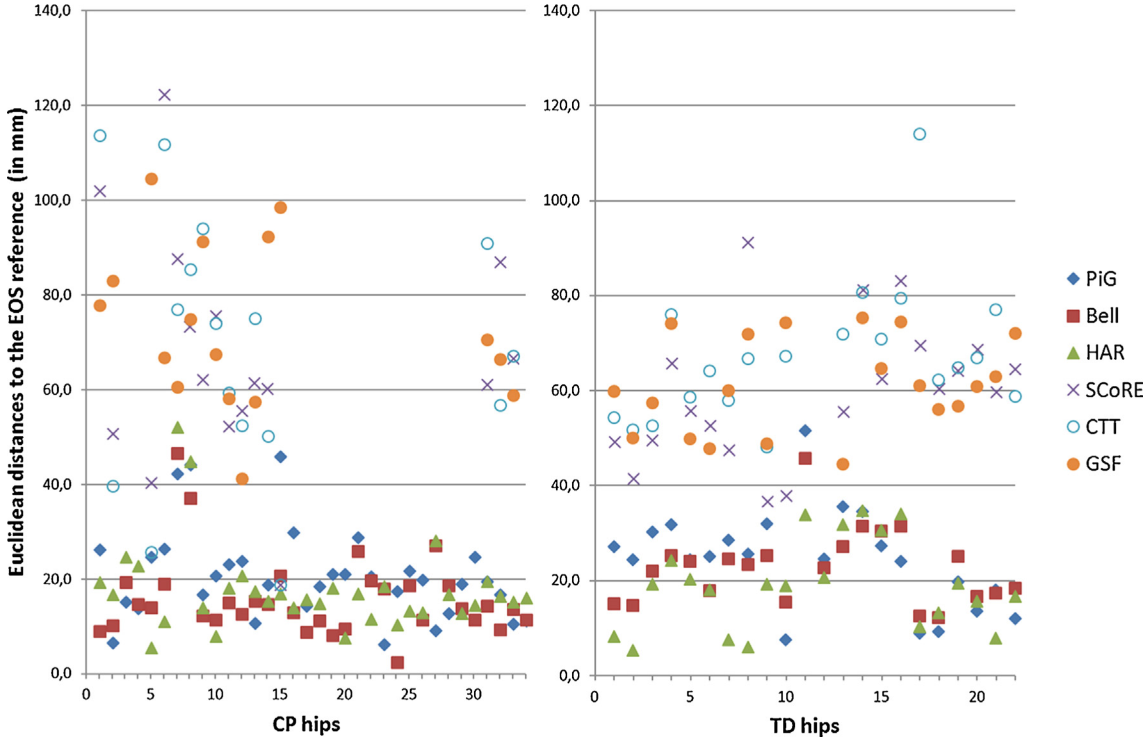

Fig. 2. Euclidean distances to the EOS reference of the 6 hip joint center localization techniques in 34 hips of children with cerebral palsy and 22 hips of typically developing children.

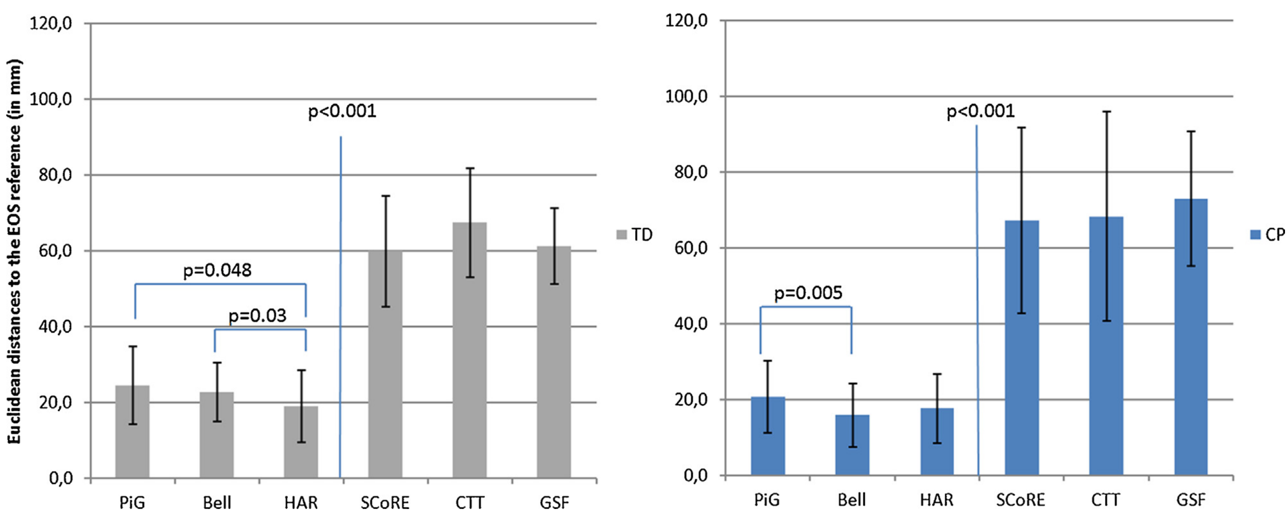

Fig. 3. Euclidean distances to the EOS reference (means and standard deviations) of 6 hip joint center localization methods (Plug in Gait, Bell, Harrington, symmetrical center of rotation estimate, center transformation technique, geometrical sphere fitting) in typically developing children (left) and children with cerebral palsy (right).

to be the most accurate in TD children. Both the Harrington and Bell methods were equally accurate in the CP group.

Previous validation studies of HJC localization techniques have been based on either fluoroscopy or 3D ultrasound (3DUS) [9,15,17,25,26]. While the former method is known to expose the subjects to a high dose of radiation, the latter does not. The 3D EOS® imaging technique does entail a certain dose of radiation to the subject; however, this dose is known to be 2–5 times less than the conventional X-ray [27]. Moreover, it has been shown that this technique is more reliable than 3D ultrasound (2.9 ± 1.3 mm vs. 4 ± 2 mm) [16,19] and crucially, allows the simultaneous acquisition of: the 3D subject-specific reconstruction of the skeletal segments, the external reflective markers and the HJC reference, which contributes to the reduction of errors.

Our results were comparable to those obtained by Peters et al. [26], where predictive and functional HJC localization methods were compared to a 3D ultrasound-based image technique in CP children. The authors found that the distance between the reference and the HAR technique was approximately 14 ± 8 mm. While both Harrington and Plug in Gait techniques showed similar results between our study and Peters et al.'s study, the large difference of errors on functional methods (i.e. GSF technique, current study ≈ 66 mm vs. Peters study ≈ 20 mm) could be due to the difference in the image based technique used and to the fact that the star arc acquisition was assisted by an operator in Peters et al.'s study.

In a recent study, Sangeux et al. [20] used the EOS® system to validate the hip joint center localization techniques in healthy adults. The Harrington method showed the best result when a

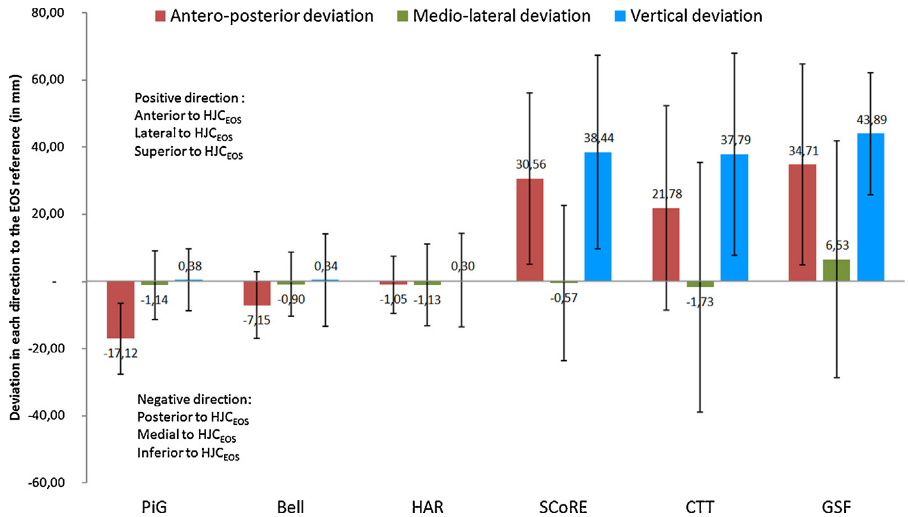

Fig. 4. Deviations in the antero-posterior, medio-lateral and vertical directions of the 6 hip joint center localization methods relatively to the reference hip joint center obtained from EOS (means and standard deviations).

reduced range of motion (<30°) was performed during hip calibration with Euclidean distances to EOS® reference similar to those obtained in our study (17 mm). However, the authors showed that with a large performed ROM (>30°) during hip star arc movement, the geometrical sphere fitting method located the HJC closer to the EOS® reference (11 mm) compared to the other methods. The differences in the results obtained between adults (Sangeux et al.) and children (current study) using the same image based reference technique could be related to the smaller segment of the thigh in children; the smaller segment moves the thigh markers closer to the hip, which might increase the noise when sphere fitting or transformational techniques are used to locate the center of rotation. Moreover, even though the CP group performed a significantly lower range of motion than the TD group in this study, average range of motion in both groups was higher than 30°. Furthermore, the ANCOVA test showed that the ROM was not a confounding factor on the errors on the HJCs calculated by the functional methods.

The propagation of the errors in the localization of the hip joint center on kinematics and kinetics has been previously evaluated in the literature [24,28]. It was shown that hip joint center misplacement could result in significant errors on both hip and knee kinematics and kinetics. A threshold of 30 mm was defined as the limit of acceptable errors on the hip joint center localization, below which the kinematics and kinetics are not significantly affected [20,24]. In the current study, the proportion of errors on hip localization that fall above the threshold of 30 mm was shown to be high in functional methods. Therefore, the errors on HJC localization techniques could lead to erroneous gait data and thus to an inadequate clinical interpretation. While different studies have shown that the functional methods are the best for the localization of the HJC [9,20,25,26], the current study has thus shown that the functional methods are less accurate than the predictive ones in both CP and TD children.

In this study, deviations to the reference of HJC localization techniques were mostly comparable to those obtained in the literature in the case of adult subjects, using the EOS imaging technique [20], except for a few differences. While the Plug in Gait (PiG) technique was shown to place the HJC anterior to the reference in the previous study on adults (≈+10 mm), we found that the PiG technique was posterior to the reference in the case of children (≈−14 mm). This could be due to the fact that the regression equation used by the Davis method, which was computed from adult cadavers [7], is inadequate for use in children. Moreover, the results obtained in our study, in the case of children, showed that the functional techniques placed the hip joint center further anteriorly to the reference compared to adults (≈30 mm in children vs. 12–25 mm in adults [20]) and more superiorly.

As previously indicated, the significant deviations of hip joint center localization techniques from the gold standard used in this study (EOS® system) would implicate major errors on kinematics and kinetics [28]. These errors can influence various uses of gait analysis such as evidence-based decision-making, choice of dosages of botulinum toxin injections and/or musculoskeletal surgery evaluation.

In conclusion, a novel technique was used to validate predictive and functional methods of hip joint center localization used in the setting of gait analysis in children with cerebral palsy and typically developing children. The 3D EOS® imaging technique has shown that the predictive methods perform better than the functional methods and that the Harrington regression method has the best results in both CP and TD children. While the Harrington method showed slightly better results than the Bell method, both could be used with quasi-equivalent performance. Moreover, the bias was quantified for each of them in each direction, which can allow correction of those predictive methods. Since the Harrington method was based on data from adults and children, the computation of a children-specific regression equation could better predict the location of the hip joint center to be used in gait analysis. When available, the EOS® system could be an alternative to estimation methods by detecting the exact location of the hip joint center, which can be integrated in the computation of the kinematic waveforms.

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