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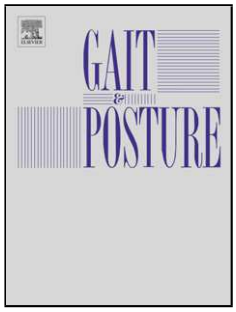

Title: Reliability of functional and predictive methods to estimate the hip joint centre in human motion analysis in healthy adults

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Research highlights

- Predictive method located the hip joint centre more reliable than functional method
- No differences in inter-session hip kinematics between both approaches
- Functional method was sensitive to the functional trial performance
- The initial guess in the GSF method did not show a significant difference in the final HJC location

Title page

Title

Reliability of functional and predictive methods to estimate the hip joint centre in human motion analysis in healthy adults

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Reliability of functional and predictive methods to estimate the hip joint centre in healthy adults

Abstract

In human motion analysis predictive or functional methods are used to estimate the location of the hip joint centre (HJC). It has been shown that the Harrington regression equations (HRE) and geometric sphere fit (GSF) method are the most accurate predictive and functional methods, respectively. To date, the comparative reliability of both approaches has not been assessed. The aims of this study were to (1) compare the reliability of the HRE and the GSF methods, (2) analyse the impact of the number of thigh markers used in the GSF method on the reliability, (3) evaluate how alterations to the movements that comprise the functional trials impact HJC estimations using the GSF method, and (4) assess the influence of the initial guess in the GSF method on the HJC estimation. Fourteen healthy adults were tested on two occasions using a three-dimensional motion capturing system. Skin surface marker positions were acquired while participants performed quite stance, perturbed and non-perturbed functional trials, and walking trials. Results showed that the HRE were more reliable in locating the HJC than the GSF method. However, comparison of inter-session hip kinematics during gait did not show any significant difference between the approaches. Different initial guesses in the GSF method did not result in significant differences in the final HJC location. The GSF method was sensitive to the functional trial performance and therefore it is important to standardize the functional trial performance to ensure a repeatable estimate of the HJC when using the GSF method.

1. Introduction

Three-dimensional (3D) motion analysis is a powerful clinical tool that can be used to objectively quantify the gait of individuals with movement disorders [1]. Clinical gait laboratories typically use conventional biomechanical models that calculate joint centres and kinematics directly from the 3D position of retro-reflective markers mounted on the skin surface [2, 3]. The joint kinematics are used in combination with additional gait measures (e.g. joint moments and powers) and physical assessment to inform clinical interventions [4]. Therefore, it is imperative that gait analysis methods are both accurate and reliable.

The location of the hip joint centre (HJC) is crucial in biomechanical models of human gait. It influences the definition of the long axis of the thigh segment, and thus the calculation of the hip and knee joint kinematics. The HJC cannot directly be identified from the skin surface and is estimated relative to the pelvis segment using predictive or functional methods. Predictive methods use regression equations based on cadaveric [5] or medical imaging studies [2], to estimate the HJC location. Functional methods use the relative movement of femur and pelvis segments from functional calibration trials to calculate the centre of rotation, which is assumed to be the HJC [6-8]. A recent systematic review [9] indicated that the Harrington regression equations (HRE) [10] and the geometric sphere fit (GSF) [6, 11] method were the most accurate predictive and functional methods, respectively. [9] also reported that only a small number of studies assessed the reliability of predictive and functional methods. Reliability of joint kinematics is important in clinical practice as the patient's gait is typically compared pre- and post-intervention. Functional methods have been shown to result in more reliable gait kinematics than regression methods [7, 12], but other studies have not found

notable differences between the approaches [13]. All these studies [7, 12, 13], however, included functional determination of the HJC together with functional determination of the knee joint axis. The reported reliability, therefore, was not an independent evaluation of functional HJC methods. To date, the reliability of the most accurate predictive (HRE) and functional (GSF) methods to estimate the HJC alone has not been compared.

Pelvis marker locations are not likely to impact on the accuracy of functional methods to estimate the HJC, but do affect reliability as the HJC is stored relative to the pelvic anatomical coordinate system (ACS), which is based on the 3D location of manually placed pelvis markers. The reliability of functional methods may be additionally affected by soft tissue artefacts (STA) associated with the number of thigh markers used to determine the centre of rotation and range of motion (RoM) used during the functional calibration trial. The reliability of predictive methods is dependent on the location of pelvis markers alone. In functional methods, however, the pelvic ACS does not impact on the reliability of the thigh ACS, whereas in predictive methods any errors in the definition of the pelvic ACS would propagate to the HJC, thigh ACS, and potentially reducing reliability of joint kinematics.

It is currently recommended that functional calibration trials for the GSF method should be performed in a 'StarArc' movement pattern [14] with a RoM as large as possible [15, 16]. The effect of number and placement of markers on the precision of the HJC estimation has been previously evaluated, although not with respect to the GSF method [17]. The impact of the chosen functional method, movement pattern and number of markers on the accuracy of the HJC estimation has also been assessed [14, 16, 18, 19]. To our knowledge no previous study has assessed the influence of the number of markers used on the reliability of HJC calculations. Furthermore, the influence of the initialization of the GSF method and the impact of movement asymmetry in the functional trials on HJC estimation has not been previously addressed.

The aims of this study were to (1) compare intra- and inter-session reliability between the HRE and GSF method, (2) analyse the influence of the number of markers used in the GSF method on the reliability of HJC estimates, (3) evaluate the influence of functional trial perturbations on HJC estimations using the GSF method, and (4) assess the influence of the initialization of the GSF method on the HJC estimation. Using predictive methods, the HJC estimation depends on the placement of the pelvis markers and how well the regression model, developed from small mostly healthy sample individuals, represents the pelvis of the individual. Functional methods depend on the number and placement of pelvis and thigh markers and functional movement trial performance [14, 16, 18, 19]. The precision of the SCoRE functional method increased with the number of markers used [17], and functional trial performance has been shown to influence HJC estimation [16, 18]. Thus, the following hypotheses were proposed: (1) there is no difference in the reliability of HJC estimates between the HRE and GSF method, (2) including more markers in the GSF method improves reliability of HJC estimates, (3) movement perturbations in functional trials will influence the results of the GSF method, and (4) HJC estimates from the GSF method are independent from the initial guess.

2. Methods

Fourteen healthy adults (10 males, 4 females; mean (standard deviation) age: 27.7(4.3)years; height: 1.74(0.09)m; BMI: 23.0(2.4)kg/m^2) free from musculoskeletal impairment were recruited. All participants gave informed, written consent prior to participation. The study protocol was approved by the University Human Research Ethics Committee. Testing was conducted on two occasions separated by at least one week.

Ten retro-reflective markers were placed on the pelvis and right thigh segments of each participant. Markers were placed on the left and right Anterior Superior Iliac Spine (ASIS), left and right Posterior Superior Iliac Spine (PSIS), lateral knee, medial knee, lateral to the distal third of the thigh (wand marker), and lateral to the thigh a triad (CL1, CL2, CL3). The distance between markers on the long axis of the triad (CL1-CL3) was 18cm and the third marker of the triad (CL2) was perpendicular to the long axis 7cm from the midpoint. The triad long axis was aligned with the long axis of the femur with the CL2 marker pointing anterior. The most distal triad marker (CL3) was approximately 8cm proximal to the lateral knee marker. In all sessions, the same rater (MSc in Rehabilitation Engineering) performed marker placement and collected motion capture data. A motion analysis consultant with several years of experience in marker placement trained and supervised the rater. For each testing session, participants performed a static standing calibration trial, functional calibration trials as described below and 3 walking trials at preferred walking speed. Based on pilot testing, 70 beats per minute (bpm) was a natural velocity for the functional calibration trial. A metronome, set to 70bpm, was used to cue participants as they performed the StarArc motion for the functional calibration trials, as per [14]. Participants performed between two and four practice trials of the StarArc motion prior to data collection. All participants were able to confidently execute the task without any obvious limitations. The trial order for each session is described in Table 1.

Marker trajectories were collected at 200Hz using a 9-camera 3D motion capture system (Vicon Motion Systems, Oxford, UK). Two force plates (Type: 9287A & 9865C; Kistler, Amherst, USA) were used to detect foot contact and toe off events for the gait trials. Vicon Nexus software v.1.8.5 (Vicon Motion Systems, Oxford, UK) was used to label and filter (Butterworth, 4^{th} order zero–lag, 6Hz low pass cut-off) marker trajectories.

HJC estimations were calculated using the predictive HRE [10] and functional GSF [11] methods in Matlab (R2013a, The Math Works, Natick, USA). Pelvis and femur ACS were created following the ISB conventions [20]. The HRE method calculated the HJC using pelvis width and depth (HRE-PW-PD), which were determined from the 3D positions of the left and right ASIS and PSIS markers from the static calibration trial. We also tested a modified HRE method that used only pelvis width (HRE-PW), and has been shown to improve the accuracy of the HJC estimation by 3mm [21].

To address the second aim of the study, the GSF method was used to calculate the HJC location with nine different thigh marker set combinations (MS 1-9) (Table 2) using data from the normal full RoM functional calibration trial. To address the third aim of the study, the GSF method was used to calculate the HJC for all the functional calibration trials described in Table 1 using MS 5 as described in Table 2. MS 5 was chosen because it didn't use knee or wand markers, and therefore was potentially less susceptible to STA than the other MS [22]. To address the fourth aim of this study, two different regression equations (Shea [23] and HRE-PW [21]) were used to initialize the GSF method.

Hip joint angles were calculated as Cardan angles between the femur and pelvis frames following the rotation sequence flexion/extension, adduction/abduction, internal/external rotation [24]. For all walking trials, hip angles were calculated using the HJC from the HRE-PW-PD and GSF method using the non-perturbed functional trials and MS 5.

The reliability between the HRE-PW-PD, HRE-PW and GSF method using all MS (aim 1) were compared using inter- and intra-session differences in HJC location, as well as intra-trial, inter-trial and inter-session standard deviations (SD) in hip kinematics [25]. Intra-trial SD was obtained from the difference in hip kinematics calculated from the marker locations of the same trial but with different HJC definitions. For the HRE, the HJC was defined based on static poses collected at the beginning and end of the session. For the GSF method, the HJC was defined using functional trials with full RoM collected at the beginning and end of the session. Inter-trial SD was obtained from the marker locations of two different trials using

the same HJC definition in each trial. Inter-session SD was obtained from the differences in hip kinematics calculated from the marker locations of trials from different sessions including different HJC definitions. Intra-trial SD represented the variability solely caused by the difference in HJC locations, while inter-trial SD represented the variability solely caused by differences in the walking pattern. Inter-session SD represented the combined variability caused by different HJC definitions, different walking patterns and slightly different marker locations between sessions.
The influence of the number of markers on the reliability of HJC estimation using the GSF method (aim 2) was analysed by comparing inter- and intra-session differences in HJC location obtained with the GSF method using different thigh MS.
The influence of functional trial alterations on HJC calculations using the GSF method (aim 3) was evaluated by comparing the differences in HJC location obtained with the normal and altered function trials.
The influence of the initial guess on the HJC estimation using the GSF method (aim 4) was assessed by calculating the difference in the obtained HJC locations.
All data was normally distributed and therefore a repeated measures general linear model with Greenhouse-Geisser correction was used for all comparisons. In the case of significant interactions, post-hoc comparisons were performed using Bonferroni corrections. All statistical analyses were performed in IBM SPSS Statistics 22 (IBM Corporation, Ney York, USA) and the significance level was set to $p=0.05$.

3. Results

Intra-session and inter-session differences in HJC locations were significantly smaller (all $p<0.05$) for the HRE (HRE-PW-PD and HRE-PW) compared to the GSF method for all marker sets (Figures 1). HRE-PW showed no differences in the reliability of locating the HJC compared to HRE-PW-PD. Intra-trial hip angles SD in all three planes were significant smaller (all $p<0.05$) for the HRE-PW-PD compared to the GSF method, but inter-trial and inter-session SD were not significantly different between both approaches (Figure 2).
No differences in the reliability of the HJC estimates were found when using the GSF method with MS that included two or more thigh markers (Figure 1). The only significant inter-session difference in HJC estimates was between MS 4 and MS 8 ($p=0.028$). MS 8 and MS 9 intra-session differences were significantly larger than most other MS, i.e. significant differences between MS 8 and MS 1, 2, 3, 4, 5, 7 (all $p<0.05$), and MS 9 and MS 1, 2, 4 (all $p<0.05$).
The functional trials without alterations took 3056(288) frames, which was 15(1) seconds. The average percent of time spent in the anterior, lateral and posterior positions was 43/34/23, 23/54/23 and 23/34/43 for the anterior, lateral and posterior alterations, respectively.
Functional movement trial perturbations that remained in the anterior postures for longer periods of time and using only half of the hip RoM significantly (all $p<0.05$) affected HJC estimates (Figure 3). Posterior and lateral biased functional trials did not significantly change the location of the HJC compared to the normal full RoM functional trial.
Using Shea or HRE-PW regression equations to initialize the GSF method had negligible effect on HJC location (0.002(0.003)mm), although a mean difference in the initial guess of 12.8(1.0)mm was observed between both regression equations.

4. Discussion

This study revealed significantly smaller intra-session and inter-session differences in HJC locations for both HRE methods compared to the GSF method, which was in disagreement with our first hypothesis. Furthermore, the influence of differences in HJC location on intra-trial SD in hip kinematics was significantly smaller for the HRE compared to GSF method. Nonetheless, average intra-trial SD in hip kinematics for the GSF method was below 0.3°, and therefore the above mentioned significant differences would not influence clinical interpretation of hip kinematics. This was expected as intra-trial SD are the result of different HJC estimations based on the same walking trial and therefore do not include variations due to different marker placements and/or gait pattern. Although the HJC was more reliably located using HRE than the GSF methods, this had negligible impact on inter-session hip kinematics. The hip kinematic waveforms inter-session SDs were very similar between HRE-PW-PD and GSF methods (Figure 2), which supported our first hypothesis. The SD ranged between 1.7° and 4.2°, consistent with previously published reliability values for hip kinematics [26], and could be due to a number of factors, such as different hip and knee joint centre estimates, variations between walking trials and different marker locations between sessions. It is important to highlight that our reliability results are not sufficient to favour one method over another. In both analysed approaches systematic errors, caused by modelling errors in the HRE and STA in the GSF method, may affect accuracy without any impact on reliability.

Our second hypothesis was only partially supported as using >2 markers in the GSF algorithm produced no improvements in the reliability of the HJC estimates.

Our third hypothesis was confirmed as alterations to functional trial performance did impact the results of the GSF method. Functional trials with more time spent in the two anterior StarArc end positions and using half of the RoM significantly moved the HJC to a more anterior, lateral and lower position compared to the normal full RoM functional calibration trial. Most people can more readily flex their hip than extend or abduct, and this may explain why lateral and posterior alterations did not change the HJC location compared to the normal functional trials.

Our forth hypothesis was confirmed, as different regression equations used to initialize the GSF method did not show a significant difference in the final HJC location.

Several considerations need to be taken into account when interpreting our results. First, although the findings showed that the GSF method was less reliable in locating the HJC compared to the HRE, it is possible that the GSF method was more accurate in estimating the actual HJC position. However, accuracy analysis was beyond the scope of this study and according to [9] both methods have similar accuracy. Second, since no clinical population was tested in this study, the results may differ in populations with pathologies or obesity. Excessive STA, limited RoM and/or uncoordinated movement could decrease the reliability of functional methods. Third, only adult participants were included in this study. Variability in the HJC location in a paediatric population could have a larger impact on intra-trial hip kinematics due to the shorter femur length [27, 28]. Fourth, a metronome was used to guide the functional trial to ensure that approximately the same number of samples in each position were analysed in the GSF method. This approach did not guarantee that the exact same number of frames were analysed for each position, however, using 200 frames from the peak of each position of the functional trial for the GSF method instead of the whole trial did not increase reliability of HJC estimates. Fifth, performing the functional calibration trials with a slower velocity could potentially decrease STA and increase the reliability of the GSF method. In two participants, we collected additional functional trials at 40, 50 and 70bpm, which led to mean inter-session differences in the HJC location of 6.8, 5.9 and 4.0mm,

respectively; indicating that in our lean, young adult population slower functional trial performance probably would not have improved the reliability of the GSF method. Sixth, predictive methods cannot account for pathological conditions that affect geometry (e.g. dwarfism) or induce asymmetry in the HJCs, and therefore would not be suitable for certain patient populations. Seventh, joint kinetic analyses were not included in this study although variations in the HJC location have been shown to impact on joint moments [28-30]. Eighth, different marker sets and/or marker locations could increase or decrease STA and therefore lead to slightly different results.

In conclusion, both forms of HRE were more reliable in locating the HJC than the GSF methods. However, the differences between HRE and GSF method had little effect on inter-session hip kinematics. The GSF method was sensitive to the performance of the functional trial and therefore should only be used if the participant is able to perform the functional trials with adequate RoM in a consistent manner pre- and post-intervention. If this cannot be achieved actively, reliability may be improved if a therapist assists by moving the limb though the RoM in a consistent manner.

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Table 1. Overview of trials collected during both testing sessions. Normal functional full range of motion (RoM) and half RoM trials required participants to pause for 1 beat at each of the 7 StarArc end positions. Biased trials required participants to pause for 3 beats at the 2 most anterior StarArc end positions (Anterior bias), the 3 most lateral StarArc end positions (Lateral bias) and the 2 most posterior StarArc end positions (Posterior bias).

		Functional trial description					
	Static	Full RoM	Half RoM	Anterior bias	Lateral bias	Posterior bias	Gait
Session 1							
Trial 1	✓						
Trial 2		✓					
Trial 3			✓				
Trial 4		✓		✓			
Trial 5		✓			✓		
Trial 6		✓				✓	
Trial 7	✓						
Trial 8		✓					
Trial 9-11							✓
Session 2							
Trial 1	✓						
Trial 2		✓					
Trial 3	✓						
Trial 4		✓					
Trial 5-7							✓

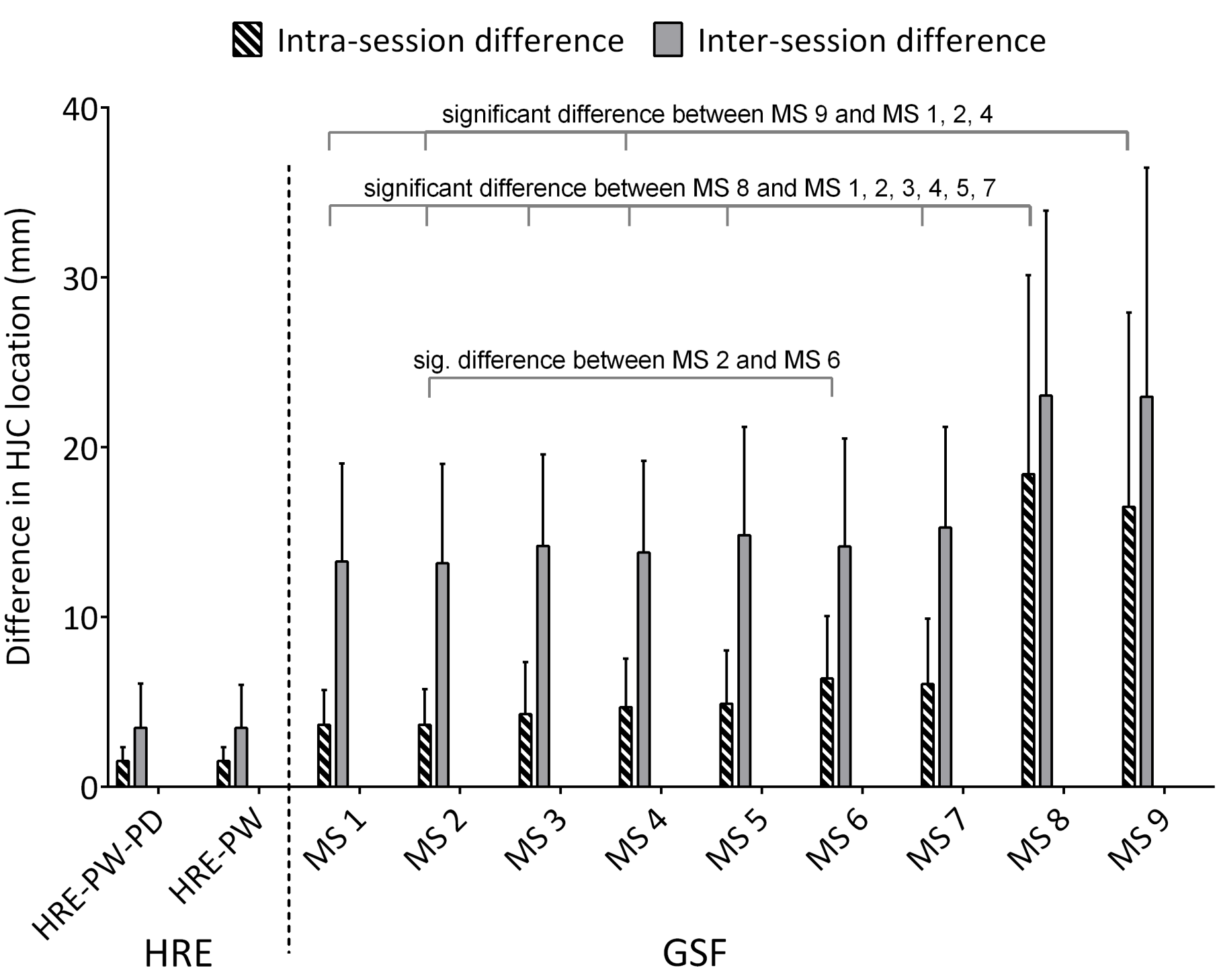
Table 2. The thigh marker sets used for calculating the hip joint centre with the geometric sphere fit (GSF) method. All these markers were transformed to the pelvic reference frame before the GSF calculation was performed. KneeLat=lateral knee marker, KneeMed=medial knee marker, THW=thigh wand marker, CL1-3=markers on triangular thigh cluster; C1=most proximal cluster marker, C3=most distal cluster marker.

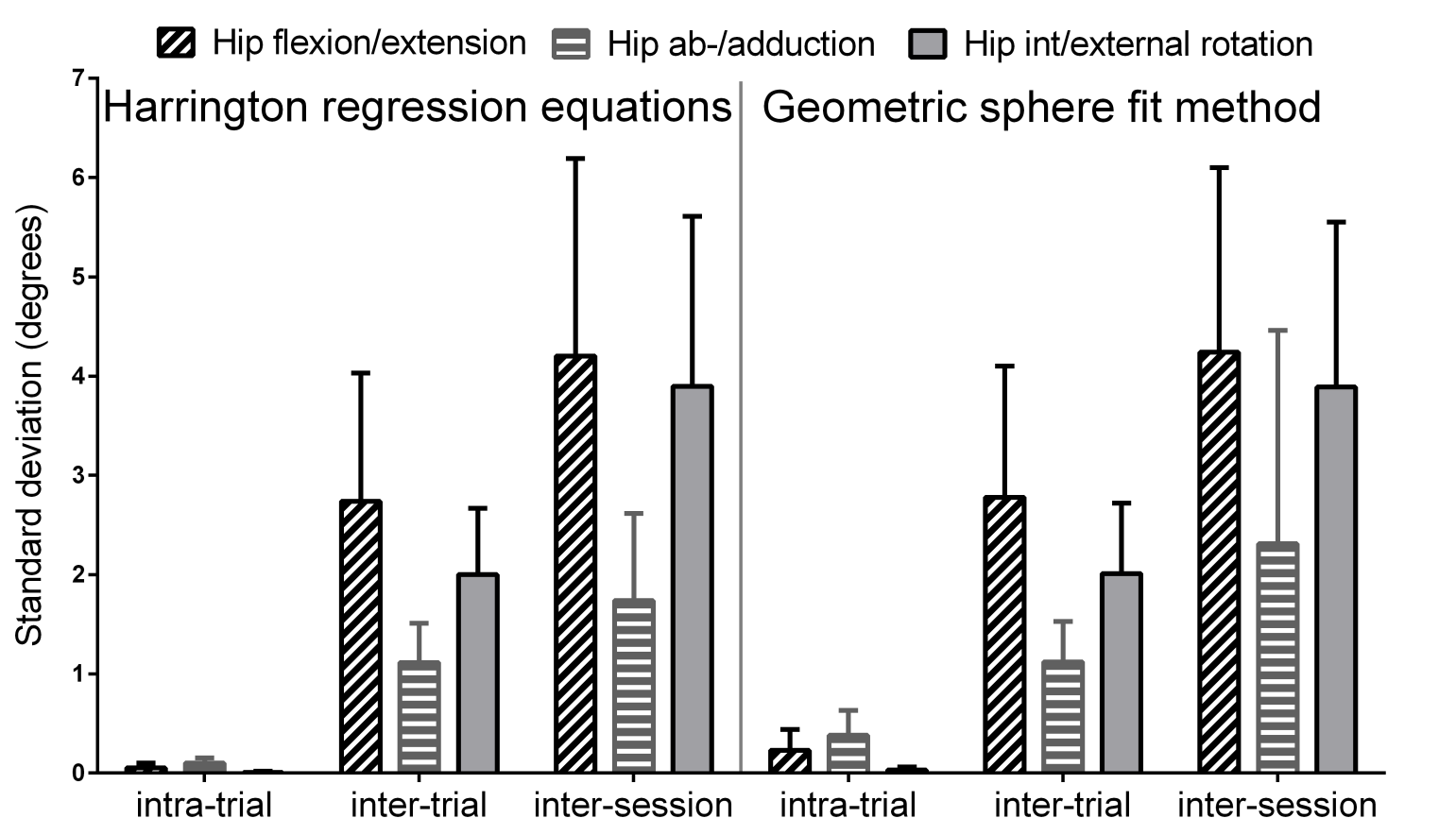
Thigh marker set	Markers Used					
	1	2	3	4	5	6
MS 1	CL2	THW	KneeLat	CL1	KneeMed	CL3
MS 2	CL2	THW	KneeLat	CL1	KneeMed	
MS 3	CL2	THW	KneeLat	CL1		
MS 4	CL2	THW	KneeLat			
MS 5	CL1	CL2	CL3			
MS 6	KneeLat	KneeMed	THW			
MS 7	KneeLat	CL2				
MS 8	KneeLat					
MS 9	CL1					

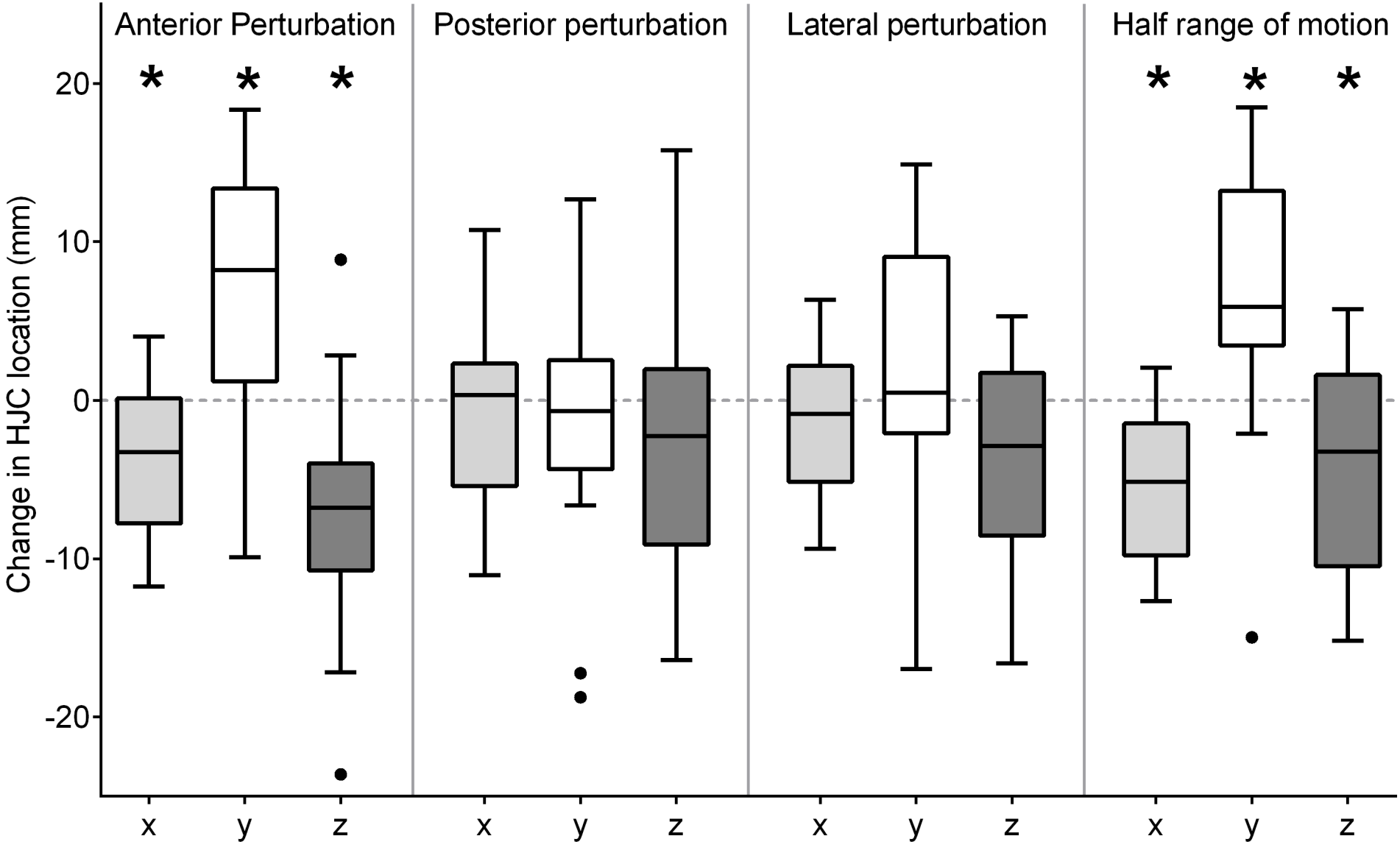
Figure 1. Mean intra- and inter-session differences in HJC locations obtained with the Harrington regression equations (HRE) using pelvis width and depth (HRE-PW-PD) and pelvis width as inputs (HRE-PW). Also shown are the results from the geometric sphere fit (GSF) method for all marker sets. Error bars represent one standard deviation. MS 1-9=Marker sets 1-9. Significant intra-session differences between marker sets are highlighted in the figure.

Figure 2. Mean intra-trial, inter-trial and inter-session standard deviation in hip kinematics obtained with the Harrington regression equations (HRE-PW-PD) and geometric sphere fit (GSF) methods. Intra-trial standard deviation in hip angles in all three planes were significant differently between the HRE-PW-PD and GSF methods. Inter-trial and inter-session standard deviations were not significantly different between both approaches. Error bars represent one standard deviation. Representative kinematic waveforms of one participant can be found online in the supplementary Figure S1. Differences between HJC locations obtained with the HRE and GSF method are shown online in the supplementary Figure S2.

Figure 3. Tukey boxplot showing the impact of altered functional trials on the estimation of the hip joint centre (HJC). The directions are x=posterior(+)/anterior(-), y=inferior(+)/superior(-), and z=medial(+)/lateral(-). *indicates a significant difference between the HJC location obtained with the normal and altered function trials ($p<0.05$). Whiskers present lowest/highest datum still within 1.5 interquartile range of the lower/upper quartile.


Intra-session difference
Inter-session difference
significant difference between MS 9 and MS 1, 2, 4
significant difference between MS 8 and MS 1, 2, 3, 4, 5, 7
sig. difference between MS 2 and MS 6
Difference in HJC location (mm)
40
30
20
10
0
HRE-PW-PD
HRE-PW
MS 1
MS 2
MS 3
MS 4
MS 5
MS 6
MS 7
MS 8
MS 9
HRE
GSF


Hip flexion/extension
Hip ab-/adduction
Hip int/external rotation
Harrington regression equations
Geometric sphere fit method
Standard deviation (degrees)
0
1
2
3
4
5
6
7
intra-trial
inter-trial
inter-session
intra-trial
inter-trial
inter-session


Anterior Perturbation
Posterior perturbation
Lateral perturbation
Half range of motion
Change in HJC location (mm)
20
10
0
-10
-20
*
x
y
z