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Regression models to predict hip joint centers in pathological hip population

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ABSTRACT

The purpose was to investigate the validity of Harrington's and Davis's hip joint center (HJC) regression equations on a population affected by a hip deformity, (*i.e.*, femoroacetabular impingement). Sixty-seven participants (21 healthy controls, 46 with a cam-type deformity) underwent pelvic CT imaging. Relevant bony landmarks and geometric HJCs were digitized from the images, and skin thickness was measured for the anterior and posterior superior iliac spines. Non-parametric statistical and Bland-Altman tests analyzed differences between the predicted HJC (from regression equations) and the actual HJC (from CT images). The error from Davis's model (25.0 $\pm$ 6.7 mm) was larger than Harrington's (12.3 $\pm$ 5.9 mm, $p < 0.001$). There were no differences between groups, thus, studies on femoroacetabular impingement can implement conventional regression models. Measured skin thickness was 9.7 $\pm$ 7.0 mm and 19.6 $\pm$ 10.9 mm for the anterior and posterior bony landmarks, respectively, and correlated with body mass index. Skin thickness estimates can be considered to reduce the systematic error introduced by surface markers. New adult-specific regression equations were developed from the CT dataset, with the hypothesis that they could provide better estimates when tuned to a larger adult-specific dataset. The linear models were validated on external datasets and using leave-one-out cross-validation techniques; Prediction errors were comparable to those of Harrington's model, despite the adult-specific population and the larger sample size, thus, prediction accuracy obtained from these parameters could not be improved.

1. Introduction

Motion analysis and musculoskeletal modelling are highly sensitive to the location of the hip joint center (HJC). Inverse dynamics studies reported differences of up to 22% in hip flexion-extension moments, with discrepancies of 3 cm in HJC [1]. Muscles' capacity to generate moment at the hip joint is most sensitive to vertical displacements of HJC; a 2-cm superior displacement decreases hip abduction moment by about 50% [2] and, consequently, leads to inaccurate muscle and hip contact force estimations.

Although the gold standard to identify HJC is medical images, regression equations can be used when imaging data are not available [3–7]. Among other factors, the regression equation parameters depend upon the sample size and its characteristics. Several established HJC regression models were developed from specific demographics, however, their abilities to represent populations with different characteristics (from those on which they have been developed) are often disputed. An early model by Bell (1989) was established from 39 healthy children and 31 healthy adults [3,4], whereas a conventional model by Davis (1991) provided no specific information about the original cohort data as to which the regression equations were developed from [6]. Seidel's study later analyzed 65 healthy cadaveric pelves, but the use of pelvic height as predictor prevents the clinical use of this model [7]. More recently, a model by Harrington and associates (2007) examined a mixed population of 14 healthy children, 10 cerebral palsy children, and 8 adults [5]. They also investigated the validity of models developed from adult populations when applied to children and young cerebral palsy patients, and found that the prediction errors were similar in all three groups [5]. Andersen and colleagues investigated patients who underwent hip resurfacing, where the geometrical features of the pelvis were known to be different from the normal population, and found significant differences in these two groups according to the type of regression equation used [8]. Among the available HJC regression

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models, recent studies showed that Harrington equations provided the highest accuracy [8–11], although this set of equations was developed from a non-homogeneous and relatively small size sample.

Cam femoroacetabular impingement (FAI) is the result of bone overgrowth on the femoral head and neck, characterized by an elevated alpha angle, femoral retro-torsion and acetabular retroversion, and decreased femoral neck-shaft angle [12], thus it cannot be assumed *a priori* that the same regression equations can properly locate HJCs in individuals with a cam deformity. However, no study has investigated the accuracy of these regression equations applied to subjects with hip deformities such as cam-type FAI.

Therefore, the objective was to evaluate the validity of HJC regression models for a population characterized with a cam-type deformity (FAI) compared to a healthy, control population; where the actual geometric HJC was measured using computed tomography (CT) images. Two models were compared: (1) Harrington's, as it is considered to be the most accurate [11]; and (2) Davis's, as it is still one of the most used and a standard in some commercial software. Moreover, new regression equations were proposed to verify if the predictors used by Harrington [5] could provide better estimates in adults when tuned on a larger and adult-specific dataset. Lastly, skin thickness was measured to provide reference values to account for a source of error, when regression equations are applied to surface markers instead of bony landmarks.

2. Methods

2.1. Experimental data

Sixty-seven subjects consented to participate in the study approved by the Research Ethics Board of the institution: 21 control participants (CON) and 46 with cam FAI deformity. Gender composition, age, height, and body mass index (BMI) were comparable in the two groups (Table S.1, Supplementary Material). Pelvic CT images were acquired from each participant using either the Toshiba Acquilion (Toshiba Medical Systems Corporation, Otawara, Japan) or the Discovery CT750 (GE Healthcare, Mississauga, ON, Canada). The scan was executed in a supine position, with a pillow underneath the lumbar vertebra to mimic the natural lordosis of the standing position. FAI participants were selected based on their hip deformity, quantified by an alpha angle larger than 50.5° in the axial or 60° in the radial 1:30 view on CT data [13–15]. CON participants did not show any sign of hip deformity and both groups were not affected by any other lower limb musculoskeletal disorder. The hips of every participant were divided into highest and lowest alpha angles (labelled 'low alpha' and 'high alpha' in Table 1).

The CT data were blinded and read using ITK-SNAP 2.4 (PICSL, USA), in a multi planar reconstruction view [16]. For every participant, the 3D coordinates of the bony landmarks for left and right, anterior and posterior superior iliac spines were recorded, and the skin thicknesses were measured as the distance between these bony landmarks and the skin surface in the transverse plane. The local pelvic coordinate system was based on these coordinates and defined according to ISB guidelines [17]. The hip geometric centers were located as the center of a maximum-radius circumference fitting the contour of the femoral head on the three planes, and considered as the actual HJC [16]. The CT measurements were completed by two readers, each performing three readings, with near-perfect inter- and intra-observer reliability ($ICC > 0.90$).

2.2. Data analysis

The HJCs were estimated from the two regression models in the common pelvic coordinate system. Harrington regression equations depend on pelvic width (PW—the distance between right and left anterior superior iliac crest) and pelvic depth (PD—the distance between the mid-points of the two anterior and the two posterior superior iliac crests) [5]:

$$\begin{aligned} x &= -0.24\mathrm{PD} - 9.9 \\ y &= -0.30\mathrm{PW} - 10.9 \\ z &= -0.33\mathrm{PW} + 7.3 \end{aligned} \tag{1}$$

(expressed in mm), where x, y and z are the anterior-posterior (AP), superior-inferior (SI) and medial-lateral (ML) coordinates, respectively. Davis regression equations depend on PW, leg length (L) and the AP distance between the HJC and the ipsilateral anterior-superior iliac spine (denoted as D):

$$\begin{aligned} x &= -0.95D + 0.031L - 4 \\ y &= -0.31D - 0.096L + 13 \\ z &= 0.5\mathrm{PW} - 0.055L + 7 \end{aligned} \tag{2}$$

The regression equations from both models were applied directly to the pelvic bony landmarks.

The errors between the estimated and the actual HJC were calculated in the three orthogonal directions (e_{ML}, e_{AP} e_{SI}) together with their linear distance (e_L). HJCs from each regression model were directly compared to the actual HJC, using: (1) Bland-Altman scatter plots [18] to calculate the limits of agreement; and (2) the

Table 1
Median (and 25/75 percentile-range) of prediction errors in antero-posterior (e_{AP}), superior-inferior (e_{SI}), medial-lateral (e_{ML}) directions and relative linear distance (e_L). The results are divided by prediction method (Davis, Harrington), group (CON, FAI), side (Low alpha, High alpha).

	Davis								Harrington							
	CON				FAI				CON				FAI			
	Md	25%	75%		Md	25%	75%		Md	25%	75%		Md	25%	75%	
Low alpha side																
e_{AP}	−0.8	−9.9	1.3		−1.4	−4.7	3.0		0.1	−4.3	3.2		2.9	−0.2	4.8	
e_{SI}	−13.5	−15.9	−9.1	**	−15.7	−19.0	−10.7	**	4.0	2.4	11.3	*	6.2	−0.7	9.8	**
e_{ML}	−15.7	−21.6	−11.8	**	18.2	12.2	24.3	**	−4.8	−7.2	−1.5	**	5.6	2.6	9.7	**
e_L	22.3	17.9	28.6	**	26.1	21.0	29.2	**	10.3	6.7	17.9	**	11.7	8.2	16.3	**
High alpha side																
e_{AP}	−2.0	−8.5	1.1		−2.5	−6.0	3.1		−0.3	−4.8	2.7		1.6	−1.5	4.8	
e_{SI}	−13.2	−16.2	−10.2	**	−14.5	−19.3	−11.3	**	5.1	1.1	13.3	*	5.4	1.4	11.4	**
e_{ML}	14.4	10.0	21.5	**	−18.4	−22.4	−13.4	**	2.0	0.3	8.3	*	−6.0	−10.4	−2.5	**
e_L	24.7	19.0	27.1	**	26.3	21.3	29.2	**	11.0	8.6	15.7	**	12.3	8.5	15.5	**

** Wilcoxon signed rank test, P-value < 0.001.
* Wilcoxon signed rank test, $0.001 \leq P$-value < 0.013.
Kruskal-Wallis test was non-significant for group and side comparisons.