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Using a sacral cluster to improve pelvic tracking during gait in overweight individuals

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ABSTRACT

Background: Pelvic tracking in three-dimensional (3D) human motion analysis commonly uses skin-mounted anterior superior iliac spines (ASIS) markers. However, these conventional methods are prone to soft tissue artifacts, especially in overweight individuals. Using a sacral marker cluster with pointer-defined virtual ASIS markers might be an alternative approach for more accurate pelvic tracking across different body compositions.
Research Question: What are the differences in pelvic and hip joint mechanics measured during gait using conventional pelvic tracking versus pelvic tracking with a sacral cluster in healthy-weight and overweight individuals?
Methods: Ten healthy-weight and ten overweight/obese participants underwent 3D gait analysis. The pelvis was simultaneously tracked using skin-mounted markers and a sacral cluster with pointer-defined virtual ASIS markers. Pelvic kinematics and hip kinematics and kinetics were compared between tracking methods using statistical parametric mapping paired t-tests. Root mean squared differences (RMSD) and paired Cohen's d_z were calculated for significantly different waveform regions.
Results: Frontal-plane pelvic kinematics differed between methods more substantially in the overweight group (RMSD=4.6° ± 1.7°, d_z=-0.9) than in the healthy-weight group (RMSD=2.8° ± 0.8°, d_z=0.3). Frontal-plane hip kinematics also differed more substantially in the overweight group (RMSD=5.4° ± 2.3°, d_z=-0.8) than in the healthy-weight group (RMSD=2.7° ± 1.7°, d_z=1.4). Hip kinetics differed mostly in the sagittal plane, with more substantial differences in the overweight group (RMSD=0.22 ± 0.09Nm/kg, d_z=2.3) than in the healthy-weight group (RMSD=0.11 ± 0.04Nm/kg, d_z=2.7).
Discussion: Pelvic tracking using a sacral cluster with pointer-defined virtual ASIS markers provides different, and potentially more accurate, pelvic and hip mechanics across different body compositions than conventional methods using skin-mounted ASIS markers.

1. Introduction

Three-dimensional (3D) motion analysis is widely used in clinical and research settings to study human movement and disorders affecting mobility. Optical motion capture is a commonly used method in which tracking of skin-mounted markers enables full-body motion analysis in a large measuring volume. However, a known limitation of measuring bony kinematics using optical motion capture methods is the limited accuracy, caused by soft tissue artifacts (STA) due to movement of the skin-mounted markers relative to the underlying bone [1,2]. These errors are particularly pronounced in overweight or obese individuals due to the increased amount of adipose tissue [3]. Given the global rise of obesity [4] and associated musculoskeletal conditions, such as osteoarthritis [5], there is a growing need for accurate and reliable 3D motion analysis methods adapted to this population to identify biomechanical factors driving joint degeneration and inform biomechanical treatment strategies. This underscores the importance of optimizing measurement techniques to enhance its clinical applicability across different body

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types and is reflected by a growing interest in this topic [3,6,7].

To track the pelvis, anatomical markers are typically placed on the skin over the anterior and posterior superior iliac spines (ASIS and PSIS, respectively) [8–11]. In overweight and obese individuals, however, adipose tissue around the anterior aspect of the pelvis may cause substantial STAs, and anterior markers may even be obscured by increased abdominal adiposity [1,12]. Different strategies to address this issue have been explored, such as alternative marker placement [13], marker wands [14] or the use of an exoskeleton [15]. However, these methods have not consistently reduced kinematic errors due to STAs across different body types [15].

An alternative approach uses a sacral marker cluster combined with pointer-defined virtual ASIS markers, based on the principle of calibrating anatomical landmarks as described by Cappozzo et al. (1995) [16]. To our knowledge, only one study, using a rigid sacral cluster, has compared this approach to conventional methods of pelvic tracking across different body compositions, in a limited secondary analysis with the Coefficient of Multiple Correlations (CMC). They reported lower similarity between methods when tracking gait according to CMC values, especially in overweight or obese individuals, although this metric is not appropriate to actually evaluate the kinematic differences between the two methods [13]. A more recent study by Langley et al. (2019) [17], using a larger, non-rigid sacral cluster, has shown promise in tracking gait in individuals with a healthy body mass index (BMI). However, the kinematics of this approach and specific marker model have not yet been evaluated in an overweight or obese population. In this study, we aimed to compare pelvic and hip mechanics during gait in healthy-weight and overweight individuals derived from two pelvic tracking methods: (i) a conventional marker model using skin-mounted ASIS markers; and (ii) a non-rigid sacral cluster combined with pointer-defined virtual ASIS markers. As secondary objective, we aimed to assess the intra-rater reliability of pointing the virtual ASIS markers in both weight groups.

2. Methods

2.1. Participants

Twenty healthy adults participated in this study and were divided into two equal groups according to their BMI (healthy-weight: 19–27 kg/m^2, overweight or obese: >27 kg/m^2). This resulted in a healthy-weight group (4 female, age: 37.0 ± 18.6 years, BMI: 23.0 ± 1.8 kg/m^2) and an overweight group (6 female, age: 42.0 ± 19.5 years, BMI: 33.7 ± 5.5 kg/m^2). None of the participants suffered from any acute or chronic disease or physical limitation that prevented them from walking for at least ten minutes or standing on one leg. Written informed consent was obtained prior to participation. This study was approved by the TU Delft Human Research Ethics Committee (application number 4898).

2.2. Marker Model

The CGM2.4 lower body marker model, consisting of 34 retroreflective markers, was used as the conventional marker model [11]. It was extended to include two additional posterior pelvic markers: the superior (SS) and inferior sacral (IS) markers. These were placed in the anatomical midline of the spine, approximately 2 centimeters above and below the two PSIS markers, forming a non-rigid technical sacral cluster to which the virtual ASIS markers, identified using a 3D-printed pointing stylus, could be calibrated (Fig. 1). Care was taken not to let participants' clothing push against the IS marker during measurements.

2.3. Data collection

All participants underwent a gait analysis protocol at the Motion Biomechanics and Imaging (MOBI)-lab at the Erasmus MC University Medical Center, Rotterdam. The protocol included collection of anthropometric measurements, including body mass, height, leg length, and knee width. All markers were placed by a single, experienced examiner. First, all markers except for both ASIS skin markers were applied. With participants standing in the anatomical position, a single examiner identified the ASIS using visual inspection and palpation. The tip of the pointing stylus was then placed in contact with the ASIS during a 5-second recording to calibrate the virtual ASIS marker location to the coordinate frame of the sacral cluster. The stylus was held parallel to the ground, although the orientation of the stylus would not affect the calculated position of the tip as long as all three markers were visible to the cameras. Virtual ASIS markers were calibrated, alternating between left and right ASIS, twice before and twice immediately after the gait trial, resulting in a total of four measurements per side obtained in a single session. Following the initial pointing trials, the skin-mounted ASIS markers were placed and a standard static and dynamic calibration protocol was performed to define segment coordinate systems and calculate static joint angles. Subsequently, participants walked for at least six minutes to familiarize themselves with treadmill walking [18] and to select their preferred walking speed. Gait was then recorded for at least one minute at the self-selected comfortable walking speed. Marker positions were recorded at 100 Hz using a ten-camera optical motion capture system (VICON, Oxford, UK), synchronized with a 1x2m dual-belt instrumented treadmill (M-Gait, Motek, Netherlands) to collect ground reaction forces. VICON Nexus 2.16 was used to capture and process data.

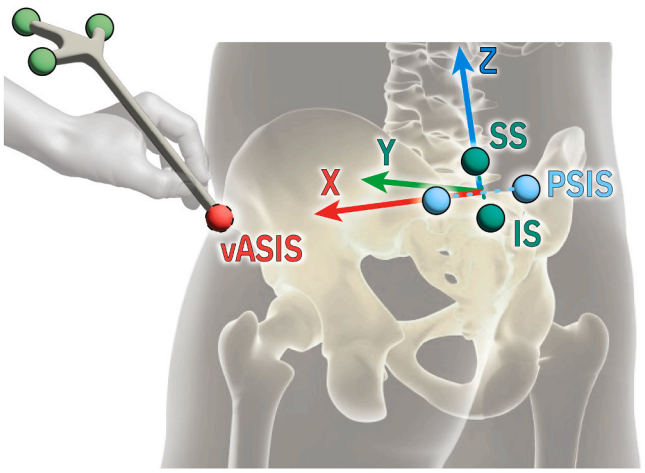


Fig. 1. Overview of the sacral cluster method. The cluster is formed by two anatomical posterior superior iliac spine (PSIS) markers and two additional superior- and inferior sacral (SS and IS) markers. The left virtual anterior superior iliac spine (vASIS) marker is pointed using a 3D-printed pointing stylus.

2.4. Data analysis

Collected marker trajectory data and ground reaction forces were filtered with a 6 Hz and 10 Hz Butterworth low-pass filter respectively. To correct for potential outlying virtual ASIS positions, the median positions from the four measurements for left and right virtual ASIS markers were calculated and used to reconstruct the virtual ASIS trajectory throughout the entire trial using the sacral cluster as reference coordinate frame. Data from five consecutive and representative right-leg steps were selected, ensuring participants did not cross the treadmill midline to prevent force-plate crosstalk. These steps were normalized from 0% to 100% of the gait cycle between two consecutive heel-strike events, automatically identified from the ground reaction force data in the Nexus software. The Nexus CGM2.4 processing pipeline (including Inverse Kinematics) was used to derive pelvic and hip kinematics, hip kinetics and hip joint center location estimations for both

pelvic tracking methods.

Statistical analyses were performed for the healthy-weight group and overweight group separately. For every participant, mean waveforms for pelvic kinematics, hip kinematics and hip kinetics were calculated from five steps. Statistical parametric mapping (SPM) paired *t*-tests were used to compare these mean waveforms between the two tracking methods across the gait cycle [19]. For regions showing statistically significant differences in the SPM analysis, the root mean squared difference (RMSD) was calculated for each participant to assess the magnitude of the difference using the formula: $RMSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_{B,i} - y_{A,i})^2}$ with y_B being the waveform value from the sacral cluster method at timepoint i and y_A the corresponding value from the conventional method. Participant-level RMSDs were then averaged to obtain a group-level mean RMSD. For the same regions, paired Cohen's d_z (i.e. the mean of the paired differences divided by their standard deviation) was calculated to assess the effect size of the differences. Effect sizes d_z were interpreted as small (<0.20), medium (0.20–0.80) or large (> 0.80) [20]. Intra-rater reliability of the right virtual ASIS localization was evaluated using ICC(3,1) and ICC(3,k) calculated from the Euclidean distance for the four pointed virtual ASIS locations from the origin of the sacral cluster across four repeated trials. ICC values were interpreted as poor (<0.50), moderate (0.50 – 0.75), good (0.75–0.90) or excellent (>0.90) [21]. Additionally, the Standard Error of Mean (SEM) was calculated directly from the residual mean square from the repeated-measures ANOVA [22]. All statistical tests were performed in Python (version 3.13.9) using the libraries spm1d (version 0.4.18) [19] and pingouin (version 0.6.0) [23] and significance level was set at $p = 0.05$.

3. Results

Compared with the virtual ASIS marker, the skin-mounted ASIS marker exhibited larger average offsets in the overweight group than in the healthy-weight group in all three directions (Fig. 2). In the overweight and healthy-weight groups, respectively, the mean offsets (±SD) of the skin-mounted marker to the virtual marker were 1.9 ± 1.3 cm versus 0.8 ± 0.6 cm in the medial direction and 4.1 ± 1.7 cm versus 1.7 ± 0.7 cm in the anterior direction. In the superior-inferior direction, the marker was positioned 1.4 ± 2.0 cm more inferiorly in the overweight group and 0.2 ± 1.0 cm more superiorly in the healthy-weight group. Larger mean excursions throughout the gait cycle were noted in the overweight group than in the healthy-weight group, with the largest excursions occurring in the superior-inferior direction in both groups. In the overweight and healthy-weight groups, respectively, mean excursions were 1.5 ± 0.4 cm versus 1.3 ± 0.7 cm in the mediolateral direction, 1.0 ± 0.5 cm versus 0.5 ± 0.3 cm in the anteroposterior direction and 2.3 ± 1.0 cm versus 1.5 ± 0.4 cm in the superior-inferior direction. Among individual participants, vertical excursions of the skin-mounted ASIS marker compared to the virtual ASIS marker occurred up to 4.7 cm (overweight group) and 2.3 cm (healthy-weight group). This resulted in significant differences in frontal-plane pelvic kinematics in both weight groups during the early stance phase and most of the swing phase (Table 1, Fig. 3). RMSD values and paired effect sizes were larger for the overweight group (RMSD = 4.6° ± 1.7°, $d_z = -0.9$) than for the healthy-weight group (RMSD = 2.8° ± 0.8°, $d_z = -0.3$). Frontal plane pelvic kinematics differed between methods by up to 10.1° (overweight group) and 5.4° (healthy-weight group) among individual participants.

Hip kinematics in the healthy-weight group differed significantly between methods, with the largest differences in the sagittal (RMSD = 3.7° ± 2.6°, $d_z = 1.2$) and frontal planes (RMSD = 2.7° ± 1.7°, $d_z = 1.4$) (Table 1, Fig. 4). In the overweight group, differences between methods in the frontal plane were larger (RMSD = 5.4° ± 2.3°, $d_z = -0.8$) and were significant over a greater portion of the gait cycle. Frontal plane hip kinematics differed between methods by up to 11.6° (overweight group) and 5.5° (healthy-weight group) among individual participants.

Hip kinetics demonstrated a similar pattern in both groups (Table 1, Fig. 5). Both showed differences in flexion moment during most phases of the gait cycle (RMSD overweight group 0.22 ± 0.09 Nm/kg, $d_z = 2.3$; healthy weight group 0.11 ± 0.04 Nm/kg, $d_z = 2.7$). Hip flexion moments differed between methods by up to 0.46 Nm/kg (overweight group) and 0.28 Nm/kg (healthy-weight group) among individual participants. Additionally, there were some differences in internal rotation moments between methods, albeit for slightly different phases of gait in both groups.

Intra-rater reliability was assessed in 9 out of 10 overweight participants due to one corrupted pointing trial for one participant. Intra-rater reliability was excellent for both single and average pointing trials, with

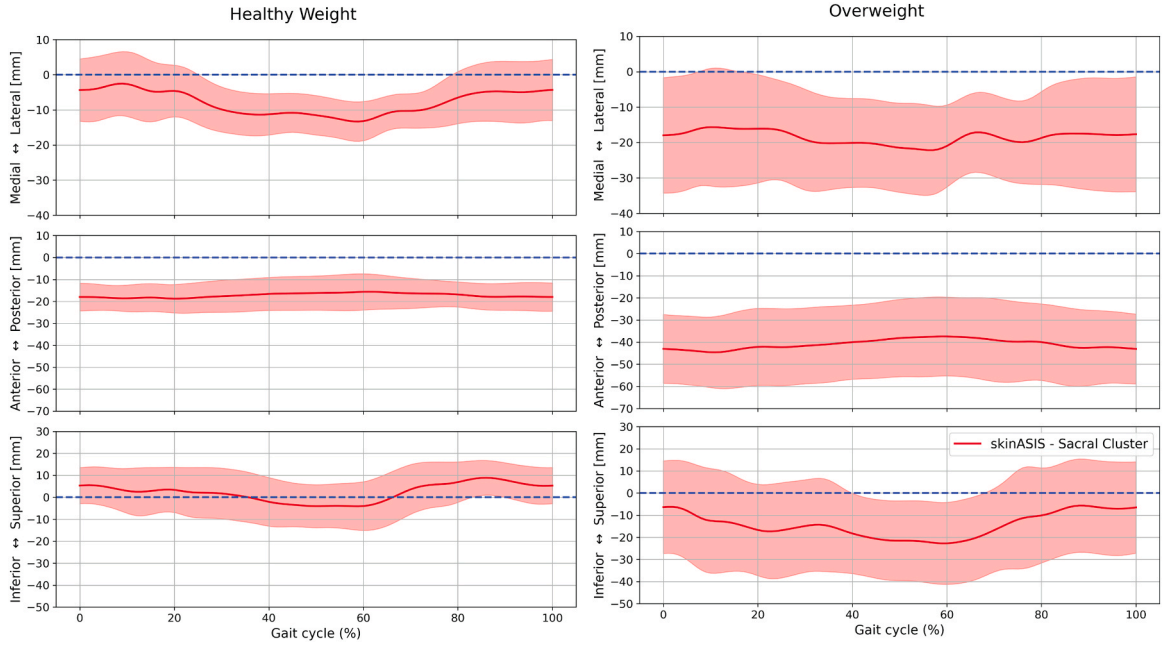


Fig. 2. ASIS marker trajectory. Side-to-side, forward-backward and vertical differences between the right skin-mounted anterior superior iliac spine (skinASIS) position (red) compared to the right virtual ASIS (vASIS) position (blue) during gait in healthy-weight and overweight groups.

Table 1
Comparing observed kinematics and kinetics across anatomical planes during gait between pelvic tracking methods for both weight groups separately. Values represent overall root mean squared difference (RMSD) with standard deviation (SD) and paired Cohen's d_z effect size for regions of statistically significant differences between methods and total percentage of the gait cycle exhibiting significant differences. N.S. signifies that no statistical differences were found using SPM paired *t*-tests and RMSD and d_z were not calculated accordingly.

		Healhty-Weight			Overweight		
		RMSD (SD)	Cohen's d_z	% Gait Cycle	RMSD (SD)	Cohen's d_z	% Gait Cycle
Pelvic kinematics	**Sagittal**	N.S.	-	-	N.S.	-	-
	Frontal	2.77° (0.78°)	0.31	58.4	4.55° (1.65°)	−0.88	76.2
	Transverse	N.S.	-	-	N.S.	-	-
Hip kinematics	**Sagittal**	3.69° (2.56°)	1.24	37.6	N.S.	-	-
	Frontal	2.67° (1.72°)	1.37	26.7	5.37° (2.29°)	−0.76	63.4
	Transverse	0.94° (0.57°)	1.59	4.0	3.65° (1.96°)	1.51	21.8
Hip Kinetics (Nm/kg)	**Sagittal**	0.11 (0.04)	2.67	78.2	0.22 (0.09)	2.33	73.3
	Frontal	N.S.	-	-	0.02 (0.01)	1.60	1.0
	Transverse	0.01 (0.01)	−2.24	25.7	0.03 (0.01)	−1.87	14.9

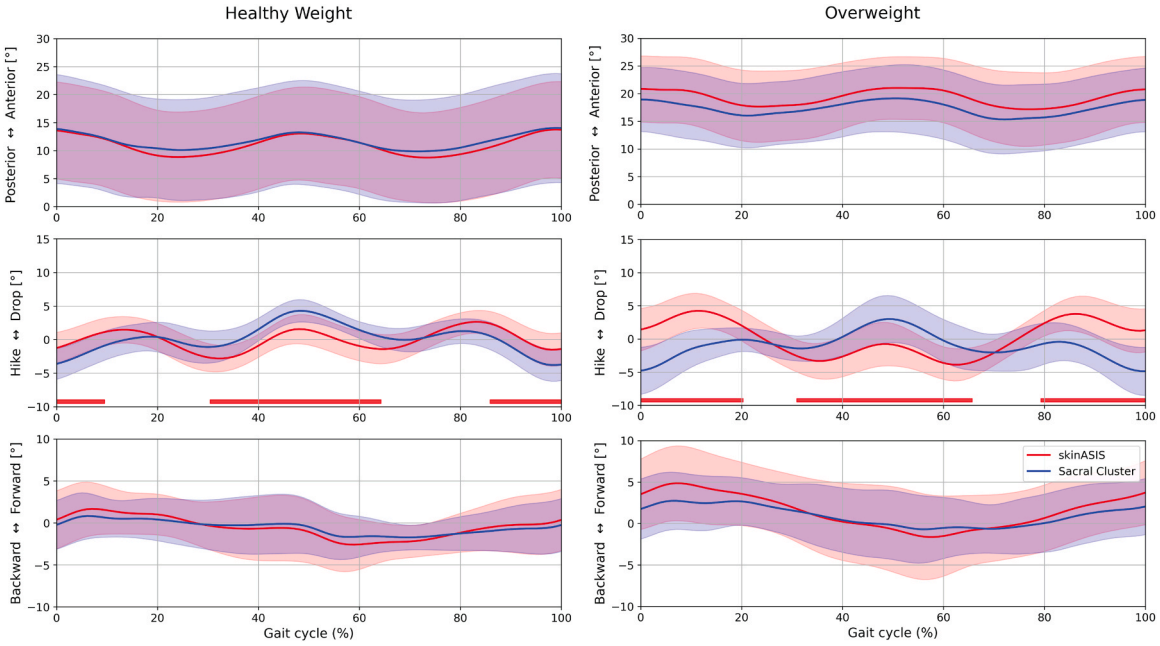


Fig. 3. Pelvic kinematics. Sagittal, frontal and transverse plane pelvic kinematics calculated using the conventional pelvic tracking method (red) using skin-mounted anterior superior iliac spine (skinASIS) markers and the alternative method using a sacral cluster (blue) during gait in healthy-weight and overweight groups. Red boxes on the bottom of the graphs depict regions of statistically significant differences between waveforms from SPM paired *t*-test analysis.

all ICCs being at least 0.97, while SEMs were larger in the overweight group (3.5 mm) than in the healthy weight group (2.4 mm).

4. Discussion

The aim of this study was to compare pelvic and hip mechanics in healthy-weight and overweight individuals derived from two pelvic tracking methods: (i) a conventional marker model using skin-mounted ASIS markers; and (ii) a sacral marker cluster combined with pointer-defined virtual ASIS markers. In individuals with a healthy BMI, hip joint kinematic waveforms derived from both methods did show significant differences in certain parts of the gait cycle. However, these differences were marginal, as reflected by maximum group-level RMSD values lower than 5°, which is generally considered a cut-off value for clinically relevant errors [24]. In contrast, overweight and obese participants exhibited larger differences between the two methods during greater parts of the gait cycle, with RMSD values often exceeding 5°. In particular, pelvic and hip kinematics in the frontal plane differed between methods in this group. These differences occurred mainly around ipsilateral and contralateral heel-strike. The skin-mounted markers exhibited cyclic superior-inferior excursions relative to the virtual ASIS markers, with the left and right markers moving in opposite directions. This resulted in differences predominantly in the frontal rather than the sagittal plane. This pattern was more pronounced in the overweight group, likely due to the inertia of the increased adipose tissue. Relevant gait abnormalities associated with musculoskeletal disease can occur in this plane, such as pelvic drop or increased step-width. Therefore, the finding of differences which exceed the threshold of clinical relevance in this plane could have implications for detecting and adequately correcting these kinds of pathological gait adaptations in early stages of diseases such as osteoarthritis, potentially helping to slow down disease progression. Hip kinetics showed similar patterns with substantial differences in hip flexion moment in both groups, with larger differences in the overweight group. This is likely caused by a notable posterior offset in hip joint center estimation in both groups (healthy-weight: 1.7 cm ± 0.6 cm; overweight: 3.5 cm ± 1.5 cm) when using the alternative pelvic tracking method (Figure A.1). Our results show that similar patterns of differences between the two methods occur in healthy-weight and overweight individuals, but are more substantial and clinically relevant in overweight or obese individuals.

The predominant movement of the skin-mounted ASIS markers compared to the virtual ASIS markers occurred in the superior-inferior

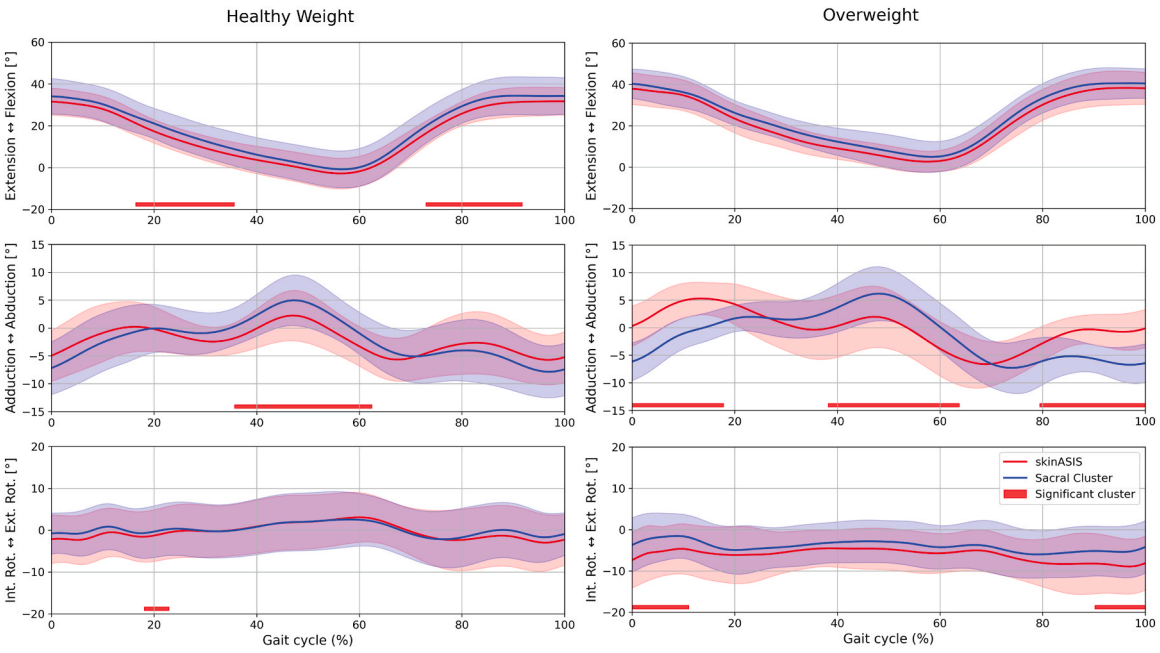


Fig. 4. Hip joint kinematics. Sagittal, frontal and transverse plane right hip joint kinematics calculated using the conventional pelvic tracking method (red) using skin-mounted anterior superior iliac spine (skinASIS) markers and the alternative method using a sacral cluster (blue) during gait in healthy-weight and overweight groups. Red boxes on the bottom of the graphs depict regions of statistically significant differences between waveforms from SPM paired *t*-test analysis. Int. Rot. = Internal Rotation; Ext. Rot. = External Rotation.

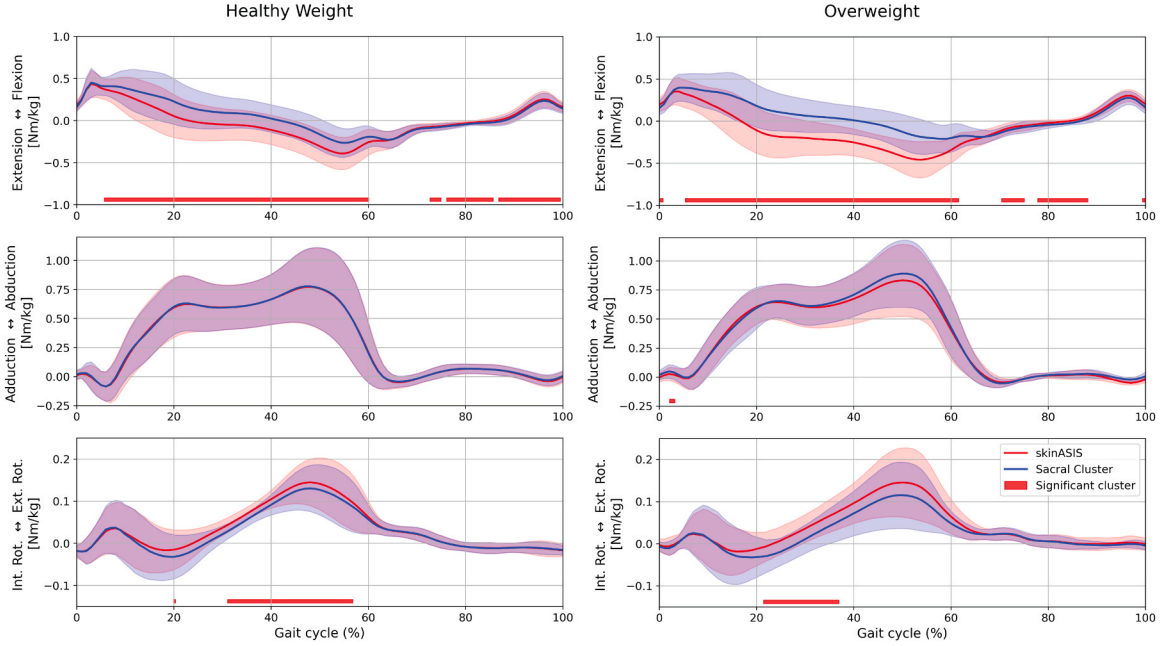


Fig. 5. Hip joint kinetics. Sagittal, frontal and transverse plane right hip joint kinetics calculated using the conventional pelvic tracking method (red) using skin-mounted anterior superior iliac spine (skinASIS) markers and the alternative method using a sacral cluster (blue) during gait in healthy-weight and overweight groups. Red boxes on the bottom of the graphs depict regions of statistically significant differences between waveforms from SPM paired *t*-test analysis. Int. Rot. = Internal Rotation; Ext. Rot. = External Rotation.

direction in our study. Previous work by Hara et al. (2014) and Camomilla et al. (2017) characterized STAs of the ASIS markers in several static calibrations through a functional range of motion of the hip joint and found the largest displacements to occur in this direction [3,12]. Our differences between models in this direction may therefore reflect the mitigation of STAs when using the sacral cluster. The small differences between the two methods in the healthy-weight group align with previous results from Langley et al. (2019) [17], who evaluated the same marker configuration and two tracking methods in fourteen participants with a healthy BMI. Although we found large d_z effect sizes for hip kinematics and kinetics in this group in our study, the corresponding RMSD values were small. This suggests that the large effect sizes are primarily driven by low variability between individuals rather than by large absolute differences between tracking methods, and therefore may

not indicate a meaningful difference. We chose not to include the iliac crest model in our study as proposed by Langley et al. as a second alternative technical model, because adiposity would likely cause STAs of comparable magnitude around the iliac crest as it does around the ASIS region. The larger differences observed in the overweight group are partially in line with previous results from Borhani et al. (2013) [13]. They showed lower similarity between methods in overweight compared to healthy-weight individuals, although they reported predominant differences in the sagittal plane. The discrepancy between these results and our findings is likely due to the difference in sacral clusters used. The larger, non-rigid cluster used in the current study, likely is less sensitive to errors caused by STAs than a smaller rigid cluster, since markers are further apart and local effects of STAs affecting any single marker are averaged out when estimating the segment pose compared to when markers are rigidly fixated on a baseplate. In addition to being less susceptible to STAs, posterior markers have been shown to be less affected by occlusion in healthy-weight individuals [25], indicating they may likely offer a particular advantage in overweight individuals, where increased adipose tissue may further compromise marker visibility.

Whether the pelvic orientation measured using the sacral cluster is truly more accurate cannot be determined from our data, as we did not directly measure bony orientation using a gold-standard method, such as radiostereometric analysis or dynamic fluoroscopic imaging. However, it seems likely that pelvic tracking using a sacral cluster with virtual ASIS markers will mitigate the effect of STAs in both groups, given that posterior markers have been shown to be less affected by STAs than anterior markers, especially in overweight individuals [3]. Our results therefore suggest that this approach holds face validity. Similarly, the more posteriorly estimated hip joint center cannot be validated in the absence of a true reference from 3D imaging. The regression method by Hara et al. (2016) [26], which is included in the CGM processing pipeline and thus this study, has however been shown to be most accurate in overweight individuals [6]. Compressing the soft tissue between the skin and bony ASIS when using the pointing stylus explains the more posterior localization of the ASIS landmarks compared to the markers sitting on the skin surface. This leads to a more posterior HJC estimate from the regression model. Literature has shown the localization of bony landmarks in overweight individuals using a stylus to be more accurate than by using skin-mounted markers [27], making it likely that the estimated hip joint center is more accurate using the pointed virtual ASIS markers. Lastly, potential bias due to marker misplacement, another important source of bias besides STAs, could not be evaluated in absence of a true reference from 3D-imaging in this study. However, given that we use the same anatomical PSIS markers for both methods compared in this study, this likely would not have influenced the comparative results between methods.

Intra-rater reliability for pointing the virtual ASIS location, assessed in a single examiner, was excellent for both the healthy-weight and overweight groups, as indicated by high ICC and low SEM values. These results indicate that a single pointing trial per ASIS may be sufficient for reliable measurement, given the small variability across repeated trials. However, further reliability testing is required to also assess inter-rater reliability for pointing the virtual ASIS location, test-retest reliability of the kinematics obtained using the sacral cluster method and to validate these findings in other laboratories.

A potential limitation of our study is the fact that inverse kinematics was applied to the traditional method using skin-mounted ASIS markers. This may have attenuated the impact of STAs in that method compared to forward kinematic approaches. However, if anything, this approach would have underestimated the differences between skin-mounted and virtual ASIS locations in our study. Moreover, the application of inverse kinematics reflects commonly used data-processing pipelines and therefore makes our findings more applicable to current 3D gait analysis practices.

In conclusion, the use of a sacral cluster with pointer-defined virtual ASIS markers for pelvic tracking provides a potentially more accurate method for calculating pelvis and hip kinematics and kinetics during 3D gait analysis in both healthy-weight and overweight individuals. This approach could therefore increase the generalizability of biomechanical studies of pelvic and hip mechanics and enhance the clinical applicability of 3D motion analysis in overweight individuals. We encourage others to implement this method, particularly in studies including overweight individuals.

Ethics declaration

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place. This study was approved by the TU Delft Human Research Ethics Committee. (Approval No. 4898).

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Declaration of Generative AI and AI-assisted technologies in the writing process

The coauthors declare that no generative AI was used in the writing of this manuscript.

CRediT authorship contribution statement

N.B.J. Dur: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **L.M.S. Damink:** Writing – review & editing, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **E.M. Macri:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization. **M.G.H. Wesseling:** Writing – review & editing, Methodology, Conceptualization. **R.A. Van der Heijden:** Writing – review & editing. **E.H.G. Oei:** Writing – review & editing. **J. Harlaar:** Writing – review & editing, Supervision, Methodology, Conceptualization. **W. Schallig:** Writing – review & editing, Validation, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Resource Availability Statement

The source code, scripts and STL file for the pointing stylus used for this study are available upon request from the corresponding author ND.

Appendix

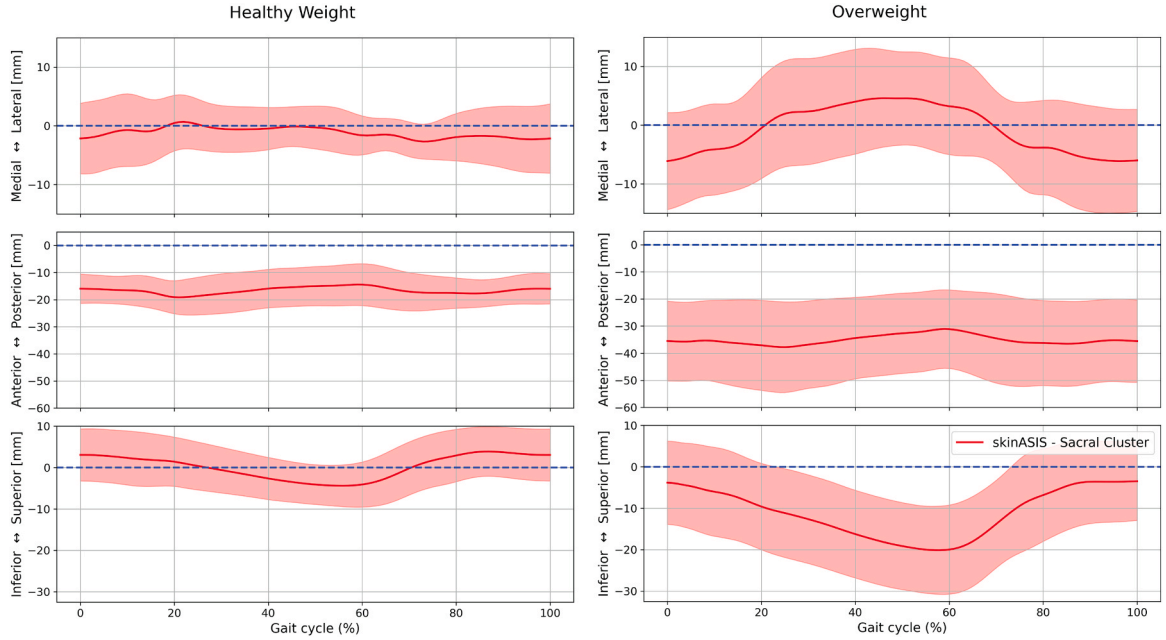


Figure A.1. Hip joint center (HJC) trajectory. Side-to-side, forward-backward and vertical differences between right HJC derived from a conventional pelvic tracking method (red) using skin-mounted ASIS markers (skinASIS) compared to pelvic tracking using a sacral cluster (blue) during gait in healthy-weight and overweight groups

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