Published in final edited form as:
J Mech Med Biol. 2023 January 28; 23(3): . doi:10.1142/s021951942350015x.

AGREEMENT OF HIP KINEMATICS BETWEEN TWO TRACKING MARKER CONFIGURATIONS USED WITH THE CODA PELVIS DURING ERGONOMIC ROOFING TASKS

KEVIN D. MOORE[*],
ASHLEY L. HAWKE,
ROBERT E. CAREY,
JOHN Z. WU,
SCOTT P. BRELOFF

Health Effects Laboratory Division, National Institute for Occupational Safety & Health, Centers for Disease Control and Prevention, 1095 Willowdale Rd., Morgantown West Virginia 26505, USA

Abstract

The anterior and posterior iliac spine markers frequently used to define the pelvis, are commonly occluded during three-dimensional (3D) motion capture. The occlusion of these markers leads to the use of various tracking marker configurations on the pelvis, which affect kinematic results. The purpose of this investigation was to examine the agreement of CODA pelvis kinematic results when two different tracking marker configurations were used during roofing tasks. 3D motion data were collected on seven male subjects while mimicking two roofing tasks. Hip joint angles (HJAs) were computed using the CODA pelvis with two different tracking marker configurations, the trochanter tracking method (TTM), and virtual pelvis tracking method (VPTM). Agreement between tracking marker configurations was assessed using cross-correlations, bivariate correlations, mean absolute differences (MADs), and Bland–Altman (BA) plots. The correlations displayed no time lag and strong agreement (all $r > 0.83$) between the HJA from the VPTM and TTM, suggesting the timing occurrence of variables are comparable between the two tracking marker configurations. The MAD between the VPTM and TTM displayed magnitude differences, but most of the differences were within a clinically acceptable range. Caution should still be used when comparing kinematic results between various tracking marker configurations, as differences exist.

Keywords

Tracking markers; technical markers; motion capture; pelvis; ergonomics; kinematics

1. Introduction

Optical marker-based motion capture systems are a common tool used to analyze aspects of human movement, such as gait and ergonomic tasks. Retro-reflective markers are placed

[*]Corresponding author. qcp5@cdc.gov.

on human participants, which are used to define body segments and calculate kinematic data.[1] Marker set configurations can contain just anatomical markers, or both anatomical and tracking (technical) markers. Anatomical markers are located on bony landmarks with anatomical relevance, which allows for accurate and repeatable placement when done properly.[2] The anatomical markers are used to define the morphology of the body segment and create the local coordinate system used to compute kinematics.[2] In cases where anatomical markers become obscured from view during movement, tracking markers are utilized to trace the segments' motion as these markers can be placed at alternative locations on that segment, unlike anatomical markers.[2] During a static motion capture trial, tracking markers are calibrated with respect to the segment (local) coordinate system that was defined using the anatomical markers.[1] In certain situations, some of the anatomical and tracking markers can be virtual instead of physical markers (physical markers are placed on the participant). Virtual markers are markers that are created using geometry relative to the location of physical markers, and virtual markers are usually used in situations where a physical marker is not an optimal choice.[2] One body segment that often uses tracking markers, is the pelvis, as the anatomical markers are often obscured during tasks that involve bending, lifting, or twisting.

Although attempts have been made to create a standardized pelvis marker set configuration for three-dimensional (3D) motion capture, it is common for researchers to use different methods that are specific to their situations (i.e., lab size, task requirements, and equipment).[3] When components of pelvis marker set configurations differ — including marker type and location (anatomical or tracking markers), number of markers, and marker cluster shape — it causes variances in the amount of soft tissue artifact (STA) between the marker set configurations, which is known to create differences in kinematic results.[4–6] When kinematic results differ due to the use of various pelvis tracking marker configurations, researchers may misunderstand or misinterpret the biomechanical data, therefore, understanding the effect that the tracking marker configurations have on pelvis kinematics is important for investigators.

The pelvis segment is commonly modeled using the right and left anterior superior iliac spine (RASI and LASI) and the right and left posterior–superior iliac spine (RPSI and LPSI) markers. These four commonly used anatomical markers make capturing accurate pelvis kinematics difficult as these markers suffer from increased STA and are predisposed to occlusion during tasks that involve hip and trunk flexion,[7,8] leading to the use of a variety of tracking marker configurations on the pelvis.[8,9] One method that uses the RASI, LASI, RPSI, and LPSI markers to define the pelvis is the CODA model (Codamotion Ltd., UK). The standard CODA pelvis model does not use tracking markers, thus if any of the anatomical markers are obscured form the motion capture cameras, pelvis kinematics can be challenging to compute, resulting in a need to improvise with custom tracking marker configurations. The use of custom tracking marker configurations on the CODA pelvis establishes a need to evaluate the agreement between those custom tracking marker configurations.

Currently, there is limited literature available examining the agreement of kinematic data between different tracking marker configurations used on the CODA pelvis during dynamic tasks, especially in an ergonomic setting. With the variety of tracking marker configurations being used on the CODA pelvis and the potential of kinematic differences as a result, further investigation of these tracking marker configurations is needed. Therefore, the purpose of this investigation was to examine the agreement of kinematic results obtained using two different tracking marker configurations on the CODA pelvis during kneeling and standing ergonomic roofing tasks. We hypothesized that the kinematic hip joint angles (HJAs) computed using the two different CODA pelvis tracking marker configurations would display strong agreement between each other's time series. Additionally, we hypothesized that the two tracking marker configurations would exhibit strong agreement between each other's kinematic HJA magnitudes.

2. Methods

2.1. Participants

Seven healthy males (age: 24 ± 8 yrs, height: 1.81 ± 0.07 m, weight: 91.5 ± 10.0 kg) with no prior roofing experience participated in this study. Healthy was defined as no musculoskeletal injuries, neurological disorders, or visual impairments that could not be corrected by lenses. The study was conducted under a National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board (IRB)-approved protocol and subjects read and completed informed consent prior to data collection.

2.2. Experimental setup & procedures

Participants came to the NIOSH biomechanics laboratory, where anthropometrics were recorded, and 46 retro-reflective motion capture markers (9 mm) were placed on the pelvis and lower extremities. The data in this study are a subset of a larger study, eighteen of the aforementioned 46 markers were used in this investigation (Fig. 1). Marker trajectories were collected using 14 MX Vicon cameras (Vicon Inc., Oxford, England), sampling at a rate of 100 Hz.

Data were collected on a 1.2 × 1.6 m custom-handmade roofing simulator, which could be adjusted to no pitch (0°) or a 15° pitch.[10,11] Subjects were asked to mimic the installation of three roof shingles in two conditions: 1) a conventional bent over standing posture with no roof pitch (0°) and 2) a kneeling posture with a 15° roof pitch.[11] The installation of the roof shingles followed the procedure from Breloff[11] and Dutta.[12] The kneeling and standing posture used during the shingle installation procedure is shown in Fig. 2, during the kneeling posture, the right and left knee were both facing the ground. Three trials were recorded for each condition. Ample rest was given between trials to avoid muscle fatigue and viscoelastic creep.

2.3. Data analysis

The raw exported marker trajectories were filtered using a lowpass fourth-order Butterworth filter, with a cutoff frequency of 6 Hz.[10,13] The right and left thigh segments[11] and the CODA pelvis were modeled in Visual3D (v. 6.0, C-Motion Inc., Germantown, MD). The CODA pelvis model (Codamotion Ltd., UK) uses the RASI, LASI, RPSI, and LPSI markers to define and track the pelvis segment and create virtual hip joint centers.[14,15] This study investigated if two different tracking marker configurations for the CODA pelvis — the trochanter tracking method (TTM) and the virtual pelvis tracking method (VPTM) (Fig. 3) — would create differences in computed hip kinematics. The TTM and VPTM were selected as the two tracking marker configurations for the CODA pelvis in this study for two reasons: (1) the TTM and VPTM do not require adjustments to standard marker set conventions and (2) the TTM and VPTM serve as a solution for the standard CODA pelvis which suffers from anatomical marker occlusion, resulting in the loss of kinematic data during activities such as the roofing tasks in this investigation.

2.3.1. TTM—The TTM CODA pelvis used the default anatomical CODA method to create the origin of the pelvis segment and define the local coordinate system but used a modified tracking method. Right and left trochanter markers (RLH and LLH, respectively) replaced the LASI and RASI makers, thereby the TTM CODA tracking markers were RLH, LLH, RPSI, and LPSI (Fig. 3).

2.3.2. VPTM—The VPTM also used the default CODA model to define the pelvis segment but then used a second virtual CODA pelvis to track the segment. Using the RASI, LASI, RPSI, and LPSI markers, a second "Kinematic Only" virtual CODA pelvis (RPV_2) was created with virtual hip joint centers defined with calculations from Bell.[14,15] The virtual hip joint centers from RPV_2 were used to create two additional virtual markers, RHip_Track, and LHip_Track. RHip_Track and LHip_Track were located at the origin of the right and left virtual hip joint centers and were used as tracking markers in addition to the LASI, RASI, LPSI, and RPSI (Fig. 3). Global Optimization, or Inverse Kinematics (IK) was used in the VPTM to prevent noise that could occur when the RASI and LASI markers disappear.[16] An IK chain was added in Visual3D to attach the pelvis, thigh, shank, and foot segments.[16] When using an IK chain, constraints are applied between segments that restrict relative motion between the segments.

2.3.3. Hip kinematics—The right and left HJAs were calculated using the pelvis as the reference and the right and left thigh segments as the parent, respectively. All joint angle rotations were computed as 3D Euler angles and an X–Y–Z Cardan sequence. All thigh segment and hip computations were identical for the TTM and VPTM configurations to prevent any kinematic differences from arising that were not related to the tracking configurations themselves.

2.4. Statistical analysis

A cross-correlation determined if a phase shift existed between the two tracking marker configurations. A Pearson bivariate correlation examined the agreement of the HJA time series between the VPTM and TTM, with statistical significance set a priori as $\alpha = 0.05$. For the bivariate correlation, the strength of the relationship was examined using the normalized correlation coefficient value (−1 to 1).[17] Mean absolute differences (MADs) between the VPTM and TTM were computed to examine agreement by determining the magnitude of difference, and a one-tailed t-test between the absolute differences and zero (best possible outcome) was used to determine statistical significance ($p < 0.05$). Bland–Altman plots (BA plots) of the maximum HJAs and average HJAs for each trial were also used to assess agreement between the two different tracking marker configurations, with limits of agreement calculated as mean difference ±2 standard deviation of differences (std).[18] All statistics were computed using MATLAB (The MathWorks, Inc., Natick, MA).

3. Results

The correlation coefficient was strongest when there was no phase shift for all the cross-correlations between the VPTM and the TTM. All bivariate correlations between the VPTM and TTM were statistically significant ($p < 0.001$), the whole dataset had a strong positive relationship ($r = 0.99$), hip flexion/extension had a strong positive relationship ($r = 0.99$), hip abduction/adduction had a strong positive relationship ($r = 0.95$), and hip internal/external rotation had a strong positive relationship ($r = 0.89$). Bivariate correlations for left hip flexion/extension had a strong positive relationship ($r = 0.99$), left hip adduction/abduction had a strong positive relationship ($r = 0.96$), and left hip internal/external rotation had a strong positive relationship ($r = 0.88$). All bivariate correlations for the right hip also had strong positive relationships, right hip flexion/extension ($r = 0.99$), right hip adduction/abduction ($r = 0.95$), and right hip internal/external rotation ($r = 0.95$). The bivariate correlations categorized by task are displayed in Tables 1 and 2.

The MADs between the VPTM and TTM HJAs for the same trials in this study were all significantly different ($p < 0.001$). The MAD for the whole dataset was 5.4° ± 7.3°, hip flexion/extension was 9.3° ± 7.3°, hip abduction/adduction was 2.5° ± 3.7°, and hip internal/external rotation was 4.5° ± 6.0°. The MAD for left hip flexion/extension was 8.5° ± 6.6°, for left hip adduction/abduction was 2.4° ± 3.7°, and for left hip internal/external rotation was 4.36° ± 5.6°. The MAD for right hip flexion/extension was 10.0° ± 8.0°, for right hip adduction/abduction was 2.7° ± 3.4°, and for right hip internal/external rotation was 4.4° ± 5.6°. The MAD categorized by task are displayed in Tables 1 and 2.

The BA plots (with upper and lower limits of agreement) of the maximum and average HJAs are displayed in Figs. 4 and 5, respectively.

For a representative subject, the average HJAs for the kneeling and standing roofing trials are displayed in Figs. 6 and 7, respectively.

4. Discussion

The purpose of this study was to investigate the agreement of calculated hip kinematic results when two different pelvis tracking marker configurations (VPTM and TTM) were applied to a CODA pelvis during ergonomic roofing tasks. The data from this study supported our hypothesis that the HJA time series from the TTM and VPTM would not display a time lag and would exhibit strong agreement. However, the data also indicated that magnitude differences between the HJAs from the TTM and VPTM do exist, with agreement varying based on the joint angle and task.

The results from the cross-correlations between the VPTM and TTM HJAs all had the highest correlation coefficient when there was no phase shift, indicating there was no time lag between the signals. The absence of a time lag between the TTM and VPTM is important when examining time-related events, as it indicates that the occurrence of peaks or other key measurables would happen within the same time-related event and at about the same moment within that event. While this does not necessarily mean that the magnitudes of the peaks or measurables would be the same, the time in which they occur would, suggesting the timing occurrence of kinematic data computed using the VPTM and TTM would agree and could be directly compared.

The bivariate correlations demonstrated strong agreement between the VPTM and TTM HJA-time series, with correlation coefficients ranging from 0.84 to 0.99 (Tables 1 and 2). Gait research examining full marker sets found similar correlation coefficients to the ones reported in this study[19,20] and while our data for hip internal/external rotation had a slightly stronger association, both our study and Mantovani[20] identified that internal/external rotation exhibited the weakest associations when compared to the other joint angle rotations of the hip (Tables 1 and 2).

While the correlations display strong agreement, this information alone is not sufficient to properly evaluate agreement between the TTM and VPTM, as the correlations do not account for magnitude differences. The results from the MAD show that the HJAs calculated using the VPTM and TTM do display significantly different magnitudes, but not all the MADs fall outside of the clinically acceptable range of 5° difference (Tables 1 and 2).[21] Hip adduction/abduction for both tasks and internal/external rotation for the kneeling task had MADs that were less than 3.6°, which is considered clinically acceptable (Tables 1 and 2).[21] However, the MADs between the HJAs from the VPTM and TTM for flexion/extension from both roofing tasks and internal/external rotation from the standing roofing task, were not within the clinically acceptable threshold (Tables 1 and 2). The CODA pelvis tracking marker configurations used by Langley[22] during gait reported better overall agreement than those in this study with mean differences between kinematics no greater than 3° for all HJAs, while the kneeling roofing task had mean differences no greater than 7° and the standing roofing task had none greater than 13° for all HJAs. The differences between the tasks examined and the variations of CODA pelvis tracking marker configurations used between the two investigations, may explain the differences in agreement reported.

The BA plots of the average HJAs displayed better overall agreement for both the kneeling and standing roofing task than the BA plots of the maximum HJAs (Figs. 4 and 5). The reduced agreement displayed by the max BA plots, indicates that comparing kinematic results between the VPTM and TTM could be of the most concern when looking at peak values (Figs. 4 and 5). For both the MAD and the BA plots in this study, hip flexion/extension for both roofing tasks were not clinically acceptable, suggesting that hip flexion/extension is also of greater concern when comparing kinematic results from different tracking marker configurations used on the CODA pelvis (Tables 1 and 2) (Figs. 4 and 5). This study and Langley[22] both reported that hip flexion/extension had reduced agreement between tracking marker configurations compared to the other HJAs. Based on the MAD and the BA plots from this study, the kneeling roofing task exhibited stronger agreement between HJAs than the standing roofing task, and gait displayed stronger agreement compared to both roofing tasks examined in our study,[22] suggesting that agreement between kinematic results from different tracking marker configurations vary on a task-by-task basis (Tables 1 and 2) (Figs. 4 and 5).

The MAD and the BA plots from this study determined that differences exist between kinematic results from the TTM and VPTM. Regardless of whether the differences between kinematic result from different tracking marker configurations are considered clinically acceptable or not, caution should always be exhibited when comparing these results as also suggested by Mantovani[20] and Gorton[3] (Tables 1 and 2) (Figs. 4 and 5).

4.1. Limitations and future considerations

This investigation included only male subjects. The female and male pelvis have differences in morphology which could affect the agreement exhibited between the tracking marker configurations. The subjects used in this study were not experienced roofers. It is possible that the tasks could have been performed differently by experienced roofers compared to a novice. The VPTM and TTM are only two tracking marker configurations that can be added to the CODA pelvis. It is possible that other tracking marker configurations for the CODA pelvis could exhibit varying levels of agreement when compared to the configurations used in this investigation. This study examined two roofing tasks. Other tasks could exhibit varying levels of agreement between tracking marker configurations compared to the roofing tasks in this investigation. The purpose of this study was to examine agreement between the TTM and VPTM tracking marker configurations used with the CODA pelvis to provide additional tracking options for the CODA model and to aid in preventing researchers from misinterpreting biomechanical data. It was outside the scope of the study to determine which configuration is more accurate, as the only way to properly determine accuracy of joint kinematics either requires invasive or highly specialized techniques, such as markers fixed directly to participants' bones or a dynamic stereo radiographic system.[23–25]

Future research should examine different tasks, larger and more diverse subject populations, and more tracking marker configurations/methods. Future research should also aim to examine the accuracy of HJAs by comparing those from pelvis marker configurations established in published research, such the ones in this investigation, to real world joint kinematics obtained by using "gold standard methods".

5. Conclusion

No time lag existed between the HJAs from the VPTM and TTM and the time series displayed strong agreement, suggesting that the timing occurrence of variables are comparable between the two tracking marker configurations. The HJA time series from the VPTM and TTM display strong agreement, however, there is a difference in magnitude of the hip joint kinematics. A majority of the differences identified in this study between the VPTM and TTM HJAs were within a clinically acceptable range, except for hip flexion/extension in both the kneeling and standing task. In this study, agreement between HJAs from the VPTM and TTM was stronger in the kneeling task, suggesting that agreement can vary based on the task being examined. While the agreement between all HJAs other than flexion/extension is clinically acceptable, and therefore, comparable between the VPTM and

TTM, it is recommended that caution should always be exhibited when comparing kinematic results between different tracking marker configurations, as differences do exist.

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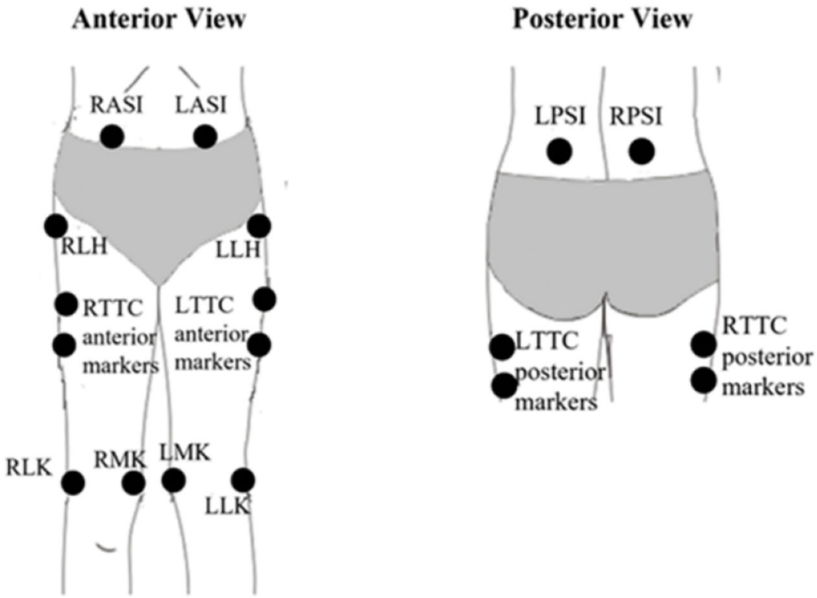

Abbreviation	Description
R/LASI	Right / left anterior superior iliac spine
R/LPSI	Right / left posterior superior iliac spine
R/LLH	Right / left trochanter
R/LTTC	Right / left thigh four marker cluster (tracking)
R/LLK	Right / left lateral epicondyle (femur)
R/LMK	Right / left medial epicondyle (femur)

Fig. 1.

Placement of the 18 markers located on the pelvis and thigh that were used to create segments and compute joint kinematics.

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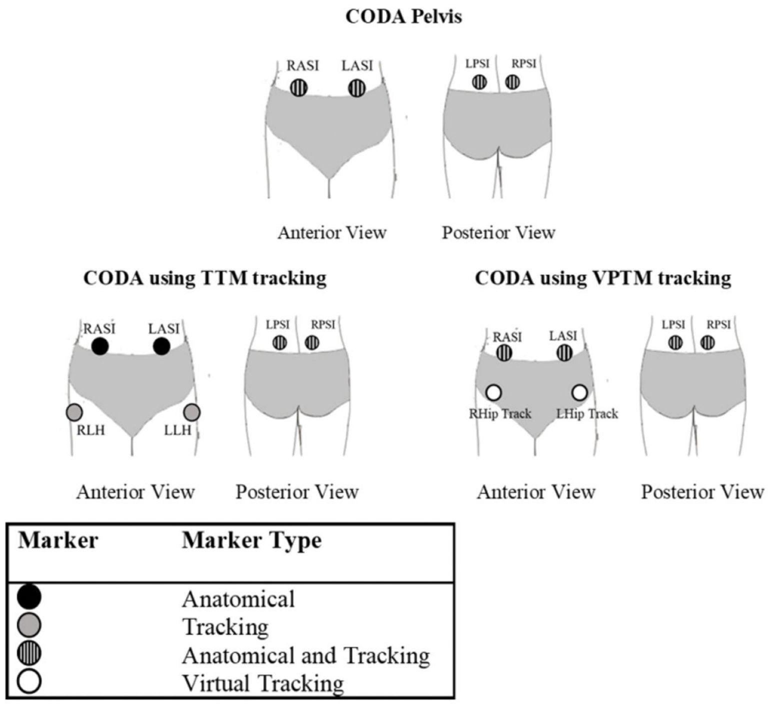
Fig. 2.

The kneeling posture (left) and the standing posture (right) used during the roof installation procedures.



Abbreviation	Description
R/LASI	Right / left anterior superior iliac spine
R/LPSI	Right / left posterior superior iliac spine
R/LLH	Right / left trochanter
R/LHip Track	Right / left virtual tracking marker created for VPTM

Fig. 3.
The CODA pelvis marker set used for anatomical purposes and the TTM and VPTM tracking marker configurations applied to the CODA pelvis.

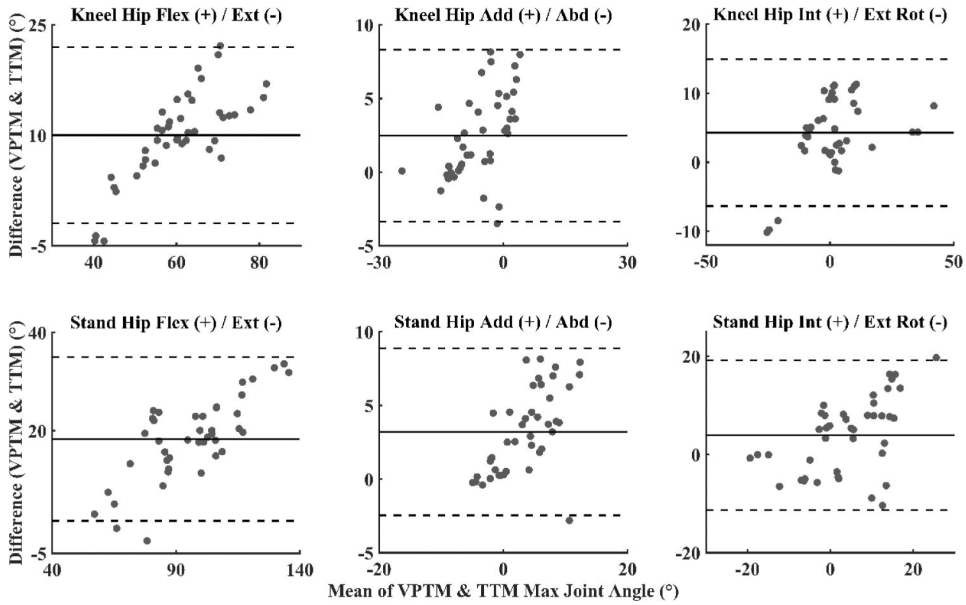


Fig. 4.

BA plots of the maximum HJAs for all trials. The black solid line represents the mean difference, and the black dashed lines represent the mean difference ±2 std (upper and lower limits of agreement). Flexion/Extension (Flex/Ext), Adduction/Abduction (Add/Abd), Internal/External Rotation (Int/Ext Rot).

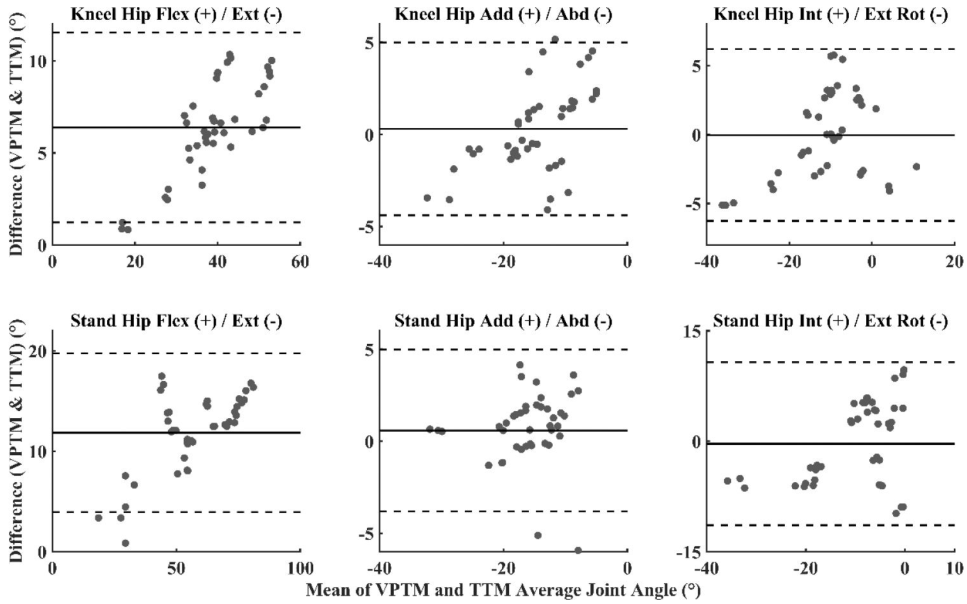


Fig. 5.

BA plots of the average HJAs for all trials. The black solid line represents the mean difference, and the black dashed lines represent the mean difference ±2 std (upper and lower limits of agreement). Flexion/Extension (Flex/Ext), Adduction/Abduction (Add/Abd), Internal/External Rotation (Int/Ext Rot).

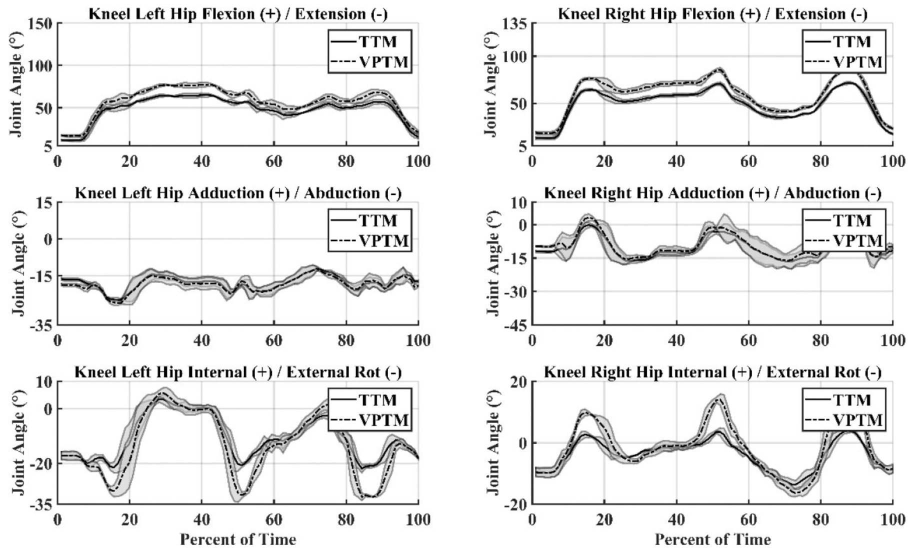


Fig. 6.

A representative subject's mean kneeling task HJAs with standard deviation (shaded region) for the TTM and VPTM.

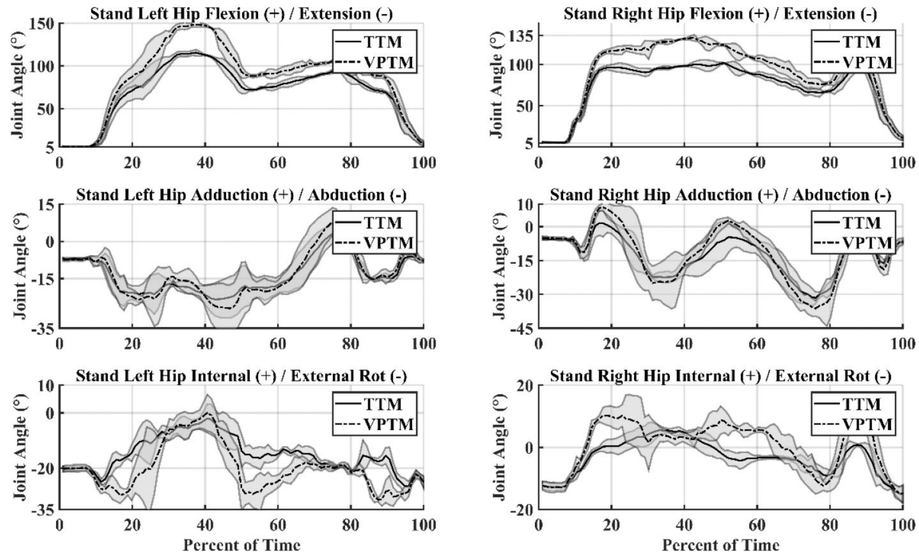


Fig. 7.

A representative subject's mean standing task HJAs with standard deviation (shaded region) for the TTM and VPTM.

Table 1.

Statistics for kneeling roofing task left and right HJAs.

	Kneeling left HJAs			Kneeling right HJAs		
	Flex/Ext	**Abd/Add**	**Int/Ext**	**Flex/Ext**	**Abd/Add**	**Int/Ext**
Bivariate correlation (*r*)	0.99 *	0.96 *	0.93 *	0.99 *	0.92 *	0.97 *
Mean absolute diff (MAD ± SD)	6.1° ± 3.8° *	2.0° ± 2.8° *	3.5° ± 4.6° *	7.0° ± 4.4° *	2.2° ± 2.8° *	3.2° ±4.1° *

Note:

* Indicates that bivariate correlation coefficient and MAD (different) are statistically significant ($p < 0.001$). Flex/Ext is flexion/extension, Abd/Add is abduction/adduction, and Int/Ext is internal/ external rotation.

Table 2.

Statistics for standing roofing task left and right HJAs.

	Standing left HJAs			Standing right HJAs		
	Flex/Ext	**Abd/Add**	**Int/Ext**	**Flex/Ext**	**Abd/Add**	**Int/Ext**
Bivariate correlation (*r*)	0.95 *	0.95 *	0.84 *	0.99 *	0.95 *	0.94 *
Mean absolute diff (MAD ± SD)	10.7° ± 7.7° *	2.8° ± 4.4° *	5.6° ± 6.1° *	12.8° ± 9.4° *	3.0° ± 3.9° *	5.5° ± 6.4° *

Note:

* Indicates that bivariate correlation coefficient and MAD (different) are statistically significant ($p < 0.001$). Flex/Ext is flexion/extension, Abd/Add is abduction/adduction, and Int/Ext is internal/ external rotation.