İKÇÜSBFD

ARAŞTIRMA / RESEARCH

The Effects of Functional Hip Calibration Movements on the Kinematic Data of Gait Analysis in Children with Cerebral Palsy

Fonksiyonel Kalça Kalibrasyon Hareketlerinin Serebral Palsili Çocuklarda Yürüyüş Analizinin Kinematik Verilerine Etkileri

Orhan ÖZTÜRK[1,2], İlkşan DEMİRBÜKEN[2], Mine Gülden POLAT[2], Sebastian WOLF[3]

[1]*İzmir Katip Celebi University, Faculty of Health Sciences Department of Physiotherapy and Rehabilitation Çiğli, İzmir*
[2]*Marmara University Faculty of Health Sciences Department of Physiotherapy and Rehabilitation Maltepe, İstanbul*
[3]*Heidelberg University Hospital Orthopedics and Trauma Surgery Clinic Heidelberg Germany*

Geliş tarihi/Received: 07.07.2021
Kabul tarihi/Accepted: 10.09.2021

İletişim/Correspondence:

Orhan ÖZTÜRK, PT, MSc
İzmir Kâtip Çelebi University Faculty of Health Sciences Main Campus Central Offices 1, Floor: 2, Room No: 238, 35620 Çiğli/İZMİR
E-posta: fzt.orhanozturk@gmail.com
ORCID: 0000-0003-1924-1413

İlkşan DEMİRBÜKEN, Doç. Dr.
ORCID: 0000-0003-0566-5784

Mine Gülden POLAT, Prof. Dr.
ORCID: 0000-0002-9705-9740

Sebastian WOLF, Prof. Dr.
ORCID: 0000-0003-3921-6629

Abstract

Objective: Although there are studies investigating the effects of functional hip calibration movements on the hip joint centre in gait analysis, the clinical reflections of these calibration movements have not been examined. The aim of the present study is to examine the effects of hip joint centres obtained with three different functional calibration movements (Flexion/Extension-Abduction/Adduction-Circumduction (FAC), Modified Star Motion (Mstar) and Contra Lateral Side Modified Star Motion (CsMstar)) on kinematic outcomes.

Material and Method: Twenty-three participants with cerebral palsy (10 female, 13 male, mean age: 15.57 ±7.55 years) were included in the study. The hip joint centre was determined by using the functional method in gait analysis by performing three different calibration movements. Kinematic data of the lower extremities were obtained via three-dimensional gait analysis. The effects of functional hip joint centres on kinematic results were evaluated by using the Gait Profile Score (GPS) and peak kinematic values. In addition, the root mean square difference (RMS) and the mean difference of the kinematic waveforms were investigated.

Results: GPS value, obtained with FAC calibration movement, was statistically different from Mstar and CsMstar ($p<0.001$). The difference between the mean GPS values is 0.34o between FAC and Mstar, and 0.29o between the FAC and CsMstar. The difference in peak kinematic values between FAC and Mstar was found to be highest in the sagittal plane (1.95o) in the knee joint, and between the FAC and CsMstar in the sagittal plane of the hip joint (1.87o). The RMS differences of the kinematic waveform of the hip and knee joint were found below 3o.

Conclusion: Hip joint centres obtained by using three different calibration movements in gait analysis did not alter the kinematic parameters clinically. One of the three movements can be used to determine the functional hip joint centre for gait analysis of children with cerebral palsy.

Keywords: Gait analysis, hip joint centre, kinematics, cerebral palsy.

Öz

Amaç: Fonksiyonel kalça kalibrasyon hareketlerinin yürüyüş analizinde kalça eklem merkezi üzerine etkilerini inceleyen çalışmalar bulunsa da bu kalibrasyon hareketlerinin kliniğe yansımaları incelenmemiştir. Bu çalışmanın amacı üç farklı fonksiyonel kalibrasyon hareketi (Fleksiyon/Ekstansiyon-Abduksiyon/Adduksiyon-Sirkümdüksiyon (FAC), Modifiye Star Hareketi (Mstar) ve Kontralateral Taraf Modifiye Star Hareketi (CsMstar)) ile elde edilen kalça eklem merkezlerinin yürüyüş analizi kinematik sonuçlara etkilerinin incelenmesidir.

Gereç ve Yöntem: Çalışmaya 23 serebral palsili (10 kız, 13 erkek, ortalama yaş: 15.57 ±7.55 yıl) katılımcı dâhil edildi. Üç farklı kalibrasyon hareketi yapılarak yürüyüş analizinde kalça eklem merkezi fonksiyonel metot ile belirlendi. Üç boyutlu yürüyüş analizi yapılarak alt ekstremitelerin kinematik verileri elde edildi. Fonksiyonel kalça eklem merkezlerinin kinematik sonuçlar üzerine etkileri Yürüyüş Profil Skoru (GPS) ve pik kinematik değerler kullanılarak değerlendirildi. Ayrıca, kinematik verilerin dalga formlarının kök ortalama kare farkı (RMS) ve ortalama farkı incelendi.

Bulgular: FAC kalibrasyon hareketi ile elde edilen GPS değeri, Mstar ve CsMstar'a göre istatistiki olarak farklılık gösterdi ($p<0,001$). Ortalama GPS değerleri arasındaki fark FAC ile Mstar arasında 0,34o, FAC ile CsMstar arasında ise 0,29o idi. FAC ile Mstar arasındaki pik kinematik değerleri farkı en fazla diz ekleminde sagittal planda (1,95o), FAC ile CsMstar arasında ise kalça ekleminin sagittal planında (1,87o) olduğu saptandı. Kalça ve diz ekleminin kinematik dalga formunun RMS farkları 3o'nin altında bulundu.

Sonuç: Yürüyüş analizinde üç farklı kalibrasyon hareketleri kullanılarak elde edilen kalça eklem merkezleri, kinematik parametrelere klinik açıdan etki etmemişlerdir. Serebral palsili çocukların yürüyüş analizi için fonksiyonel kalça eklem merkezinin belirlenmesinde üç hareketten biri kullanılabilir.

Anahtar Kelimeler: Yürüyüş analizi, kalça eklem merkezi, kinematik veriler, serebral palsi.

1. Introduction

Hip joint centre (HJC) is one of the essential points for calculation of kinematics in the gait analysis for both normal and pathological gait (1). Because the palpation of the HJC is not possible, and imaging techniques are not readily available for the most of gait analysis laboratories, the position of the HJC is usually estimated in predictive or functional approaches (2). In several studies, functional methods have been used frequently to develop reliable results for the estimation of the HJC location (3-5).

Functional methods depend on calibration movements of adjacent segments (hip and thigh) for estimation of the HJC (3). Type of the functional calibration movement is one of the factors which have a direct impact on the location of the HJC (6). Several studies have been performed to investigate the effect of the different functional hip calibration movements such as stair ascending/descending, standing from sitting, walking, Star and Star-arc, a combined movement consisted of flexion-extension, abduction-adduction, and circumduction movements (7, 8). It was indicated that Star and Star-arc movements provide more accurate location of the HJC than others (9). However, it may not be easy to perform these two hip calibration movements in patients with neurological movement disorders, such as cerebral palsy (CP). Although patients with cerebral palsy are evaluated frequently for gait abnormalities (10, 11), there is no consensus on which type of functional hip calibration movement should be used.

In the gait analysis, the kinematic values of the joints are obtained by evaluating the positions of the axes of the segments relative to each other. The position of the HJC in the three-dimensional plane directly affects the determination of the axes of the upper and lower leg segments. It has been reported that deviations in the position of the HJC significantly affect the kinematic and kinetic results of gait analysis (1). Although the effects of different functional calibration movements in determining the position of the HJC have been investigated (6, 7), there is no study examining the effects of these calibration movements on gait analysis kinematic data. Therefore, the purpose of the present study was to evaluate the effects of three functional hip calibration movements on kinematic results in patients with CP.

2. Materials and Methods

Twenty-three participants with CP who consulted for gait analysis were recruited to the study. Sample size was stated according to similar studies (12-14). Sufficient compliance, understanding the task for calibration movements and being level I-III in gross motor function classification system (GMFCS) (15) were the inclusion criteria. Participants with insufficient compliance and level IV, V in GMFCS were excluded. The demographic parameters including age, weight, height, body mass index, CP type and GMFCS level were presented in Table 1. The approval of the study was obtained from the Ethics Committee of the Heidelberg University School of Medicine (S-215/2019). The protocol was described to all participants and their parents, and informed consent forms were signed by each participant and their parents prior to participation. This experimental study was carried out Heidelberg University Gait Analysis Lab between March 2019 – December 2019.

Table1. Demographics of Participants

N	Age (year)	Height (cm)	Weight (kg)	BMI (kg/m²)	Type of CP		GMFCS Level
23 (Female=10) (%43) (Male=13) (%47)	15.57 ± 7.55	154.35 ± 17.61	47.32 ± 17.80	19.17 ± 4.09	Spastic Diplegia: Spastic Hemiplegia :	N= 19 N= 4	I: N=12 II: N=8 III: N=3

BMI: body mass index, GMFCS: gross motor function classification system

A total of twenty-seven reflective skin markers were used for tracing lower extremities during gait analysis and determination of functional HJCs. Fifteen of them were placed on the lower extremity, according to the Plug-in Gait protocol (16). Six additional markers were located on the anterior and posterior area of the thigh segments and the other six were placed on the anterior surface of shank segments (Figure 1) (17). Optimal common shape technique was applied to reduce the soft tissue artefact (18). Three-dimensional motion data was obtained using twelve MX3 cameras (Vicon, Oxford Metrix, UK) and the Nexus software.

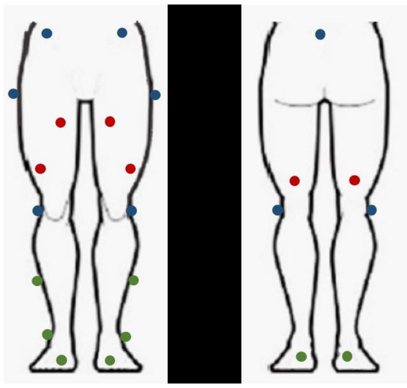

Figure 1. Marker Set Placed on the Pelvis and Lower Extremit

Red and blue markers were used to monitor the movements of the pelvis and thigh segment during functional calibration movements. Blue and green markers were used to obtain kinematic data in the gait cycle.

For identification of the effect of different hip joint calibration movements (Flexion-Extension/Abduction-Adduction/Circumduction (FAC); Modified Star Motion (M-Star); Contralateral Side Modified Star Motion (CsM-Star)) on kinematic results, calibration movements were performed prior to walking trials. All three calibration movements were shown by the examiner to be replicated by participants. Participants were permitted to hold the examiner's hand or a tripod with the contralateral hand to maintain the balance during the calibration motion. Hip joint calibration movements were described below.

- For the FAC, participants were asked to stand on one leg and then to perform hip flexion-extension and hip abduction-adduction movement, ending with a circumduction movement with the unloaded leg without touching the ground (6) (Figure 2).

- The M-Star is the modified version of the star motion (19). Following the star shape, the ground was taped as a half circle with seven points which were distantly equal to each other. Participants were asked to stand in the middle of the half-circle. While one leg was steady in the middle of the half-circle, the other leg performed step forward to the points and backward. Participants were asked to touch the ground in taped points (Figure 2).

• A third calibration movement (CsM-Star) was obtained by analysing the movement of the contralateral hip of the M-Star movement since it turned out that also the stance leg shows pronounced hip motion.

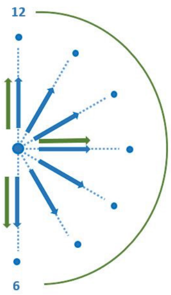

Figure 2. Functional Calibration Movements

The starting position for all movements is in the middle of the semicircle, with the trunk facing towards 12. Participants were asked to complete movements without changing the direction of their bodies.

For the FAC movement, participants were asked to stand on one foot and perform flexion – extension, then abduction – adduction, and finally circumduction with the other lower extremities (the moving foot touched the ground) (Green arrows).

For the Mstar movement, one foot was stationary in the middle of the semicircle, while the other foot was asked to step back towards the blue marked points.

In the CsMstar, the hip movements of the extremity of the stance limb were analysed.

Functional HJC estimation was computed using SCoRE algorithm developed by Ehrig et al. (2006) (3). Participants were asked to walk through the path of gait analysis 10 times to obtain kinematic parameters. Quantitative kinematic gait data was collected via Nexus 2.8 (Vicon, Oxford Metrix, UK).

Effects of three different functional HJCs on kinematics were compared using Gait Profile Score (GPS) which was developed to facilitate the understanding of the results of gait analysis by summarizing the data on nine kinematic variables (pelvic tilt, pelvic obliquity, pelvic rotation, hip flexion, hip adduction, hip rotation, knee flexion, ankle dorsiflexion and foot progression) (20). GPS is a composite measure of gait quality. Peak kinematic values of hip and knee joints in the stance phase were analysed. Kinematic waveforms of hip and knee joints were compared using root mean square (RMS) differences. The RMS of a continuous-time waveform is the square root of the arithmetic mean of the squares of the continuous waveform. In addition, mean differences of the kinematic waveforms were analysed in 5o categorisations. Outcomes of FAC were used as reference for mean and RMS difference comparison of kinematic waveforms.

All statistical analyses were processed using Statistical Package for the Social Science (SPSS) (v20, IBM Corp. NY). Statistical analysis had been performed after the distribution of all variables was tested for normality using the Kolmogorov-Smirnov test. Data sphericity was evaluated using Mauchly's test. Peak kinematic values of hip and knee joints in three planes and GPS values were tested using repeated measure ANOVA, with multiple pairwise comparisons using Bonferroni (p value = 0.05). Mean differences of the kinematic waveforms in 5o categorisations presented in percentage.

3. Results

HJCs which were obtained with different functional calibration movements affected the peak kinematics and GPS values of the hip and knee joints statistically. Comparisons between functional calibration movements were presented in Table 2. The difference in the mean GPS values is 0.34o between FAC and Mstar, and 0.29o between the FAC and CsMstar. The difference in peak kinematic values between FAC and Mstar was found to be highest in the sagittal plane in the knee joint (1.95o), and between FAC and CsMstar in the sagittal plane of the hip joint (1.87o).

The RMS difference of the kinematic waveforms of the hip and knee joint was found less than 3o (Table 3). In the kinematic waveforms, the mean difference of the flexion/extension value of the hip and knee joint between the FAC and Mstar was within the range of ±5o in 87% of the extremities, and within the range of ±5o in all other kinematic parameters. Between the FAC and CsMstar, the mean difference of the abduction/adduction value of the hip joint was within the range of ±5o in 98% of the extremities, and all other kinematic parameters were within the range of ±5o (Table 4).

Table 2. The GPS and Peak Kinematic Values

		FAC		Mstar		CsMstar		p
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	
GPS		11.05	2.92	10.71	2.98	10.76	2.97	<0.001 (‡ϒ)
Hip	**Flex/Ext**		7.25	43.01	7.90	42.99	7.65	<0.001 (‡ϒ)
	Add/Abd		4.37	7.51	4.64	8.32	4.41	0.015 (§)
	Rot (Int/Ext)	8.66	11.09	8.91	11.03	8.85	11.15	<0.001 (‡ϒ)
Knee	**Flex/Ext**		6.56	59.09	6.21	59.20	6.85	<0.001 (‡ϒ)
	Val/Var		3.66	-1.06	3.93	-1.80	3.99	0.006 (‡§)
	Rot (Int/Ext)	13.50	7.90	13.84	8.30	13.23	7.97	<0.001 (§)

The mean of GPS and peak kinematic values of groups were presented. Comparisons between groups were made with Bonferroni multiple comparison test after repeated ANOVA test. ‡ sign indicates a statistically significant difference between FAC and Mstar, ϒ sign between FAC and CsMstar, and § sign between Mstar and CsMstar. Flex/Ext: Flexion/Extension, Add/Abd: Adduction/Abduction, Int/Ext: Internal/External, Valg/Var: Valgus/Varus

Table 3. The RMS Differences of Kinematic Waveforms Referenced on FAC

		FAC – Mstar		FAC – CsMstar	
		Mean	**SD**	**Mean**	**SD**
Hip	**Flex/Ext**	2.10	1.79	1.96	1.17
	Add/Abd	1.43	1.02	1.49	1.27
	Rot (Int/Ext)	0.28	0.24	0.26	0.19
Knee	**Flex/Ext**	2.16	1.78	1.98	1.17
	Valg/Var	1.19	0.82	1.30	1.11
	Rot (Int/Ext)	0.72	0.49	0.80	0.65

Flex/Ext: Flexion/Extension, Add/Abd: Adduction/Abduction, Int/Ext: Internal/External, Valg/Var: Valgus/Varus

Table 4. The Kinematic Waveforms Differences within 5-degree Categorisation Referenced to the FAC

			>=-10º, -5º<	>=-5º, 0º<	>=0º, 5º<	>=5º, 10º<
FAC vs M-Star	**Hip**	**Flex/Ext**	0	7	36	3
		Add/Abd	0	18	28	0
		Rot (Int/Ext)	0	29	17	0
	Knee	**Flex/Ext**	0	6	37	3
		Valg/Var	0	31	15	0
		Rot (Int/Ext)	0	30	16	0
FAC vs CsM-Star	**Hip**	**Flex/Ext**	0	5	41	0
		Add/Abd	0	29	16	1
		Rot (Int/Ext)	0	31	15	0
	Knee	**Flex/Ext**	0	5	41	0
		Valg/Var	0	19	27	0
		Rot (Int/Ext)	0	18	28	0

Flex/Ext: Flexion/Extension, Add/Abd: Adduction/Abduction, Int/Ext: Internal/External, Valg/Var: Valgus/Varus

4. Discussion

The present study was carried out to investigate the effects of the HCJs which were obtained with different functional calibration movements, on kinematic outcomes in gait analysis. Although there are studies which reported the effects of the HJCs on kinematics (6, 7), this is the first study examining the effects of different the HJCs depending on the calibration movement on kinematic results in children with CP. The differences between the GPS values of the kinematic data were less than the reported minimal clinically important differences (1,6o) (17). Although there was a statistically significant difference between the peak kinematic values of the hip and knee joint, the RMS differences of the kinematic waveforms were less than 3o.

GPS indicates the composition of gait quality. A statistically significant difference was found among the GPS value of the kinematic outcomes obtained with the FAC functional calibration movement and the Mstar, and CsMstar. However, reported clinically significant difference for GPS was 1.6o in children with CP (21). In the present study, the mean difference in the GPS value was 0.34o between FAC and Mstar, 0.29o between FAC and CsMstar. This result indicated that HJCs obtained with different functional calibration movements do not clinically alter the gait quality. Although there are studies examining the effects of functional hip calibration movements on HJCs in the literature, the clinical implications of these calibration movements have not been examined (9). However, studies examining the effects of HJCs which are determined by different predictive methods on kinematic outcomes have been presented (12, 13). In these studies, it was stated that the difference between the GPS value of the kinematic data obtained with different estimation methods was lower than the clinically significant value.

Changes in the position of the HJC in gait analysis directly alter the kinematic values of the hip and knee joints (22). Therefore, it is important to examine the kinematic parameters of these two joints in detail. In the present study, the first comparison was made between the peak values of the kinematic data. Although there was a statistical difference between the peak kinematic values of the hip and knee joint, the greatest difference between the means of the peak values was found below 2o, in the movement of the knee joint in the sagittal plane (FAC-Mstar: 1.95o and FAC-CsMstar: 1.85o). This indicates that there are negligible differences in the clinical interpretation of the data.

The RMS differences of the waveforms of the kinematic parameters are important in the detailed examination of the effects of the HJCs on the gait cycle. The differences over 5o indicate a clinically meaningful impact (23). In the comparison, referenced to FAC values in the present study, the greatest differences between RMS means in the gait cycle were found in both hip (FAC-Mstar: 2.10o; FAC-CsMstar; 1.96o) and knee joint (FAC-Mstar: 2.16o; FAC- CsMstar; 1.98o), and were determined to be in sagittal plane movements. The mean RMS differences of the kinematic waveform of the gait cycle in the frontal and transverse planes were less than 2o.

As mentioned above, although there are studies examining the effects of calibration movements on HJC, their effects on kinematic parameters have not been evaluated (9). In a study conducted by using predictive methods, waveforms of the kinematic values of the gait cycle of HJCs were examined and it was stated that the RMS difference was higher in the frontal plane than in the other two planes (12). It is thought that this difference between studies is due to the position of the HJCs relative to the reference HJC.

RMS difference was used to eliminate the neutralizing effect of the waveforms (12). However, making the comparison only by using RMS may cause the results to be always positive, and it may not provide information about which HJC gives kinematic outcomes were more in flexion/extension, abduction/adduction, or internal/external rotation. Therefore, the waveforms of the kinematic values of all participants were compared one by one and were presented as 5o categorisations. As a result of the comparison of the kinematic waveforms obtained using the FAC and Mstar calibration movement, it was determined that the sagittal plane differences of the hip and knee joints were more than 5o. When FAC and CsMstar data were compared, it was found that the difference in the mean kinematic value of the knee joint in the frontal plane was more than 5o. All other differences were below 5o, which is defined as the clinically significant. It was determined that FAC kinematic values in the hip joint were more in flexion, adduction and external rotation compared to Mstar, and were more in flexion, abduction and external rotation compared to CsMstar. When the knee joint was evaluated, FAC kinematic values were found to be in flexion, in knee varus and in external rotation according to Mstar, and in flexion, in knee valgus and in internal rotation according to CsMstar.

The main limitation of the study was not using medical imaging method to determine the exact location of the HJCs. Therefore, comparisons were made between kinematic values using the HJCs obtained using the FAC functional calibration motion as a reference. Another limitation of the study is that the participants were different types of spastic CP.

5. Conclusion and Recommendations

HJCs obtained using different hip calibration movements in children with cerebral palsy did not alter the kinematic parameters clinically. The kinematic outcomes were found to be very similar to each other and it was determined that all three of them could be used in the functional determination of HCJ, considering the differences mentioned above.

6. Contribution to the Field

The kinematic outcomes of gait analysis are the basis for determining the pathological condition or evaluating the effectiveness of the treatment. In gait analysis, the location of the hip joint centres in the three-dimensional plane directly alters the kinematic results. As a result of the present study, it was determined that using any of the above-mentioned hip calibration movements to determine the functional hip joint centre in children with CP did not make a clinical difference.

7. Ethical Aspect of the Research

The ethical approval of the study was obtained from the Heidelberg University, Faculty of Medicine, Ethics Committee on 25.04.2019 with the decision number S-215/2019. After the protocol of the study was described to all participants and their parents, the informed consent form was obtained from each participant and one of their parents prior to participation.

Conflict of Interest

This article did not receive any financial fund. There is no conflict of interest regarding any person and / or institution.

Authorship Contribution

Concept: OÖ, İD, MGP, SW; **Design:** OÖ, İD, SW; **Supervision:** OÖ, İD, MGP, SW; **Funding:** None; **Materials:** Yok; **Data Collection/Processing:** OÖ, İD, MGP, SW; **Analysis / Interpretation:** OÖ, İD, MGP, SW; **Literature Review:** OÖ, İD, MGP, SW; **Manuscript Writing:** OÖ, İD, MGP, SW; **Critical Review:** OÖ, İD, MGP, SW.

References

1. Stagni R, Leardini A, Cappozzo A, Grazia Benedetti M, Cappello A. Effects of hip joint centre mislocation on gait analysis results. J Biomech. 2000;33(11):1479-87.

2. Kainz H, Carty CP, Modenese L, Boyd RN, Lloyd DG. Estimation of the hip joint centre in human motion analysis: a systematic review. Clin Biomech (Bristol, Avon). 2015;30(4):319-29.

3. Ehrig RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for determining the centre of rotation of ball joints. J Biomech. 2006;39(15):2798-809.

4. Fiorentino NM, Atkins PR, Kutschke MJ, Foreman KB, Anderson AE. In-vivo quantification of dynamic hip joint center errors and soft tissue artifact. Gait Posture. 2016;50:246-51.

5. Heller MO, Kratzenstein S, Ehrig RM, Wassilew G, Duda GN, Taylor WR. The weighted optimal common shape technique improves identification of the hip joint center of rotation in vivo. J Orthop Res. 2011;29(10):1470-5.

6. Begon M, Monnet T, Lacouture P. Effects of movement for estimating the hip joint centre. Gait Posture. 2007;25(3):353-9.

7. McGibbon CA, Fowler J, Chase S, Steeves K, Landry J, Mohamed A. Evaluation of Anatomical and Functional Hip Joint Center Methods: The Effects of Activity Type, Gender, and Proximal Reference Segment. J Biomech Eng. 2016;138(1).

8. Sangeux M, Pillet H, Skalli W. Which method of hip joint centre localisation should be used in gait analysis? Gait Posture. 2014;40(1):20-5.

9. Piazza SJ, Erdemir A, Okita N, Cavanagh PR. Assessment of the functional method of hip joint center location subject to reduced range of hip motion. J Biomech. 2004;37(3):349-56.

10. Peters A, Baker R, Morris ME, Sangeux M. A comparison of hip joint centre localisation techniques with 3-DUS for clinical gait analysis in children with cerebral palsy. Gait Posture. 2012;36(2):282-6.

11. Assi A, Sauret C, Massaad A, Bakouny Z, Pillet H, Skalli W, et al. Validation of hip joint center localization methods during gait analysis using 3D EOS imaging in typically developing and cerebral palsy children. Gait Posture. 2016;48:30-5.

12. Leboeuf F, Reay J, Jones R, Sangeux M. The effect on conventional gait model kinematics and kinetics of hip joint centre equations in adult healthy gait. J Biomech. 2019;87:167-71.

13. Kiernan D, Malone A, O'Brien T, Simms CK. The clinical impact of hip joint centre regression equation error on kinematics and kinetics during paediatric gait. Gait Posture. 2015;41(1):175-9.

14. Miller EJ, Kaufman KR. Verification of an improved hip joint center prediction method. Gait Posture. 2018;59:174-6.

15. Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. Dev Med Child Neurol. 1997;39(4):214-23.

1**6.** Davis RB, Ounpuu S, Tyburski D, Gage JR. A Gait Analysis Data-Collection and Reduction Technique. Hum Movement Sci. 1991;10(5):575-87.

17. Kratzenstein S, Kornaropoulos EI, Ehrig RM, Heller MO, Popplau BM, Taylor WR. Effective marker placement for functional identification of the centre of rotation at the hip. Gait Posture. 2012;36(3):482-6.

18. Taylor WR, Ehrig RM, Duda GN, Schell H, Seebeck P, Heller MO. On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. J Orthop Res. 2005;23(4):726-34.

19. Camomilla V, Cereatti A, Vannozzi G, Cappozzo A. An optimized protocol for hip joint centre determination using the functional method. J. Biomech. 2006;39(6):1096-106.

20. Baker R, McGinley JL, Schwartz MH, Beynon S, Rozumalski A, Graham HK, et al. The gait profile score and movement analysis profile. Gait Posture. 2009;30(3):265-9.

21. Baker R, McGinley JL, Schwartz M, Thomason P, Rodda J, Graham HK. The minimal clinically important difference for the Gait Profile Score. Gait Posture. 2012;35(4):612-5.

22. Kainz H, Carty CP, Maine S, Walsh HPJ, Lloyd DG, Modenese L. Effects of hip joint centre mislocation on gait kinematics of children with cerebral palsy calculated using patient-specific direct and inverse kinematic models. Gait Posture. 2017;57:154-60.

23. McGinley JL, Baker R, Wolfe R, Morris ME. The reliability of three-dimensional kinematic gait measurements: A systematic review. Gait Posture. 2009;29(3):360-9.