How Different Marker Sets Affect Joint Angles in Inverse Kinematics Framework

Giulia Mantovani
School of Human Kinetics,
University of Ottawa,
200 Lees Avenue,
Ottawa, ON K1N 6N5, Canada
e-mail: gmant053@uottawa.ca

Mario Lamontagne[1]
School of Human Kinetics,
University of Ottawa,
200 Lees Avenue,
Ottawa, ON K1N 6N5, Canada;
Department of Mechanical Engineering,
University of Ottawa,
200 Lees Avenue,
Ottawa, ON K1N 6N5, Canada
e-mail: mlamon@uottawa.ca

The choice of marker set is a source of variability in motion analysis. Studies exist which assess the performance of marker sets when direct kinematics is used, but these results cannot be extrapolated to the inverse kinematic framework. Therefore, the purpose of this study was to examine the sensitivity of kinematic outcomes to inter-marker set variability in an inverse kinematic framework. The compared marker sets were plug-in-gait, University of Ottawa motion analysis model and a three-marker-cluster marker set. Walking trials of 12 participants were processed in OPENSIM. The coefficient of multiple correlations was very good for sagittal (>0.99) and transverse (>0.92) plane angles, but worsened for the transverse plane (0.72). Absolute reliability indices are also provided for comparison among studies: minimum detectable change values ranged from 3 deg for the hip sagittal range of motion to 16.6 deg of the hip transverse range of motion. Ranges of motion of hip and knee abduction/adduction angles and hip and ankle rotations were significantly different among the three marker configurations ($P < 0.001$), with plug-in-gait producing larger ranges of motion. Although the same model was used for all the marker sets, the resulting minimum detectable changes were high and clinically relevant, which warns for caution when comparing studies that use different marker configurations, especially if they differ in the joint-defining markers.

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1 Introduction

Three-dimensional gait analysis is widely used to assess functional performance and clinical outcomes. One of the most common models is plug-in-gait (PiG) [1,2]. In PiG, hip joint centers are calculated through regression equations, while knee and ankle joint centers and their frontal planes definitions rely on the lateral technical thigh and shank markers placement [2]. Slight misplacements of these markers can cause great frontal and transverse plane deviations [2]. Since the placement of anatomical skin markers is more accurate than the placement of technical skin markers (i.e., a marker which is positioned in a location that has no anatomical relevance) [3], a modified version of PiG was developed, so-called the University of Ottawa motion analysis model (UOMAM) [4]. Rather than relying on the technical skin markers of thigh and shank, in UOMAM the medial knee and ankle markers are used to define knee and ankle joint centers and frontal planes. Anatomical skin markers are necessary to define repeatable coordinate systems; however, sometimes they do not comply with the ideal characteristics for tracking markers, such as visibility from cameras and low soft tissue artifacts [5]. Cluster marker sets were introduced to solve these problems: additional technical skin markers are placed where they are less affected by skin movements [3,6–8], and then the technical markers are calibrated with respect to the anatomical coordinate system [9].

Kinematic outcomes produced by different marker sets were compared in the literature [10–13], and their validity was assessed against gold standards, such as bone pin studies [14–16]. These technical studies should be used as reference to determine whether the variability introduced by the choice of marker set impacts the clinical relevance of a study [17]. For the comparisons, a "direct kinematics" framework was used, where the anatomical markers directly define the joint axes and body segments orientation [18]. However, joint kinematic sensitivity to marker sets in an "inverse kinematic" framework is not known yet, even though markers configurations originally developed for direct kinematics are commonly used in inverse kinematics (e.g., PiG in Steele et al. [19]). In inverse kinematics, joint angles are estimated by maximizing the overlapping between experimental and model-determined (also called virtual) markers of a model with joint constraints [20]. In this case, the local coordinate system of one body segment depends on the whole marker set (hence, also known as "global optimization"), rather than just on specific joint-defining markers like in direct kinematics. Moreover, the model characteristics (e.g., joint definition, axis orientation, etc.) are independent from the marker set, and different combinations of markers can be used on the same kinematic model. Because of these substantial differences, it cannot be assumed that the results drawn from marker set comparison studies in direct kinematics can be extended to inverse kinematics.

Therefore, the purpose of this study was to examine the reliability and sensitivity of kinematic outcomes to inter-marker set variability, comparing three marker sets applied to the same kinematics model with an inverse kinematics approach during level walking. The three marker sets were: (1) PiG as commonly used in the literature and represents the minimum set of markers to model three-dimensional kinematics, (2) UOMAM, which uses PiG markers configuration with additional markers for improving the joint center definitions, and (3) cluster (three-marker clusters on thighs, shanks, and feet) as commonly used to reduce the effects of soft tissue artifacts.

2 Methods

2.1 Instrumentation. The motion capture system included: ten infrared cameras (MX-13, VICON, Oxford, UK) and two fixed Bertec force plates (models FP4060-08, Bertec Corporation, Columbus OH). Marker trajectories were captured at 200 Hz and ground reaction forces at 1000 Hz.

2.2 Participants and Protocol. Twelve participants volunteered for this study: 11 men, one woman, weight 79 ± 10 kg, height 177 ± 6 cm, and age 36 ± 7 years. Participants wore a tight suit which was instrumented with reflective markers for all the three marker sets (Fig. 1). To eliminate sources of variability other than the marker sets, all the markers were placed by the same rater and acquired simultaneously on the participant. Every participant performed a static trial, followed by five repetitions of full gait cycle (foot strike to foot strike) performed at a self-selected pace.

[1]Corresponding author.

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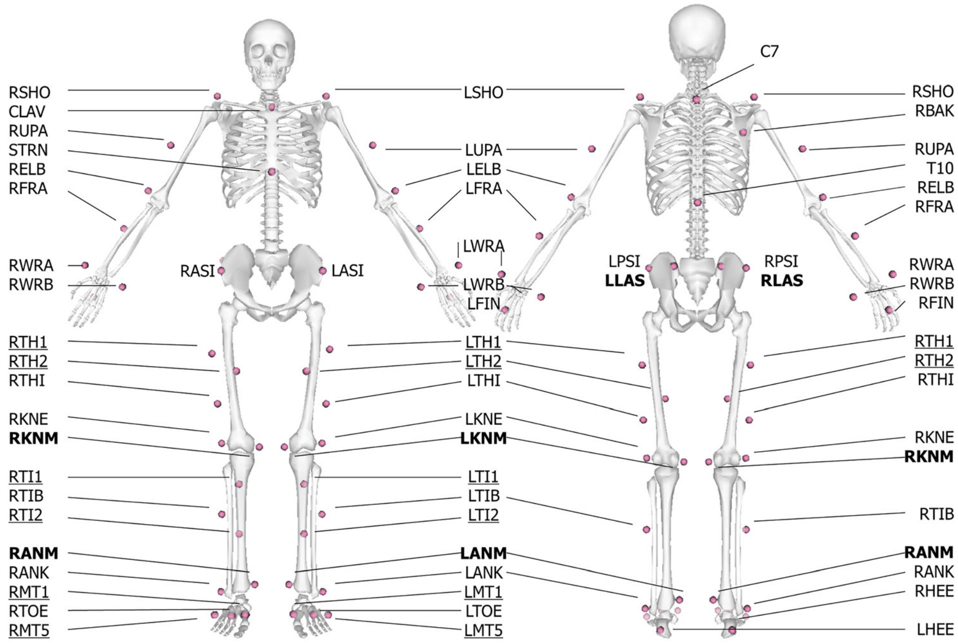

Fig. 1 Representation of the three different marker sets compared in the study. The markers labeled with regular font belong to the original plug-in-gait marker set, the ones in bold are an adjustment made for the UOMAM marker set, and the underlined ones are the extramarkers used for cluster. To be noticed, cluster uses RTHI, LTHI, RTIB, and LTIB as part of the cluster for right and left thigh and right and left tibia segments, respectively. Also, the two extra markers at the pelvis are placed in the midpoint between the anterior and posterior iliac crests and have been added to the plug-in-gait marker set to help tracking the other pelvic markers during occlusions, which occur often during movements, such as squatting.

The institution's research ethics board approved the study, and the participants provided written informed consent.

2.3 Data Processing. The three-dimensional marker trajectories and the ground reaction forces were filtered with a zero-lag fourth-order Butterworth filter (cutoff frequency at 6 Hz). Scaling and inverse kinematics were performed in OPENSIM 3.1 (Stanford University, Stanford, CA). The markers on the model were placed according to the guidelines for the anatomical marker placements by Davis et al. [1] and Kadaba et al. [2].

The two-step model scaling procedure consisted of dimensional scaling and marker adjustment. The dimensional scaling resized the model to the actual anthropometric dimensions of the participant by comparing the virtual with the experimental anatomical markers (e.g., anterior superior iliac crests, femoral epicondyles, and malleoli). The marker adjustment replaced the original locations of the virtual markers with the experimental coordinates, once the whole body pose had been estimated through global optimization. For both scaling and inverse kinematics, the weights were distributed so that every segment was equally weighted during inverse kinematics (see Table S2, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection).

The hip joint center was calculated according to the regression equation presented by Davis et al. [1]. The knee and ankle joint centers were calculated as midpoint between the lateral and medial markers at the knee and ankle, respectively. In PiG, there were no medial markers; therefore, the joint centers were identified based on the lateral thigh and shank markers, and the annotated anthropometric measurements, as suggested by Davis et al. [1] and Kadaba et al. [2]. The joint centers were treated as additional experimental markers in OPENSIM. The kinematic model was adapted from the one proposed by Hamner et al. [21]: the hip was a three degree-of-freedom ball-and-socket joint, while the one degree-of-freedom knee and ankle joints were adjusted to include knee abduction/adduction, knee internal/external rotation, and ankle eversion/inversion, to comply with the characteristics of the original PiG model [1,2].

After time normalization, max range of motion (ROM), peak max (MAX), and peak min (MIN) values were calculated for every kinematic variable of the right side (e.g., hip and knee flexion/extension, abduction/adduction, and internal/external rotations, and ankle flexion/extension and eversion/inversion).

2.4 Data Analysis and Statistics. The indices used to establish reliability and sensitivity of kinematic outcomes to marker sets were the intraclass correlation coefficient (ICC) to analyze the correlation of scalar parameters extracted from the kinematic waveforms (e.g., peaks, range of motion, and value at foot strike) [22–27], and the coefficient of multiple correlation (CMC) to investigate the overall similarity between waveforms [7,12,28–30]. Both ICC and CMC carried intrinsic limitations as they normalized measurement error to the heterogeneity of subjects [24]; therefore, absolute reliability indices such as mean absolute variation (MAV) [11] and minimum detectable changes (MDC) [22,24,26] were needed.

ICC was calculated as a two-way model, single measurement, absolute agreement, ICC(A,1) [23] for ROM, MAX, and MIN of every kinematic variables. ICC varies between 0 (no correlation) and 1 (perfect correlation).

CMC was calculated as suggested by Ferrari et al. [28]

$$\mathrm{CMC}^j = \sqrt{1 - \frac{\sum_{g=1}^{G}\sum_{p=1}^{P}\sum_{f=1}^{F}\left(Y_{gpf}^j - \bar{Y}_{gf}^j\right)^2 / GF_g(P-1)}{\sum_{g=1}^{G}\sum_{p=1}^{P}\sum_{f=1}^{F}\left(Y_{gpf}^j - \bar{Y}_{g}^j\right)^2 / G(F_g P-1)}} \quad (1)$$

where Y_{gpf}^j is the gth repetition of the kinematic variable j, at frame f (also known as time), for protocol p (also known as

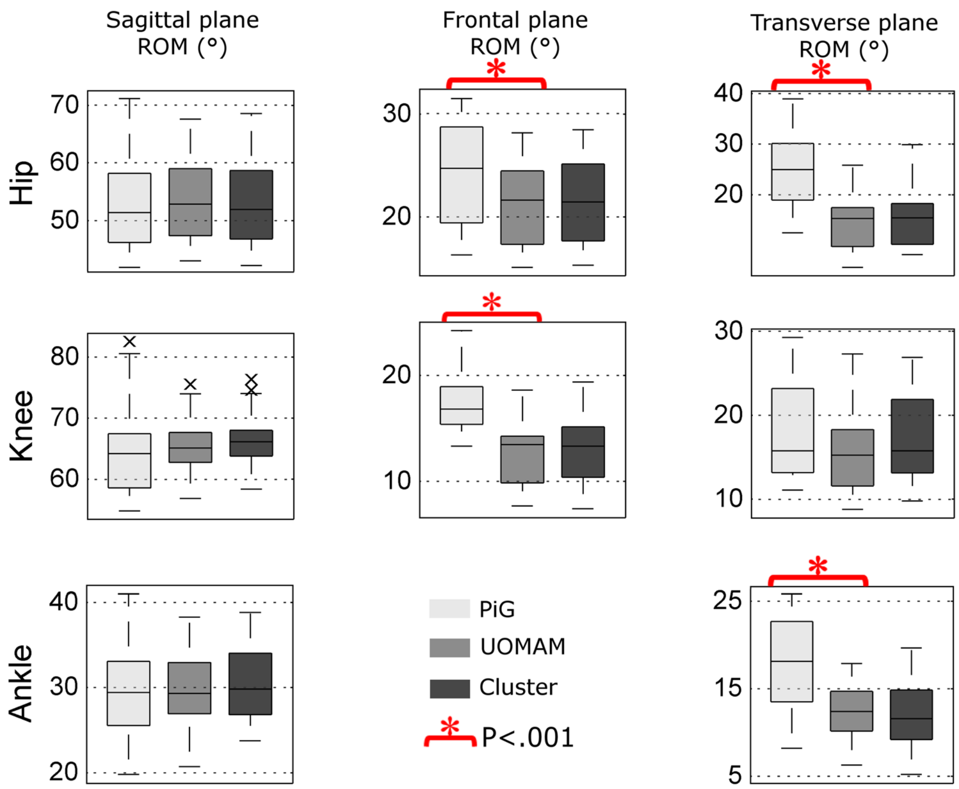

Fig. 2 Box plots of the range of motion (ROM) distributions over the eight kinematics variables for every marker set. Repeated measures ANOVA showed that the three marker sets were significantly different ($P < 0.001$) for hip and knee ab/adduction angles and hip and ankle rotations. The symbol 'X' indicates outliers.

marker set). $\bar{Y}^j_{gf}$ is the average curve of the same kinematic variable j for different marker sets, $\bar{Y}^j_g$ is the average of $\bar{Y}^j_{gf}$ over time f, and G, F_g, and P are the number of gait repetitions, frames, and protocols, respectively.[2]

MAV was measured as described by Ferrari et al. [11]

$$\mathrm{MAV} = \frac{1}{N}\sum_{f=1}^{N}\left(\max_p \bar{Y}^f_p - \min_p \bar{Y}^f_p\right) \tag{2}$$

where $\bar{Y}^f_p$ is the average of the five repetitions for protocol (i.e., marker set) p, and at frame f, and N is the total number of frames. MDC was calculated as $\mathrm{MDC} = 1.96\cdot\sqrt{2}\cdot\mathrm{SEM}$ [22,31]. Standard error of the mean (SEM) was defined as $\mathrm{SEM} = \mathrm{SD}\cdot\sqrt{(1-\mathrm{ICC})}$ [24], where SD is the standard deviation of the values for all the subjects and can be determined from the same analysis of variance (ANOVA) model employed to calculate ICC as $\mathrm{SD} = \sqrt{\mathrm{SS_{TOT}}/(N-1)}$, where $\mathrm{SS_{TOT}}$ is the total variance.

3 Results

Kinematic variables in the sagittal plane showed better agreement than in the frontal and transverse planes, where peaks and range of motion differed noticeably among the three curves. The overall similarity of the sagittal curves was reflected in the coefficients of multiple correlation above 0.99 (Table 1). The variables in frontal plane showed slightly worse agreement (0.97 for hip and 0.92 for knee), with most of the differences to be attributed to PiG, since UOMAM versus cluster comparison produced CMC values of 1.00 and 0.97 for hip and knee, respectively. Transverse plane angles demonstrated the worst agreement, especially at the hip (0.72) and ankle (0.73). The curves for one "typical" participant (whose CMC and MAV were the closest to the median values) were reported in Fig. S1, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection.

The range of motion values of all the kinematic variables are shown in Fig. 2. The hip and knee abduction/adduction angles and hip and ankle rotations showed significant differences among the three marker sets (repeated measure ANOVA $P < 0.001$), with PiG always producing larger ROMs. The variables reporting significant differences were also those with the worst inter-marker sets ICC values (Table 2). ICC values calculated between cluster and UOMAM were good ($\mathrm{ICC} > 0.79$), but the comparison of these marker configurations to PiG largely decreased the ICC, especially in the frontal and transverse planes.

The mean absolute variation values for all the kinematic variables were reported in Table 3. Overall, MAV indices showed a good absolute repeatability in knee and ankle sagittal plane and hip and knee frontal plane ($\mathrm{MAV} < 2.8$ deg), while rotational variables had MAV above 4.1 deg. However, when the comparison was restricted to UOMAM and cluster, MAV values improved considerably (0.7–2.1 deg).

Minimum detectable changes values were higher when PiG was included in the marker set comparison. When PiG was excluded from the analysis, all the kinematic variables produced MDC values below 5.2 deg (Table 4).

Intramarker set (intertrials) variability measured the reliability of kinematic variables when the same marker set was used to capture multiple trials for the same subject. The results are reported in Table S3, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection, and

[2]One of the CMC's drawbacks is that, if the protocol variability is similar or higher than the intrinsic variability of the curve, the result could be an imaginary number. To the purpose of this study, this result would be equivalent to a no correlation, thus, imaginary results were forced to zero.

Table 1 Inter-marker set coefficient of multiple correlation (CMC). Since the distributions were not normal, median, 25%, and 75% values were reported in the table. CMC was calculated comparing all the three marker sets, and for pairs comparison.

		All marker sets			PiG versus UOMAM			PiG versus cluster			UOMAM versus cluster		
CMC inter-marker sets		Median	25%	75%	Median	25%	75%	Median	25%	75%	Median	25%	75%
Flex/Ext	Hip	0.99	0.98	0.99	0.99	0.97	0.99	0.99	0.97	0.99	1.00	1.00	1.00
	Knee	1.00	0.99	1.00	1.00	0.98	1.00	1.00	0.98	1.00	1.00	1.00	1.00
	Ankle	0.99	0.98	0.99	0.98	0.98	0.99	0.98	0.95	0.99	0.99	0.99	1.00
Ab/Add	Hip	0.97	0.96	0.99	0.96	0.95	0.98	0.97	0.94	0.98	1.00	0.99	1.00
	Knee	0.92	0.88	0.96	0.91	0.82	0.94	0.89	0.83	0.94	0.97	0.96	0.99
	Ankle	—	—	—	—	—	—	—	—	—	—	—	—
Rotation	Hip	0.72	0.00	0.87	0.66	0.00	0.88	0.69	0.00	0.84	0.92	0.84	0.94
	Knee	0.89	0.84	0.92	0.88	0.81	0.92	0.86	0.77	0.93	0.96	0.93	0.97
	Ankle	0.73	0.57	0.81	0.73	0.47	0.79	0.67	0.46	0.77	0.86	0.78	0.93

showed very similar intertrial variability, with knee flexion/extension being the most variable angle and knee abduction/adduction the least.

4 Discussion

This study analyzed the sensitivity of kinematic outcomes to inter-marker set variability when using an inverse kinematic framework.

PiG marker set differed the most from the other two reporting the lowest ICC and CMC and the highest MAV values. Moreover, PiG produced significantly larger ROM, as previously found for direct kinematics by Ferrari et al. [11]. In vivo bone-pins studies showed a stable 1.2 deg abduction during stance phase and a peak abduction of 6.4 deg during swing, with an overall average ROM of about 5.0 deg [14,15]. Even considering the estimate standard error of 3.6 deg for knee abduction/adduction due to skin artifacts [16], all the marker sets still overestimated the frontal plane ROM (Fig. 2). Among the three, PiG demonstrated to be the most variable marker set with an interquartile range for knee frontal ROM of 15.5–18.9 deg, while UOMAM and cluster marker sets produced 10.5–14.4 deg and 11.2–15.4 deg, respectively.

The overall reliability as expressed by CMC was good in sagittal and frontal planes, but not in the transverse plane. MAV indices in the frontal and transverse planes were below 5.2 deg, but these values reflected poor repeatability if considering that abduction/adduction and internal/external rotations are characterized by low ROMs. Similar trends were found in previous inter-rater and intersession reliability results for studies using direct kinematics [12,25,29,32].

Table 2 Inter-marker set intraclass correlation coefficients (ICC) for ROM, peak MAX, and peak MIN parameters. Since the distributions were not normal, median, 25%, and 75% values were reported in the table. ICC were calculated comparing all the three marker sets, and for pairs comparison.

		All marker sets			PiG versus UOMAM			PiG versus cluster			UOMAM versus cluster		
		Median	25%	75%	Median	25%	75%	Median	25%	75%	Median	25%	75%
ICC inter-marker sets (ROM)													
Flex/Ext	Hip	0.98	0.94	0.99	0.97	0.89	0.99	0.97	0.90	0.99	0.99	0.98	1.00
	Knee	0.66	0.36	0.87	0.65	0.19	0.88	0.54	0.03	0.84	0.95	0.81	0.99
	Ankle	0.93	0.83	0.98	0.94	0.79	0.98	0.90	0.71	0.97	0.95	0.77	0.99
Ab/Add	Hip	0.78	0.33	0.94	0.73	−0.08	0.94	0.72	0.05	0.92	0.96	0.87	0.99
	Knee	0.48	0.02	0.81	0.33	−0.08	0.75	0.38	−0.10	0.78	0.94	0.81	0.98
	Ankle	—	—	—	—	—	—	—	—	—	—	—	—
Rotation	Hip	0.37	0.00	0.73	0.27	−0.10	0.68	0.28	−0.12	0.70	0.90	0.71	0.97
	Knee	0.80	0.56	0.93	0.64	0.17	0.88	0.87	0.61	0.96	0.89	0.47	0.97
	Ankle	0.40	0.01	0.75	0.31	−0.11	0.72	0.33	−0.11	0.74	0.92	0.75	0.98
ICC inter-marker sets (MAX)													
Flex/Ext	Hip	0.87	0.67	0.96	0.77	0.33	0.93	0.83	0.49	0.95	0.99	0.94	1.00
	Knee	0.56	0.20	0.83	0.48	−0.05	0.81	0.49	−0.03	0.81	0.96	0.84	0.99
	Ankle	0.83	0.61	0.94	0.83	0.36	0.95	0.76	0.37	0.92	0.95	0.83	0.98
Ab/Add	Hip	0.82	0.60	0.94	0.84	0.53	0.95	0.72	0.26	0.91	0.94	0.80	0.98
	Knee	0.43	0.05	0.76	0.30	−0.13	0.70	0.32	−0.13	0.72	0.94	0.71	0.98
	Ankle	—	—	—	—	—	—	—	—	—	—	—	—
Rotation	Hip	0.57	0.25	0.83	0.51	−0.02	0.82	0.51	−0.01	0.83	0.87	0.62	0.96
	Knee	0.71	0.36	0.90	0.56	−0.05	0.86	0.66	0.09	0.89	0.89	0.67	0.97
	Ankle	0.73	0.36	0.91	0.74	0.34	0.92	0.56	−0.04	0.86	0.88	−0.03	0.98
ICC inter-marker sets (MIN)													
Flex/Ext	Hip	0.93	0.75	0.98	0.87	0.37	0.97	0.92	0.63	0.98	0.99	0.91	1.00
	Knee	0.87	0.43	0.97	0.79	−0.05	0.95	0.88	0.18	0.97	0.96	0.43	0.99
	Ankle	0.84	0.55	0.95	0.87	0.20	0.97	0.74	0.10	0.93	0.91	0.74	0.97
Ab/Add	Hip	0.77	0.35	0.93	0.71	−0.06	0.93	0.74	0.12	0.93	0.96	0.75	0.99
	Knee	0.79	0.55	0.92	0.72	0.30	0.91	0.73	0.33	0.91	0.93	0.78	0.98
	Ankle	—	—	—	—	—	—	—	—	—	—	—	—
Rotation	Hip	0.34	0.01	0.70	0.22	−0.12	0.63	0.34	−0.12	0.74	0.79	0.44	0.93
	Knee	0.89	0.75	0.96	0.86	0.59	0.96	0.86	0.59	0.96	0.96	0.83	0.99
	Ankle	0.45	0.10	0.77	0.28	−0.14	0.69	0.38	−0.13	0.76	0.81	0.15	0.95

Table 3 Inter-marker sets mean absolute variation (MAV). Since the distributions were not normal, median, 25%, and 75% values were reported. MAV was calculated comparing all the three marker sets, and for pairs comparison.

		All marker sets			PiG versus UOMAM			PiG versus cluster			UOMAM versus cluster		
MAV (deg) inter-marker sets		Median	25%	75%	Median	25%	75%	Median	25%	75%	Median	25%	75%
Flex/Ext	Hip	4.5	3.4	6.5	4.2	3.3	6.4	3.3	2.2	5.6	1.2	0.8	1.8
	Knee	2.4	1.8	5.4	2.0	1.5	5.3	1.9	1.6	4.5	0.7	0.5	0.9
	Ankle	2.4	2.0	3.0	1.7	1.4	2.1	1.9	1.4	2.8	1.3	0.9	1.5
Ab/Add	Hip	2.8	1.9	3.5	2.2	1.9	2.8	2.2	1.5	3.1	0.8	0.6	1.0
	Knee	2.8	2.2	3.4	2.2	1.6	3.2	2.6	1.8	3.1	0.8	0.7	1.0
	Ankle	—	—	—	—	—	—	—	—	—	—	—	—
Rotation	Hip	5.2	4.3	10.7	4.4	3.1	9.9	4.6	3.6	7.9	1.5	1.2	2.5
	Knee	4.1	2.3	5.1	2.9	1.7	3.9	2.9	1.8	4.7	1.8	1.4	1.9
	Ankle	4.9	4.0	7.0	3.8	2.8	5.0	4.4	2.8	5.8	2.1	1.4	3.0

The comparison of curve parameters (e.g., ROM and peaks) demonstrated that the overall repeatability of curves does not necessarily lead to repeatability of relevant parameters. Only hip and ankle sagittal ROM produced good reliability over the three different marker sets (ICC > 0.8). However, when limiting the comparison to just UOMAM and cluster, ICC values for all the variables exceed 0.80, therefore, these two marker sets produced consistent relevant parameters.

Both relative and absolute reliability indices indicated that cluster and UOMAM produced very similar results, with MDC values below 2.4 deg for sagittal and frontal plane angles, and below 5 deg for transverse (fourth column in Table 4). Therefore, the addition of cluster markers does not considerably change the outcomes of the analysis. On the other hand, the variability increased drastically when PiG was included in the comparison, with MDC values up to four times higher (first three columns in Table 4). Since the only major difference between PiG and UOMAM was the joint centers definition, it can be concluded that the kinematic outcomes are highly sensitive to anatomical markers, especially those used to define joint centers [11,33].

In this study, the use of different marker sets was the only source of variability, since data processing and modeling were identical. Nevertheless, the MDC obtained when comparing all the three marker sets exceeded 5 deg for most variables, with the worst results recorded at hip internal/external rotation ROM (16.6 deg). Despite the consistency in the kinematic model, the resulting MDC values demonstrated that the variability introduced by different marker sets cannot be neglected, especially if joint center-defining markers change. When MDC values are larger than the clinically important differences, then the variability introduced by the protocol reduces and/or invalidates the clinical relevance of the study [17]. Therefore, the identified MDC values can

Table 4 Minimum detectable change (MDC) obtained when comparing ROM, peak MAX, and peak MIN parameters for all the three marker sets and for pairs comparison

		All marker sets	PiG versus UOMAM	PiG versus cluster	UOMAM versus cluster
Inter-marker set MDC (ROM)					
Flex/Ext	Hip	3.0	3.7	3.5	1.6
	Knee	7.8	8.8	10.0	2.2
	Ankle	3.2	3.2	4.0	2.4
Ab/Add	Hip	5.5	6.5	6.6	2.0
	Knee	7.6	8.9	8.4	2.2
	Ankle	—	—	—	—
Rotation	Hip	16.6	19.1	18.6	4.7
	Knee	6.4	8.7	5.2	4.5
	Ankle	10.1	11.4	11.8	2.5
Inter-marker set MDC (MAX)					
Flex/Ext	Hip	7.9	10.4	8.5	2.7
	Knee	9.4	11.6	11.0	2.0
	Ankle	4.4	4.8	5.4	2.1
Ab/Add	Hip	3.9	4.0	5.2	2.0
	Knee	7.4	8.8	8.3	1.9
	Ankle	—	—	—	—
Rotation	Hip	11.3	13.7	13.4	4.5
	Knee	5.5	6.5	5.5	3.8
	Ankle	6.5	5.9	8.3	4.5
Inter-marker set MDC (MIN)					
Flex/Ext	Hip	8.2	10.9	8.6	3.1
	Knee	3.9	5.2	3.6	2.1
	Ankle	4.3	4.0	5.4	3.2
Ab/Add	Hip	5.7	6.9	6.5	1.9
	Knee	4.1	4.8	4.8	2.2
	Ankle	—	—	—	—
Rotation	Hip	13.2	15.5	14.5	4.9
	Knee	5.3	6.1	6.1	3.3
	Ankle	10.1	12.0	11.0	5.2

be a reference to evaluate whether different protocols using PiG, UOMAM, and cluster marker sets can be used to identify clinically important changes in a specific clinical problem.

The intertrial variability of the three marker configurations was also assessed with MAV index and is reported in Table S3, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection. The three marker sets produced comparable intertrial repeatability in line with the studies of Duffell et al. [12] and Ferrari et al. [11].

Few limitations should be noted. No knee alignment device was used for more accurate lateral marker identification, which would have helped reducing the differences between PiG and the other two marker sets, especially in nonsagittal plane variables. Moreover, while the errors in the knee and ankle joint centers for UOMAM and cluster are independent from each other, in the PiG model, the ankle joint center definition depends on the knee joint center location, therefore pre-existing errors would be combined and amplified in the kinematic results. The choice of using different marker weights in the three marker sets was done to ensure that every segment had the same total weight; however, this has effects in the kinematic results, which would contribute to the total variability. The tradeoff between maintaining the weights of the single markers and preserving a balanced segment weight is an intrinsic problem of the inverse kinematics approach with no straightforward solution, which would deserve further investigation. Subjects were not recalled for a retest, and therefore, it was not possible to calculate the total variability when combining both inter-marker set and intersession variance. The population used for this study was not homogenous: one woman was included in the analysis, and 5 out of 12 participants were affected by femoroacetabular impingement, which was likely to increase the intersubject variability. This observation does not invalidate the findings of the present study since we focused on the inter-marker set and not intersubject variability, and the sample was the same for all the three marker sets. Finally, the results of this analysis are valid within the limits of the characteristics of the chosen kinematic model; it is possible that adopting different modeling choices (e.g., using one degree-of-freedom knee) could reduce the dependency of the joint kinematics on the choice of marker set.

In summary, this study established MDC values for comparisons of kinematic outcomes when using different marker sets on the same model in an inverse kinematic framework. The inter-marker set repeatability was good for sagittal angles, intermediate for frontal angles, and worse for internal/external rotation. The cluster and UOMAM marker sets produce comparable curve parameters, while PiG produces larger ranges of motion and intersubject variability. Finally, the large differences introduced by PiG with respect to the other two marker sets depend on the higher sensitivity of kinematic outcomes to anatomical markers that define joint centers rather than changes in number and/or location of technical markers. This warns caution in clinical applications that compare joint kinematics resulting from different marker sets.

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