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Short communication

The effect on conventional gait model kinematics and kinetics of hip joint centre equations in adult healthy gait

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ABSTRACT

The Conventional Gait Model (CGM) needs to benefit from large investigations on localization of the hip joint centre (HJC). Incorrect positions from the native equations were demonstrated (Sangeux et al., 2014; Harrington et al., 2007). More accurate equations were proposed but their impact on kinematics and kinetic CGM outputs was never evaluated. This short communication aims at examining if adoption of new HJC equations would alter standard CGM outputs. Sixteen able bodied participants underwent a full 3-D optoelectronic gait analysis followed by a 3-D ultrasound localization of their hips. Data were processed through the open source python package pyCGM2 replicating kinematic and kinetic processing of the native CGM. Compared with 3D ultrasound location, Hara equations improved the accuracy of sagittal plane kinematics (0.6°) and kinetics (0.02 N m kg^{-1}) for the hip. The worst case participant exhibited Harrington's equations reached a deviation of 3° for the sagittal kinematics. In the coronal plane, Hara and Harrington equations presented similar differences (1°) for the hip whilst Davis equations had the largest deviation for hip abduction (2.7°) and hip abductor moment (0.10 N m kg^{-1}).

Both Harrington and Hara equations improved the CGM location of the HJC. Hara equations improved results in the sagittal plane, plus utilise a single anthropometrics measurement, leg length, that may be more robust. However, neither set of equations had significant effect on kinematics. We reported some effects on kinetics, particularly in the coronal plane, which warrant caution in interpreting outputs using different sets of equations.

1. Introduction

The Conventional Gait Model (CGM) (Davis et al., 1991; Kadaba et al., 1990) is widely used in clinical gait analysis. Its kinematics and kinetics outputs help clinicians to identify gait impairments, guiding rehabilitation program or influence surgical treatment. The CGM became a standard thanks to its implementation in commercial software and widespread application in clinics and research. However, the way that the CGM defines the location of the Hip Joint Centres (HJC) has been widely criticised (Kainz et al., 2015; Peters et al., 2012; Sangeux et al., 2014, 2011).

The CGM located the HJC based on equations derived from planar radiographs of 25 adult subjects (Davis et al., 1991). Since the 2000s, researchers in gait analysis have investigated improved methods to locate the HJC, benefiting from advances in medical imaging (Ehrig et al., 2006; Sangeux et al., 2014). Three types of methods may be distinguished. Conventional methods use regression equations to predict the coordinates of the HJC in the pelvic coordinate system from anthropometrics measurements, such as pelvis width or leg length (Hara et al., 2016; Harrington et al., 2007; Sholukha et al., 2011). Functional calibration methods use the hip motion of the subjects (Ehrig et al., 2006; Gamage and Lasenby, 2002; Halvorsen et al., 1999; Hicks and Richards, 2005). The third category extracts the local HJC from medical imaging, such as freehand 3D ultrasound (Peters et al., 2012, 2010; Sangeux et al., 2011) or low-dose bi-plane radiographs (Sangeux et al., 2014).

Clinical gait analysis tends to favour the conventional methods (Kainz et al., 2015; Sangeux et al., 2014, 2011) because functional methods require sufficient hip range of motion, which pathological subjects may not be able to achieve themselves. Despite its accuracy, the use of medical imaging is not yet commonly implemented. A low dose bi-plane radiographs system such as the EOS (EOS imaging, France) (Pillet et al., 2014) may be rarely accessible in practice, and the use of freehand 3D ultrasound may slow down the proceedings of a 3D gait examination. A systematic review

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(Kainz et al., 2015) identified the equations of Harrington et al. as the most accurate (Harrington et al., 2007). Later, Hara et al. (2016) used a dataset of 157 pelvises to investigate the influence of age and sex on the position of the HJC, and concluded that these had little effects and provided new sets of equations, only dependent on leg length as the anthropometrics predictor.

Some studies investigated the effect of the position of the HJC position on the kinematics and kinetics outputs of various gait models (Cereatti et al., 2007; Kainz et al., 2017; Kiernan et al., 2015; Stagni et al., 2000). These authors came to the consensus that methods which minimize errors on the antero-posterior location of the HJC should be favoured in gait analysis. However, to our knowledge, no study has investigated the effect of HJC mis-location on the outputs of the CGM, because the CGM has been implemented in a proprietary commercial package that cannot be modified. We recently developed an open-source exact clone of the CGM in python (Leboeuf et al., 2017), which now allows users to modify either the geometry of CGM or its kinematic and kinetic processing. The aim of this study was to evaluate the effect of various conventional methods to locate the HJC on the kinematics and kinetics outputs of the CGM. We compared the equations of Davis, Harrington and Hara with respect to the HJC location determined using freehand 3D ultrasound.

Since the CGM is a hierarchical top-down model, errors at the hip propagates distally, so we assessed differences for all lower joints (i.e. hip, knee and ankle).

2. Methods

Sixteen able bodied participants, 8 males and 8 females, with a mean age of 36 ± 18 years and Body Mass Index (BMI) of 23.0 ± 3.6 kg/m^2, were recruited to the study after approval had been obtained from the Royal Children's Hospital (RCH) human Research Ethics Committee. Participants underwent a full 3-D optoelectronic gait analysis (Vicon, Oxford metrics UK) followed by a 3-D ultrasound localization of their hips. This sample of subjects took part in the analysis of a previous study (Peters et al., 2010) dedicated to validation of the freehand 3D ultrasound methods. Therefore, we utilised the position of HJC reported in their study.

An experienced registered physiotherapist recorded the required anthropometric measurements and placed 14 mm diameter optoelectronic markers on each participant as specified by the CGM ("Plugin gait guide," 2010).

Calibration of the CGM in the coronal plane was performed with the CGM variant including the ankle medial malleolus markers in addition with the Knee Alignment Device (KAD) on both sides. HJC location from Davis (Davis et al., 1991), Harrington (Harrington et al., 2007) and Hara (Hara et al., 2016) equations were expressed in the CGM pelvis coordinate system.

Marker trajectories, collected at 100 Hz, were filtered with Woltring cross-validity quintic spline routine (Woltring, 1986). Kinematics and kinetics were computed with the open-source python package pyCGM2 (www.pycgm2.github.io, Leboeuf et al., 2017), replicating the Vicon PiG outputs while allowing customization of HJC locations. The Gait Profile Score GPS (Baker et al., 2009) was computed with normative data from Schwartz et al. (2008). Two AMTI force plates (AMTI Inc., Watertown, MA) provided measurement of the ground reaction force at 1000 Hz, initializing the inverse dynamic problem. Joint moments were projected into the joint coordinate system, JCS (Schache and Baker, 2007).

The accuracy of the regression equations was calculated as the root mean square difference (RMSD) with the location of the HJC determined using freehand 3D ultrasound (Peters et al., 2010). For each regression, the worst-case participant maximizing the distance with the ultrasound position was identified. RMSD were also used for assessing the difference for kinematic and kinetic traces from regression equations with ultrasound.

3. Results

Fig. 1 reports, in the entire cohort and the worst cases for each equation, the difference between the HJC location of the three regression equations compared to freehand 3D ultrasound. Results for the Davis equations were worst in the transverse plane of the pelvis. Mean deviations were 7.6 ± 5.6 mm and −17.4 ± 8.6 mm along antero-posterior and medio-lateral axes, respectively. Subject 13 (female, age 17, 1.77 m, 98.5Kg) exhibited the maximal deviation with the ultrasound (9.8 mm [ant/post], −21.9 mm [med/lat] and −18.5 mm [inf/sup]). Harrington equations were best for the medio-lateral position (1.6 ± 7.2 mm), but positioned the hips too posteriorly (−7.6 ± 6.4 mm). The worst deviation (−23.7 mm [ant/post], 12.3 mm [med/lat] and 8.4 mm [inf/sup]) occurred for subject 09 (female, age 18, 1.58 m, 58.6Kg). Hara equations were best for the antero-posterior HJC location (−1.1 ± 5.4 mm) but tended to position the hips too medially (−6.5 ± 7.6 mm). The worst deviation (−3.5 mm [ant/post], −13.1 mm [med/lat] and 20.5 mm [inf/sup]) was identified for subject 10 (male, age 19, 1.73 m, 81.1 Kg). None of the equations improved the inferior-superior location of the HJC, although Davis equations placed the hips too inferior while Harrington and Hara equations placed the hips too superior.

Table 1 and Figs. 2 and 3 depict the effect of the various HJC locations on kinematics and kinetics. In the supplementary data, gait traces regarding each worst-case participant are presented.

Maximal kinematic deviations were obtained with Davis's equations in the coronal plane. Both hip and knee abduction angles reached an RMSD of 2° for the population and approximatively 3° for the worst case. RMSD for Hara and Harrington equations were similar and lesser than 1.2° for these angles while worst cases reached 1.8° and 2.37° for both equations respectively. In addition, Fig. 2 demonstrated that coronal angles from Hara and Harrington were on both sides of the ultrasound trace. In the sagittal plane, Hara equations presented minimal RMSD (0.6 ± 0.5°) for both hip and knee flexions respectively whereas Harrington and Davis deviated from about 1°. The Hara worst case reached 0.7° whilst the Harrington worst case presented difference of about 3° for hip and knee flexion.

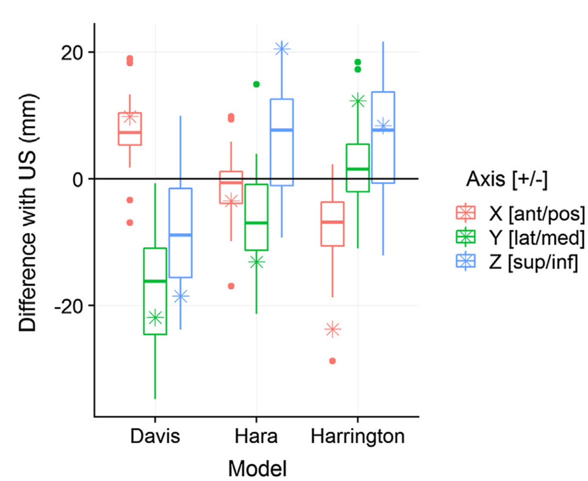

Fig. 1. Difference on the three axes of local position within the pelvic coordinate system of HJC from the three regressions (Davis, Harrington and Hara) with the measured ultrasound location. Star symbols indicate worst case participants identified within our population for each regression.

Table 1
Root Mean Square difference between CCGM outputs from the three set of equations (Davis, Hara, Harrington along with its worst cases) and the HJC location measured from freehand 3D ultrasound.

		HJC equations	Angles (°) Mean(sd)			Moments (Nm Kg^{-1}) Mean(sd)			Power (W Kg^{-1}) Mean(sd)
			Sagittal	Coronal	Transversal	Sagittal	Coronal	Transversal	
Hip	Population	Davis	1.12(0.62)	2.39(1.13)	0.92(0.47)	0.05(0.02)	0.10(0.05)	0.02(0.01)	0.10(0.05)
		Hara	0.66(0.47)	1.18(0.80)	0.70(0.50)	0.02(0.02)	0.05(0.03)	<0.01	0.06(0.03)
		Harrington	1.17(0.73)	1.21(0.92)	0.71(0.52)	0.05(0.03)	0.05(0.04)	<0.01	0.08(0.05)
	Worst cases	Davis	0.92(0.16)	2.85(0.17)	1.03(0.35)	0.04(0.01)	0.10(0.01)	0.01(0.00)	0.08(0.00)
		Hara	0.72(0.07)	1.80(0.26)	1.26(0.04)	0.02(0.01)	0.07(0.01)	0.01(0.00)	0.07(0.02)
		Harrington	2.96(0.36)	2.37(0.60)	1.04(0.89)	0.12(0.02)	0.10(0.03)	0.02(0.02)	0.24(0.07)
Knee	Population	Davis	1.06(0.90)	2.18(0.10)	1.06(0.6)	<0.01	<0.01	<0.01	<0.01
		Hara	0.62(0.47)	1.07(0.66)	0.72(0.39)	<0.01	<0.01	<0.01	<0.01
		Harrington	1.13(0.78)	1.12(0.76)	0.70(0.33)	<0.01	<0.01	<0.01	<0.01
	Worst cases	Davis	0.71(0.24)	2.74(0.09)	1.00(0.05)	0.01(0.00)	0.01(0.00)	<0.01	0.02(0.00)
		Hara	0.60(0.14)	1.51(0.26)	1.18(0.11)	0.01(0.00)	0.01(0.00)	<0.01	0.03(0.00)
		Harrington	3.12(0.55)	1.94(0.46)	0.97(0.35)	0.01(0.01)	0.01(0.00)	<0.01	<0.01
Ankle	Population	Davis	0.16(0.06)	0.05(0.03)	0.36(0.14)	<0.01	<0.01	<0.01	<0.01
		Hara	0.12(0.07)	0.03(0.02)	0.25(0.14)	<0.01	<0.01	<0.01	<0.01
		Harrington	0.11(0.06)	0.02(0.02)	0.25(0.13)	<0.01	<0.01	<0.01	<0.01
	Worst cases	Davis	0.17(0.02)	0.04(0.01)	0.42(0.02)	<0.01	<0.01	<0.01	<0.01
		Hara	0.20(0.01)	0.10(0.01)	0.42(0.02)	<0.01	<0.01	<0.01	<0.01
		Harrington	0.13(0.09)	0.02(0.01)	0.27(0.19)	<0.01	<0.01	<0.01	<0.01

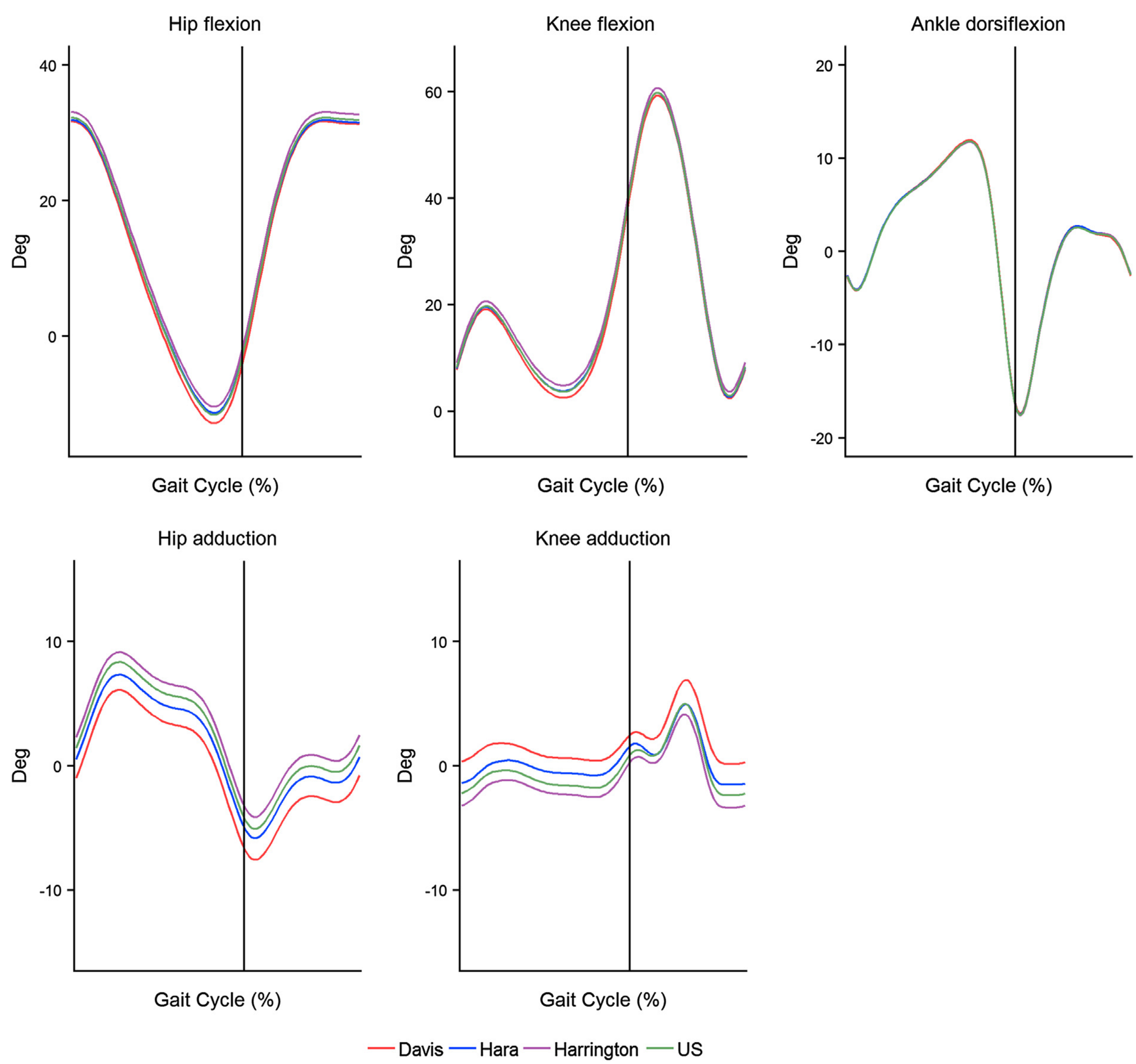

Fig. 2. (Top row) mean sagittal kinematics of hip, knee and ankle, and (bottom row) mean coronal kinematics of hip and knee, outputs of the CGM using the freehand 3D ultrasound position of the HJC and the three set of equations (Davis, Hara and Harrington). The vertical lines represent the averaged instant for foot-off.

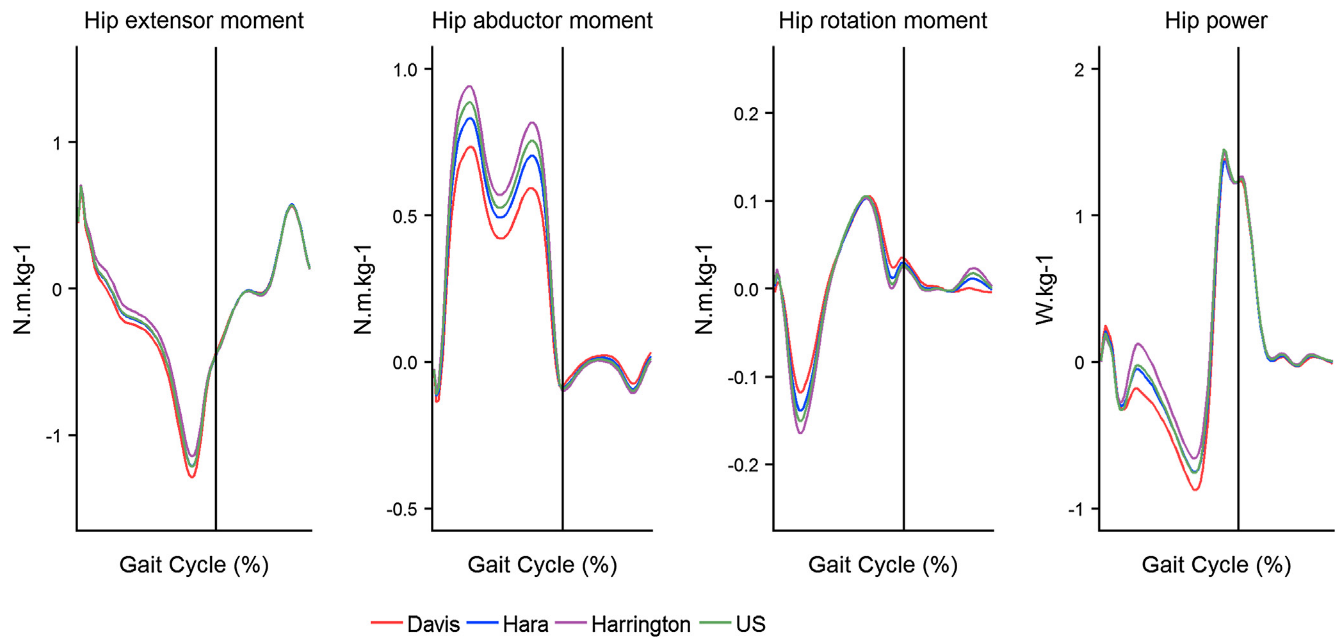

Fig. 3. Mean hip internal moments and power output from the CGM using the freehand 3D ultrasound location of the HJC and the three set of equations (Davis, Hara and Harrington). The vertical lines represent the average instant for foot-off.

The GPS, which reflects the overall effect on kinematics, was not sensitive to the set of equations: 0.15 ± 1.11°, 0.12 ± 0.08° and 0.1°±0.1° (0.02°, 0.10° and 0.41° for worst cases) for Davis, Hara and Harrington respectively.

Different set of equations mostly impacted kinetics at the hip in the sagittal and coronal planes. Negligible differences (<(0.01 N m kg^{-1}) were assessed for both knee and ankle kinetics. Hara equations presented minimal RMSD (0.02 N m kg^{-1} ± 0.02) for the hip extensor moment, whereas Davis exhibited the largest RMSD (0.10 N m kg^{-1} ± 0.05) for the hip abductor moment. The maximal deviation (0.12 N m kg^{-1}) from worst cases occurred for the hip flexor and Harrington's equations. Fig. 2 highlights that HJC location mostly affected the stance phase.

4. Discussion

Recent literature (Leardini and Cappozzo, 1999; Peters et al., 2012; Sangeux et al., 2014, 2011) demonstrated that the regression equations embedded in the CGM predict incorrect positions of the HJC. Harrington et al. (2007) and Hara et al. (2016) provided alternative equations to position the HJC. However, the adoption of new set of equations to locate the HJC requires preliminary knowledge of the effect on kinematics and kinetics. In this short communication, we investigated the effect of the set of equations to locate the HJC on the kinematics and kinetics outputs of the CGM, thanks to an open-source python package, the pyCGM2 (www.pycgm2.github.io (Leboeuf et al., 2017)), which replicates the calculations of the CGM. Overall, our results reported small effects of the choice of HJC equations on gait kinematics and kinetics of healthy adults.

In our healthy adult sample, Hara equations presented reduced errors along the anterior-posterior pelvic axis. Reduced errors in this axis lead to more accurate sagittal kinematics and kinetics. Hara equations only utilise the leg length measurement, whereas Harrington equations also require measurement of pelvis width and depth. Without medical imaging, the measurement of pelvic depth may be prone to errors, especially in subjects with excess abdominal adipose tissues. However, neither the Harrington nor Hara equations improved on the default CGM position of the HJC in the inferior-superior axis.

The influence of HJC equations on kinematics tended to be negligible overall. The maximal difference in GPS (0.15°) was far off the minimal clinical significant differences of 1.6° (Baker et al., 2012) and 3.2° (Putz et al., 2016) obtained in children and adults with cerebral palsy, respectively. This was already observed by Kiernan et al. (2015) (mean GPS difference of 0.27°), who compared various equations to locate the HJC in another commercial gait model (Codamotion Analysis software, Charnwood Dynamics Ltd., Leicestershire).

Locally, Hara equations improved the accuracy of sagittal plane kinematics for both hip and knee flexion. While Hara equations provided consistent HJC location with ultrasound along the antero-posterior direction, the worst case participant for Harrington's equations was predominantly marked by a higher deviation along this direction which affected hip and knee flexion by 3°.

In the coronal plane, Hara and Harrington equations presented similar differences (1°) for the hip and knee. In contrast, Davis equations had the largest mean deviation (2.7°) for hip abduction. These values are smaller than those reported in Kainz et al. (2017), which exceeded 5° for a gait model similar, but not identical, to the CGM. It is important to note that a difference of 2° remains below the limit of 5°, considered acceptable (McGinley et al., 2009) and thus tends to confirm the minor clinical impact of hip equations.

The HJC location mostly influenced kinetics at the hip. Altering the HJC of the CGM (i.e. from Davis to other regressions) may still be performed with caution on kinetics. Indeed, Kiernan et al. (2015), reported Harrington and Davis equations exceeded a clinical threshold set on GDI-Kinetic index (3.6 points) established in a previous article (Kiernan et al., 2014) for a population of children with a diagnosis of cerebral palsy. We obtained a similar difference (0.1 N m kg^{-1}) to Kiernan (Kiernan et al., 2015) for the hip flexor moment using Harington and Davis. In addition, we exhibited a difference for the hip abductor moment, absent in Kiernan.

A limitation of Kiernan (Kiernan et al., 2015) was not to address accuracy against a gold standard. Our analysis showed Davis's equations led to an underestimate of hip abductor moment (0.1 N m kg^{-1}). Harrington and Hara equations were similar

(0.05 N m kg^{-1}) for this joint moment. A difference of 0.05 N m kg^{-1} is clinically questionable since the minimal clinical indicator (Foucher, 2016) for the hip abductor moment after hip arthroplasty would be 0.07 N m kg^{-1} for our population. Therefore, firstly, we recommend meta-analyses involving different biomechanical models and different HJC equations. Secondly longitudinal analysis or multicentric studies must be performed with the same HJC equations.

This work has some limitations. First, the analysis was conducted on able-bodied subjects with a relatively normal BMI. Results may be different in adults with larger/smaller BMI, children, or populations with hip pathologies. The GPS was calculated relative to the spontaneous gait data provided by Schwartz et al. (2008) in typically developing children. We obtained only small difference in GPS between the Schwartz normative dataset and the adults in this study cohort. Third, Bell's equations (Bell et al., 1989) weren't considered as Harrington et al. (2007) reported a small difference on the antero-posterior axis of their regression with Bell's equation. Finally, although the freehand 3D ultrasound was validated (Peters et al., 2010), the use of a magnetic resonance imaging or low-dose 2D radiographic imaging device would have been better gold standards.

In conclusion, both Harrington and Hara equations improved the CGM location of the HJC. Hara equations are not influenced by age and sex (Hara et al., 2016). They have the additional advantage of improved results in the sagittal plane, and utilise a single anthropometrics measurement, leg length, which may be more robust to different body shapes than the pelvis width and depth measurements utilised in Harrington equations.

However, once implemented in a clone of the CGM, neither set of equations had significant effect on kinematics. Since they minimize kinetics deviations, particularly in the coronal plane, we recommend the use of Hara's equations (Hara et al., 2016).

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Conflict of interest statement

Fabien Leboeuf received funding from Vicon (Oxford UK).

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We further confirm that any aspect of the work covered in this manuscript that has involved humans has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.02.010.

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