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# The clinical impact of hip joint centre regression equation error on kinematics and kinetics during paediatric gait

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ABSTRACT

Regression equations based on pelvic anatomy are routinely used to estimate the hip joint centre during gait analysis. While the associated errors have been well documented, the clinical significance of these errors has not been reported. This study investigated the clinical agreement of three commonly used regression equation sets (Bell et al., Davis et al. and Orthotrak software) against the equations of Harrington et al. Full 3-dimensional gait analysis was performed on 18 healthy paediatric subjects. Kinematic and kinetic data were calculated using each set of regression equations and compared to Harrington et al. In addition, the Gait Profile Score and GDI-Kinetic were used to assess clinical significance. Bell et al. was the best performing set with differences in Gait Profile Score (0.13°) and GDI-Kinetic (0.84 points) falling below the clinical significance threshold. Small deviations were present for the Orthotrak set for hip abduction moment (0.1 Nm/kg), however differences in Gait Profile Score (0.27°) and GDI-Kinetic (2.26 points) remained below the clinical threshold. Davis et al. showed least agreement with a clinically significant difference in GDI-Kinetic score (4.36 points). It is proposed that Harrington et al. or Bell et al. regression equation sets are used during gait analysis especially where inverse dynamic data are calculated. Orthotrak is a clinically acceptable alternative however clinicians must be aware of the effects of error on hip abduction moment. The Davis et al. set should be used with caution for inverse dynamic analysis as error could be considered clinically meaningful.



## 1. Introduction

The accurate quantification of skeletal motion is hugely important for the assessment of both normal and pathological gait [1]. In lower limb gait analysis the location of the hip joint centre (HJC) is needed to define the thigh coordinate frame for kinematic analysis and it is the point at which inverse dynamics at the hip are calculated. As a result, accurate definition of this point is essential. Ideally the HJC location specific to the subject would be directly measured. However, the imaging techniques required to achieve this would not be available to most gait laboratories. As the HJC cannot be directly palpated, its position is usually estimated using one of two approaches. The first, referred to as functional calibration, relies on relative movement of the segments usually during a number of calibration trials [2–4]. This approach has been shown to yield the best results, however it may be difficult to implement when dealing with pathological groups such as cerebral palsy where function is impaired [5]. As a result, implementation in the clinical setting has been limited. The second approach is the use of regression equations based primarily on the anatomy of the pelvis [6–8]. These types of regression equations will usually have been derived from radiographic or cadaveric measurements and are by far the most widely used in clinical gait analysis [5,9,10]. However, while their use is considered an acceptable compromise, regression equations have their limitations. Most rely on accurate identification and measurement of pelvic bony landmarks and the subject populations on which they were originally based may be quite different to subject populations on which they are used.

The errors associated with the use of regression equations have been well documented in the literature [5,10–13]. Errors up to 31 mm have been reported between true and estimated HJC position [8,12]. Recent studies examining the accuracy of a number of regression based and functional methods for HJC location report that in the case where functional calibration is not an option, such as where subjects find it difficult to perform functional calibration exercises, the regression equations reported by Harrington and

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colleagues [8] should be used during gait analysis [5,9,10]. These equations performed very closely to the best performing functional calibration method while the older and widely used regression equations performed with less agreement. While the study was a comprehensive review of different methods, it is limited in that only two sets of regression equations were assessed [7,8], with only the Davis et al. set widely used in clinical gait analysis. In the original study where the Harrington regression equations were derived, the authors did include an analysis of other commonly used regression equation sets [8]. The authors suggest that their new proposed equations could improve estimates by up to 7 mm [8]. However, while differences between the other regression equation sets were reported, it was not possible to compare the new proposed equations of Harrington et al. directly to the other sets. Also, in both studies, the effects on kinematics and kinetics were not considered.

Few studies have examined the effect of regression equation error on kinematic and kinetic output [11,12]. While the Harrington set has been recommended as the most accurate for gait analysis [5,9,10], differences resulting from the use of other commonly used sets must be considered, not only from a statistical perspective but also from a clinical perspective. Otherwise, these older commonly used sets could be incorrectly dismissed as not suitably accurate when in fact the overall effect on clinical data is small or even negligible. Following from this, the aim of this study was to determine whether any clinically meaningful difference may exist in both kinematic and kinetic data when a number of widely used regression equation sets from the literature are used to determine HJC location during paediatric gait.

## 2. Materials and methods

### 2.1. Subjects

Eighteen healthy children ($n = 36$ limbs) participated in the study: 7 male and 11 female (Table 1). Informed written consent was obtained from all participants and from their parents when legally minor. The study was approved by the Central Remedial Clinic's Ethical Committee.

### 2.2. Data collection

A full barefoot 3-dimensional analysis was performed using the CODA cx1 active marker system (Charnwood Dynamics Ltd., Leicestershire). The marker placement protocol and underlying mathematical model followed implementation as previously described [14]. Subjects walked unassisted at a self-selected pace. Two Kistler 9281B force platforms, embedded into the laboratory walkway, were used to measure ground reaction force data. One representative walking trial containing a clean strike of the left and right force plate was recorded for each subject. Subject specific clinical examination data, required for the kinematic and kinetic models, were recorded for each subject (Table 1). Leg lengths were measured using a measuring tape as previously reported [15]. Pelvic width (PW) was taken as the distance between the anterior superior iliac spines (ASISs) while pelvic depth (PD) was taken as the distance between the ASISs and posterior superior iliac spines (PSISs). The corresponding kinematics and kinetics were calculated for each representative trial. A cut-off frequency of 10 Hz was set for force data. All kinematic and kinetic calculations were performed using custom scripts in MATLAB 8.1.0.604 (The MathWorks, Natick, Massachusetts, USA).

**Table 1**
Mean subject anthropometric data including pelvic width, depth and leg length required for regression equation offset calculations.

| Parameters | Mean (SD) ($N = 18$) |
|---|---|
| Age | 10.83 (2.45) |
| Male/female | 7/11 |
| Height (m) | 1.45 (0.14) |
| Weight (kg) | 40.17 (12.65) |
| Pelvic width | 216.67 (30.05) |
| Pelvic depth | 128.22 (20.45) |
| Left leg length (mm) | 727.78 (80.24) |
| Right leg length (mm) | 731.39 (79.87) |

### 2.3. HJC regression equations

Four regression equation sets were used in this study. The first was based on measures of pelvic width (PW), pelvic depth (PD) and leg length (LL) [8]. It has been suggested that this set performs very closely to the best functional calibration technique and should be used during gait analysis when the functional calibration technique is not an option [5,9,10]. For this reason, the equations described by Harrington (Har) are used as the reference standard against which the three other commonly used sets are compared. The second set (Bell) is based on measures of PW [6]. This set is widely used in clinical gait analysis and has been incorporated into the standard gait model as implemented in Codamotion Analysis software (Charnwood Dynamics Ltd., Leicestershire). The third set (Davis) is that which is most widely used in clinical gait analysis as part of the Conventional Gait Model implemented in Vicon Plug-in-Gait software [10], and is based on measures of LL and PW [7,8]. The final set (Ortho), based on software recommendations for Orthotrak Motion Analysis Corp., has widespread use in clinical gait analysis and is based on measures of PW [8].

### 2.4. Data analysis

The co-ordinate distance for the HJC position between the reference standard (Harrington–baseline zero) and the Bell, Davis and Orthotrak regression equation sets was calculated for anterior/posterior ($x$-axis), medial/lateral ($y$-axis) and superior/inferior ($z$-axis) directions and all expressed in the same pelvic co-ordinate system frame. Ensemble average kinematic and kinetic profiles were visually analyzed for deviations for each of the three sets when compared to the Harrington reference.

The Gait Profile Score (GPS) was calculated for each subject [16]. The GPS is a single measure of the quality of a subject's gait pattern. It was used to assess whether any Clinically Meaningful Important Difference (CMID) existed in the *kinematic* profiles derived from the different sets (Bell, Davis and Ortho) compared to the kinematic profiles derived from the Harrington (reference) set. The GPS CMID was calculated as the mean difference plus one standard deviation between each set and the reference. The minimal clinically important difference of the GPS has been shown to be 1.6° [17]. For the purposes of this study, this value of 1.6° was used as the threshold of clinical significance (CMID).

The Gait Deviation Index Kinetic (GDI-Kinetic) score was calculated for each leg [18]. The GDI-Kinetic was used to determine whether a CMID existed in the *kinetic* profiles between groups. The GDI-Kinetic is an index which scales the difference in pathological gait to normal gait and it is used to quantify the pathology present in the kinetic profiles of subjects. As with the GPS, the GDI-Kinetic CMID was calculated as the mean difference plus one standard deviation between each set and the reference. A threshold of clinical significance of 3.6 points (CMID) was used for this study based on a method previously reported [15].

As each set (Bell, Davis and Ortho) was compared directly to the Harrington reference set, HJC co-ordinate difference, GPS and GDI-Kinetic scores were statistically analyzed by means of