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Effects of the calibration procedure on the metrological performances of stereophotogrammetric systems for human movement analysis

Roberto Di Marco [a,b,*], Stefano Rossi [c], Enrico Castelli [d], Fabrizio Patanè [e], Claudia Mazzà [b,f], Paolo Cappa [a,d]

[a] Department of Mechanical and Aerospace Engineering, 'Sapienza' University of Rome, via Eudossiana, 18, Roma 00184, Italy
[b] Department of Mechanical Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK
[c] Department of Economics and Management, Industrial Engineering (DEIM), University of Tuscia, Via del Paradiso, 47, 01100 Viterbo, Italy
[d] Laboratory of Movement Analysis and Robotics (MARlab), Children Hospital 'Bambino Gesù', via della torre di Palidoro, 00050 Passoscuro, Rome, Italy
[e] School of Mechanical Engineering, 'Niccolò Cusano' University, Via Don Carlo Gnocchi, 3, 00166 Rome, Italy
[f] INSIGNEO Institute for In Silico Medicine, The University of Sheffield, The Pam Liversidge Building, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK

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ABSTRACT

This paper proposes a methodology for evaluating the effect of different stereophotogrammetric system calibration procedures on the calculation of marker-based kinematics information. The methodology, based on calibrating the system using data recorded from capture volumes of different sizes and in trials of different durations, was applied to two different systems. The calibration data were used to reconstruct the static and dynamic position and orientation in space of a rigid wand carrying markers in known positions. The inaccuracies in the reconstruction of distances and angles from the wand markers were independent on the calibration data, with average errors lower than 1.7 mm and 0.7°, respectively. Similar results were obtained from human gait data, with the highest variations observed in the transverse plane kinematics and in the foot segment, suggesting that successful calibration procedures of different durations and performed in different volumes did not affect the metrological performance of the investigated systems.

1. Introduction

In the past decades, movement analysis techniques have been increasingly used to study human/animal motion [1–4]. Besides emerging techniques based on MIMU systems [5–8] and markerless approaches [9–12], the majority of the human movement analysis techniques are based on the measurement of three-dimensional position of active or passive markers attached to the body skin, as obtained using a stereophotogrammetric approach. These markers are used to track the three-dimensional pose of the subject's bones, to which they are uniquely associated through a procedure called anatomical calibration [1]. Once the pose of a bone is known, the joint kinematics, i.e. the relative orientation between adjacent bones, are estimated and used to quantify movement alterations and limitations and to plan and evaluate a patient's treatment.

Although stereophotogrammetric systems (SS) are routinely used in research and clinical practice, relevant data suffer from a number of inaccuracy sources that could hin-

* Corresponding author at: Department of Mechanical and Aerospace Engineering, 'Sapienza' University of Rome, Via Eudossiana 18, 00184 Rome, Italy. Tel.: +39 06 44585207.
E-mail address: roberto.dimarco@uniroma1.it (R. Di Marco).

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Nomenclature

Abd/Add	abduction/adduction
CMC	coefficient of multiple correlation
ECS	embedded coordinate system
Flx/Ext	flexion/extension
GV	global volume
Int/Ext	internal/external rotation
Inv/Eve	inversion/eversion
Plt/Drs	plantar/dorsiflexion
RF	refinement frames
SS#1	stereophotogrammetric system #1
SS#2	stereophotogrammetric system #2
SS	stereophotogrammetric system
STA	soft tissue artefact
SV-LH	sub-volume left and high
SV-LL	sub-volume left and low
SV-RH	sub-volume right and high
SV-RL	sub-volume right and low

der the sought information. The main sources of inaccuracy are: (i) the soft-tissue artefacts (STA) due to the relative movement between the markers attached on the skin and the underlying bones [13]; (ii) errors in the anatomical calibration due to markers' misplacement [14]; and (iii) instrumental errors [15]. Whereas the first two errors are intrinsic in the use of skin markers, the third one is due to the use of a camera-based approach and it has been found to be dependent on: the number and position of the cameras [16,17], their lens distortion [18], the dimension of the capture volume [19,20] and, last but not least, the algorithms used for the reconstruction of a marker's 3D position [21], i.e. the marker tracking.

The effect of instrumental error on marker tracking have been originally quantified by placing a goniometer equipped with retroreflective markers in different zones of the capture volume [19,22], imposing known static angles and random trajectories to the goniometer and then comparing its outputs with the angles measured with a SS. More recently, a T-pendulum has been used for similar purposes, and it has been shown that increased angular velocities of the body under observation can decrease the accuracy of angle measurements [23]. Shifting the problem closer to the human movement analysis, a 'walking test' was proposed in [24,25]: a subject was asked to walk at a self-selected speed within the capture volume holding an aluminium bar equipped with two markers and eight SSs were tested. They showed that the systems with low noise generally seem to exhibit better performances. Subsequently, the Movement Analysis Laboratory (MAL) test has been proposed [26], which is based on recording the position of a rod carrying a 2-marker cluster, manually rotated around its tip either following a pseudo circle or two orthogonal arches. The MAL test allows to quantify both precision and accuracy associated with SS-based measurements (respectively related to random and systematic errors).

The need to move cameras, the changes in light conditions, or the presence of reflecting objects call for frequent recalibration of a stereophotogrammetric system within the human movement analysis context. As a matter of fact, the SS manufacturers recommend performing a calibration before each session of data collection. This calibration procedure is performed manually by the operator, who usually has to freely move an object within the camera capture volume, and is hence dependent on the modality of its execution. The evaluation of possible errors associated with the calibration procedure of the SS has been the object of a few investigations. In [27,28] two different methodologies to quantify the intrinsic error of the calibration algorithms that reconstruct the marker time histories have been introduced. Despite providing interesting results concerning the quantification of the calibration algorithm errors, they are by definition not useful in quantifying the variations following the need of a system recalibration. More recently, a custom-made robot, which could be used to move a L-frame equipped with retroreflective markers to perform the calibration, has been devised [16]. The authors showed that the use of the robot can significantly improve the accuracy of the calibration. However, the robot was moved within a capture volume ($180 \times 180 \times 150\ mm^3$) that is much smaller than those needed in human movement analysis. Last but not least, the effects that the calibration procedure has on the metrological performances of a SS – to the authors' knowledge – have not been fully exploited.

The aim of this paper is to propose a methodology that can be used to evaluate the effect of different calibration procedures, as executed on data capture from different acquisition volumes and of longer or shorter duration, and to use it to quantify the relevance of the effects that those calibration procedures can have on the estimate of the joint kinematics. The proposed methodology will be applied to two different SSs.

2. Material and methods

2.1. Calibration procedure

Two stereophotogrammetric systems were set up in two centres: an 8-camera Vicon system MX-series (SS#1 installed at the Movement Analysis and Robotics Laboratory 'MARLab' of the Children Hospital 'Bambino Gesù', Palidoro – Rome, Italy) and a 10-camera Vicon system T-series (SS#2 installed at The University of Sheffield, Sheffield – United Kingdom). The data collection was performed with a sampling frequency of 200 Hz and the marker position reconstruction was performed using the software Vicon Nexus 1.8.5 (Vicon Motion Systems, Oxford – UK). It is worth noticing that having a different number of cameras in the two systems does not affect the accuracy of the calibration, since at least six cameras have been used

Fig. 1. Maps of the considered laboratories with the highlighted volumes: (a) Movement Analysis and Robotics Laboratory 'MARLab' of the Children Hospital 'Bambino Gesù', Palidoro – Rome, Italy; (b) The University of Sheffield, Sheffield – United Kingdom. The blue areas are the areas where the subject was asked to walk on. The sub-volumes are bounded by the grey dashed-lines: the green tags indicate the SVs on the lower part of the GV, while the red ones indicate the higher. All the measures are given in meters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

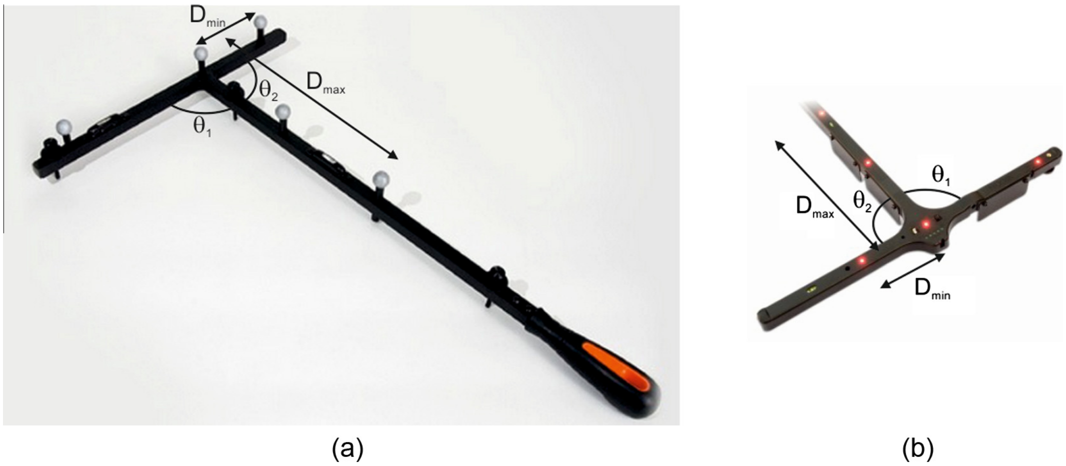

Fig. 2. Rigid calibration wand (a) equipped with retroreflective passive markers at the Movement Analysis and Robotics Laboratory 'MARLab' of the Children Hospital 'Bambino Gesù', Palidoro – Rome, Italy; (b) and equipped with active markers at The University of Sheffield, Sheffield – United Kingdom.

in both cases [17]. As shown in Fig. 1, a $2.4 \times 3.6 \times 1.6\ m^3$ capture volume (Global volume, GV) was identified. Two calibration wands of the same size were used in the two centres, both equipped with five markers, placed at a known distance between each other (Fig. 2), passive for SS#1 and active for SS#2, respectively.

Several calibration volumes, and consequently several calibration files, can be obtained moving the wand only in specific sections of the laboratory. The GV was hence partitioned into four $1.2 \times 3.6 \times 0.8\ m^3$ sub-volumes (SVs) defined by the intersections of the half-right, half-left, half-upper and half-lower parts of the GV: (i) left and lower sub-volume, SV-LL; (ii) left and upper sub-volume, SV-LU; (iii) right and lower sub-volume, SV-RL; and (iv) right and upper sub-volume, SV-RU.

The calibration procedure was performed in two phases, following the manufacturer recommendations: a *dynamic phase*, in which the rigid calibration wand was waved throughout the empty capture volume, ensuring that the markers on the wand are visible to the cameras, and a *static phase*, in which the wand was placed flat on the floor to identify the origin coordinates and axes of the global reference system. The number of frames (Refinement Frames, RF) used by the calibration and reconstruction algorithm to compute the calibration parameters has to be set before the calibration procedure. The manufacturer of the systems used in this study recommends setting the RF to a value higher than 1000 frames and possibly ranging between 3000 and 5000. Being the frame rate constant, the higher is the RF, the higher the time length of

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dynamic phase. Two sets of calibration procedures were performed: (i) the volume GV was calibrated varying RF from 1000 to 5000 in steps of 1000; and (ii) each of the SVs was calibrated setting RF = 3000 frames. In order to account for the variability related to the operator, each of the above calibration procedure was repeated three times, for a total of 27 datasets (three × five repetitions for the GV, plus three for each of the four SVs). The files containing the calibration parameters calculated by the calibration algorithm, were stored for the post-processing.

To validate the performances of the stereophotogrammetric systems, two tests were performed in each of the two centres. The first test was called *low-level* validation test and aimed at quantifying the error associated with measuring fixed distances and angles on a rigid body in static and dynamic conditions. The second test, named *high-level* validation test, aimed to assess the effect of different calibration procedures on the estimate of the joint kinematics during gait analysis. The post-processing was conducted by using Matlab (MathWorks, Natick – USA).

2.2. Test 1 – low-level validation

The calibration wand was put flat on the floor and a trial of 5 s was collected. The standard deviation of the distances between each couple of markers on the wand was calculated from the static trial data. In order to evaluate their expanded uncertainty, for each of the two systems SS#1 and SS#2, the highest among the standard deviation values was multiplied by a coverage factor $k = 3$. The same procedure was carried out on the angles between the arms of the wand, and the relevant expanded uncertainty was calculated.

The wand was then moved at a velocity comparable with the one used in the dynamic phase of the calibration procedure, and one trial of 20 s was collected. In the perspective of resembling clinical gait analysis, we focused on two couples of markers (Fig. 2) the two closest (D_{min}) and the two most distant (D_{max}) markers on the wand; in such a manner we plan to exploit the SS performances by imposing two known values as input. The calculated distances were compared with the values declared by the manufacturer. As regards the angles, differently to the chosen rationale for the measured distances and considering the options given by the wands, we decided to verify the SS capability in recognizing as equal value two angles (θ_1 and θ_2) between the arms defined by markers differently positioned. The two measured angles were compared with the known value of 90°. For each trial and each calibration file, the RMSE of the distances and angles were computed as an accuracy index. Finally, the average of the RMSEs over the three calibration repetitions were computed. When referring to RMSE values, the following notations will be used: the analysed calibration volume and RF values will be noted as superscript and the investigated variable as subscript (e.g., the RMSE computed for the distance D_{max} considering the calibration volume GV and a number of frames with RF = 2000 is $RMSE^{GV2000}_{Dmax}$). The RF is not indicated when the RMSE was evaluated for the SVs, since it was always equal to 3000.

2.3. Test 2 – high-level validation

One healthy adult (age 27, height 183 cm, mass 78 kg) was involved in this part of the study after having signed an informed written consent, approved by the two local ethical boards. The subject was equipped with 16 passive markers of 9.5 mm diameter, according to the Vicon Plug-in-Gait protocol: four markers on the pelvis, two on each thigh, two on each shank and three markers on both the feet [29]. One gait trial was acquired asking the subject to walk barefoot at a self-selected speed in the middle of the capture volume (Fig. 1 highlights the walkway in blue). The subject was asked to walk back and forth along a straight line. A total of five right and five left strides, chosen among those recorded in the centre of the measurement volume, were retained for further analysis. As in the Test 1, 27 calibration files were applied to the acquired trials, and the joint kinematics were then estimated for each of them.

As a parameter for waveform similarity, we evaluated the between-calibration coefficient of multiple correlation (CMC) [30] over the five strides. The closest is the CMC to 1, the more similar the waveforms are, with CMC values between 0.85 and 0.95 indicating very good correlation between the waveforms and CMC higher than 0.95 indicating excellent correlations [31]. The maximum angular differences ($\Delta\theta$) among all the calculated average variable waveforms were also determined.

2.3.1. Test 2a – are joint kinematics affected by the RF?

In order to test whether joint kinematics are affected by the RF, a comparison among the calibration performed within GV and changing RF was performed. Assuming that a higher number of RF can improve the calibration performances, in this step we used the values obtained with the calibration Global Volume GV at a RF of 5000 as a reference for the one obtained with other GVs at different RFs and calculated the relevant CMC and $\Delta\theta$. In the following of the paper, RF is used as superscript for the CMC and the angle for which the CMC was extracted as a subscript (e.g. $CMC^{RF}_{R\text{-}A\text{-}Abd/Add}$ stands for CMC computed among the RFs of the right (R) ankle (A) and for the Abd/Adduction). The maximum angular differences between two calibrations were defined to have the comparison as superscript and the considered kinematic variable as subscript: i.e. $\Delta\theta^{5000/2000}_{L\text{-}H\text{-}Int/Ext}$ is the maximum difference between the left (L) hip (H) internal/external rotation computed by using the calibration GV with RF equal to 5000 and 2000.

2.3.2. Test 2b – are joint kinematics affected by the dimension and the position of the calibration volume?

In order to test whether the joint kinematics are affected by the dimension and the position of the calibration volume, a series of comparisons between GV and each SV were performed. In this case, it was assumed that the calibration performances improve considering a GV rather than a SV. Then, we made a comparative analysis of the parameter CMC and $\Delta\theta$ towards the kinematic variables when applying those calibration files.

For this setting, V (Volume) was the superscript for the CMC and the angle was again the subscript: e.g. $CMC^{V}_{R\text{-}K\text{-}Flx/Ext}$ stated for CMC computed among the different volumes and for the right (R) knee (K) flexion/extension. As reported for the Test 2a, the maximum angular differences were defined to have the comparison as superscript and the considered kinematic variable as subscript: i.e. $\Delta\theta^{GV/SV\text{-}RH}_{L\text{-}H\text{-}Int/Ext}$ is the maximum difference between the left (L) hip (H) internal/external rotation computed by using the calibration GV and SV-RH.

3. Results and discussion

3.1. Test 1 – low-level validation

Considering the static trial collected in both the centres on the calibration wand and applying the whole calibration set, the expanded uncertainty was evaluated as equal to 0.1 mm for the distances between target points and 0.1° for the angles when using SS#1, and 0.3 mm and 0.3° when using SS#2, respectively. These values were considered as references to estimate the effects that the calibration procedure can have on the performances of SSs in dynamic trials.

According to the literature [23], higher inaccuracies in measuring distances and angles on the rigid wand might be expected when comparing dynamic trials to static ones. In this study, the dynamic inaccuracies were found to be up to five times higher than the static ones. Table 1 shows the mean values of the RMSEs computed for D_{max}, D_{min}, θ_1 and θ_2 and for both systems SS#1 and SS#2. For SS#1, both $RMSE_{Dmax}$ and $RMSE_{Dmin}$ for each calibration condition were always less than 0.4 mm. The lowest error (0.2 mm) was obtained for $RMSE^{GV3000}_{Dmax}$ and $RMSE^{GV4000}_{Dmax}$. Changing among the calibration conditions, we always found $RMSE_{\theta1}$ and $RMSE_{\theta2}$ equal to 0.2° and 0.5°, respectively. Considering the system SS#2, the $RMSE_{Dmax}$ and $RMSE_{Dmin}$ were found to be always less than 1.7 mm and 1.0 mm, respectively. The reference value obtained for the distances was 0.5 mm. With regard to the angles, the lowest value was found for $RMSE^{GV5000}_{\theta1}$, equal to 0.2°, and the highest for $RMSE^{SV\text{-}RH}_{\theta1}$ and $RMSE^{SV\text{-}RL}_{\theta1}$, both equal to 0.7°. For θ_2 the lowest value was found for $RMSE^{GV5000}_{\theta2}$ (0.2°), while the highest was found for $RMSE^{SV\text{-}RH}_{\theta2}$ (0.6°).

It is worth highlighting that the RMSE values did not vary when comparing the effect on the measurements of distances and angles obtained with the different calibrations. Moreover, despite of the fact that the cameras of the system SS#2 are technologically advanced with respect to those of the system SS#1, not only we did not obtain more accurate results when evaluating the data acquired from this system, but even slightly higher values of errors were found. As mentioned in the introduction, the accuracy of reconstructing marker time histories can depend on several aspects [13–21]. It was noticed only after the experiments, that the cameras of the system SS#2 were set up with a high value of aperture than those of the system SS#1. As a matter of fact, the higher is the aperture, the noisier are the measurements. This may be the reason of the slightly increase of the inaccuracy of tracking markers and measuring distances and angles using SS#2. It has to be highlighted, however, that this factor was certainly not relevant when comparing series of data acquired with the same system.

3.2. Test 2 – high-level validation

3.2.1. Test 2a – are joint kinematics affected by the RF?

As regard the test on the articular kinematics, CMC^{RF} was higher than 0.94 for both SS#1 and SS#2. It means that the waveforms were very similar to each other (Table 2). Considering SS#1 the worst case was found to be $CMC^{RF}_{R\text{-}A\text{-}Inv/Eve}$ (0.94), while for SS#2 it was $CMC^{RF}_{L\text{-}H\text{-}Int/Ext}$ (0.94). Instead, the higher values for the CMC (1.00) were obtained for $CMC^{RF}_{R\text{-}H\text{-}Flx/Ext}$, considering the SS#1, and for $CMC^{RF}_{R\text{-}H\text{-}Flx/Ext}$, $CMC^{RF}_{R\text{-}K\text{-}Flx/Ext}$ and $CMC^{RF}_{L\text{-}H\text{-}Flx/Ext}$, considering the SS#2.

The first four columns of Tables 3 and 4 show the maximum angular differences ($\Delta\theta$) between the kinematic variables when processing the static and dynamic trials with the GV calibrations. The $\Delta\theta$ was for SS#1 (Table 3) never higher than 0.3° and it was found, for most of the cases, less than 0.1°. Looking at the same results for SS#2 (Table 4), we found values lower than 0.3° for $\Delta\theta^{5000/1000}_{R\text{-}H\text{-}Flx/Ext}$, $\Delta\theta^{5000/4000}_{L\text{-}K\text{-}Flx/Ext}$, and for the entire set of comparison on the right and left hip Abd/Add; while the higher value 2.8° was reached only for $\Delta\theta^{5000/3000}_{R\text{-}K\text{-}Int/Ext}$. These results allow arguing that the number of Refinement Frames RF does not significantly affect either the waveforms or the angular values of the articular kinematic estimates during the gait cycle.

Table 1
RMSE values computed by considering the systems SS#1 and SS#2.

		GV1000	GV2000	GV3000	GV4000	GV5000	SV-LU	SV-LL	SV-RU	SV-RL
SS#1	$RMSE_{Dmax}$ (mm)	0.3	0.3	0.2	0.2	0.3	0.4	0.3	0.3	0.3
	$RMSE_{Dmin}$ (mm)	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.3
	$RMSE_{\theta1}$ (°)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	$RMSE_{\theta2}$ (°)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SS#2	$RMSE_{Dmax}$ (mm)	0.7	0.9	0.9	0.9	0.5	0.9	0.9	1.7	1.1
	$RMSE_{Dmin}$ (mm)	0.7	1.0	0.7	0.7	0.5	0.7	0.7	0.9	0.8
	$RMSE_{\theta1}$ (°)	0.3	0.4	0.4	0.4	0.2	0.4	0.3	0.7	0.7
	$RMSE_{\theta2}$ (°)	0.3	0.4	0.5	0.4	0.2	0.4	0.4	0.6	0.5

Table 2
CMC values computed on the kinematics both considering the comparison between GV5000 and other GVs (CMC^{RF}), and between GV3000 and SVs (CMC^{V}).

		CMC^{RF}		CMC^{V}	
		SS#1	SS#2	SS#1	SS#2
Right hip	$CMC_{R\text{-}H\text{-}Flx/Ext}$	1.00	1.00	1.00	1.00
	$CMC_{R\text{-}H\text{-}Abd/Add}$	0.99	0.98	0.99	0.98
	$CMC_{R\text{-}H\text{-}Int/Ext}$	0.98	0.98	0.98	0.97
Right knee	$CMC_{R\text{-}K\text{-}Flx/Ext}$	0.99	1.00	0.99	1.00
	$CMC_{R\text{-}K\text{-}Abd/Add}$	0.98	0.98	0.97	0.98
	$CMC_{R\text{-}K\text{-}Int/Ext}$	0.97	0.97	0.97	0.97
Right ankle	$CMC_{R\text{-}A\text{-}Plt/Drs}$	0.99	0.99	0.99	0.99
	$CMC_{R\text{-}A\text{-}Int/Ext}$	0.97	0.98	0.97	0.98
	$CMC_{R\text{-}A\text{-}Inv/Eve}$	0.94	0.95	0.93	0.94
Left hip	$CMC_{L\text{-}H\text{-}Flx/Ext}$	0.99	1.00	0.99	1.00
	$CMC_{L\text{-}H\text{-}Abd/Add}$	0.98	0.99	0.98	0.99
	$CMC_{L\text{-}H\text{-}Int/Ext}$	0.98	0.94	0.98	0.93
Left knee	$CMC_{L\text{-}K\text{-}Flx/Ext}$	0.99	0.99	0.99	0.99
	$CMC_{L\text{-}K\text{-}Abd/Add}$	0.97	0.97	0.97	0.97
	$CMC_{L\text{-}K\text{-}Int/Ext}$	0.97	0.97	0.97	0.97
Left ankle	$CMC_{L\text{-}A\text{-}Plt/Drs}$	0.98	0.97	0.98	0.97
	$CMC_{L\text{-}A\text{-}Int/Ext}$	0.98	0.96	0.98	0.96
	$CMC_{L\text{-}A\text{-}Inv/Eve}$	0.95	0.95	0.95	0.94

3.2.2. Test 2b – are joint kinematics affected by the dimension and the position of the calibration volume?

For the system SS#1, we obtained a CMC equal to 0.93 for the Inv/Eve of the right ankle and a CMC equal to 0.93 for the Int/Ext of the left hip (Table 2). The highest values for the CMC (1.00) were obtained for $CMC^{V}_{R\text{-}H\text{-}Flx/Ext}$ both at SS#1 and SS#2, and $CMC^{V}_{L\text{-}H\text{-}Flx/Ext}$ and $CMC^{V}_{R\text{-}K\text{-}Flx/Ext}$ at SS#2. The lowest CMC computed considering the SS#1 was obtained for $CMC^{V}_{R\text{-}A\text{-}Inv/Eve}$ (0.93), while considering SS#2 it was measured for $CMC^{V}_{L\text{-}H\text{-}Int/Ext}$ (0.93). As for the previous case, we mainly found an excellent correlation between the waveforms with each SS.

The second four columns of Tables 3 and 4 show, instead, the maximum angular differences on kinematics when processing static and dynamic trials with the GV and SVs calibrations. The $\Delta\theta$ was for SS#1 (Table 3) never higher than 0.7° ($\Delta\theta^{GV/SV\text{-}LH}_{R\text{-}A\text{-}Inv/Eve}$) and, similarly to the previous test, it was found to be less than 0.1° for a few cases. Examining the $\Delta\theta$ for SS#2 (Table 4), we found the lowest value equal to 0.2° for $\Delta\theta^{GV/SV\text{-}LH}_{L\text{-}H\text{-}Abd/Add}$, $\Delta\theta^{GV/SV\text{-}RH}_{L\text{-}H\text{-}Abd/Add}$, and $\Delta\theta^{GV/SV\text{-}RL}_{L\text{-}H\text{-}Abd/Add}$, while the higher value 3.3° was reached for $\Delta\theta^{GV/SV\text{-}LH}_{R\text{-}K\text{-}Int/Ext}$. Looking at the results with regard to both CMCs and $\Delta\theta$s, we can affirm that the effect of the considered volume, in which the operator performs the calibration procedure, is negligible on the articular kinematics during the gait cycle analysis compared to those induced from other sources of error [32]. Indeed, the similarities obtained in this research, modifying either the calibration duration or the calibration volumes, are higher than those normally obtained for intra- and inter-session repeatability analyses [33]. In these studies, an operator normally performs the marker placement more than once and in different testing-days, and the stride variability is also accounted. As an example, Pinzone and colleagues [33] observed maximum $\Delta\theta$ of 9.7°.

Coherently with the literature [33,34], higher variability was found on the transverse plane and for the foot joint data, whereas the sagittal plane was confirmed to be the most reliable. CMC and $\Delta\theta$ values confirm this assertion both for Test 2a and Test 2b. In conclusion, we can assert that the effect of the calibration procedure on articular kinematic variables is negligible both considering the waveforms similarity and the angular differences between them [32].

Table 3
Maximum angular differences between angles estimated by considering the comparison between GV5000 and other GVs ($\Delta\theta^{5000/RF}$), and between GV3000 and SVs ($\Delta\theta^{GV/SV}$) for the system SS#1.

Comparison		5000/1000	5000/2000	5000/3000	5000/4000	GV/SV-LH	GV/SV-LL	GV/SV-RH	GV/SV-RL
Right hip	$\Delta\theta_{R\text{-}H\text{-}F/E}$ (°)	<0.1	0.1	0.1	0.1	0.1	0.1	0.1	<0.1
	$\Delta\theta_{R\text{-}H\text{-}Abd/Add}$ (°)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	$\Delta\theta_{R\text{-}H\text{-}Int/Ext}$ (°)	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	0.2	0.1
Right knee	$\Delta\theta_{R\text{-}K\text{-}F/E}$ (°)	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1	<0.1
	$\Delta\theta_{R\text{-}K\text{-}Abd/Add}$ (°)	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1	0.1
	$\Delta\theta_{R\text{-}K\text{-}Int/Ext}$ (°)	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Right ankle	$\Delta\theta_{R\text{-}A\text{-}Plt/Drs}$ (°)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	$\Delta\theta_{R\text{-}A\text{-}Int/Ext}$ (°)	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2
	$\Delta\theta_{R\text{-}A\text{-}Inv/Eve}$ (°)	0.2	0.2	0.2	0.2	0.7	0.2	0.6	0.3
Left hip	$\Delta\theta_{L\text{-}H\text{-}F/E}$ (°)	<0.1	<0.1	<0.1	0.1	0.1	0.1	0.1	0.1
	$\Delta\theta_{L\text{-}H\text{-}Abd/Add}$ (°)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	$\Delta\theta_{L\text{-}H\text{-}Int/Ext}$ (°)	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Left knee	$\Delta\theta_{L\text{-}K\text{-}F/E}$ (°)	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1	<0.1
	$\Delta\theta_{L\text{-}K\text{-}Abd/Add}$ (°)	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1	0.1
	$\Delta\theta_{L\text{-}K\text{-}Int/Ext}$ (°)	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Left ankle	$\Delta\theta_{L\text{-}A\text{-}Plt/Drs}$ (°)	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2
	$\Delta\theta_{L\text{-}A\text{-}Int/Ext}$ (°)	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.2
	$\Delta\theta_{L\text{-}A\text{-}Inv/Eve}$ (°)	0.2	0.3	0.3	0.3	0.6	0.2	1.0	0.4

Table 4
Maximum angular differences between angles estimated by considering the comparison between GV5000 and other GVs ($\Delta\theta^{5000/RF}$), and between GV3000 and SVs ($\Delta\theta^{GV/SV}$) for the system SS#2.

		5000/1000	5000/2000	5000/3000	5000/4000	GV/SV-LH	GV/SV-LL	GV/SV-RH	GV/SV-RL
Right hip	$\Delta\theta_{\text{R-H-F/E}}$ (°)	<0.3	0.3	0.3	0.4	0.6	0.7	0.7	0.4
	$\Delta\theta_{\text{R-H-Abd/Add}}$ (°)	<0.3	<0.3	<0.3	<0.3	0.3	1.0	0.4	0.4
	$\Delta\theta_{\text{R-H-Int/Ext}}$ (°)	1.9	1.9	1.4	1.2	2.1	2.3	2.2	2.2
Right knee	$\Delta\theta_{\text{R-K-F/E}}$ (°)	0.6	0.8	0.6	0.3	0.9	0.9	0.9	0.8
	$\Delta\theta_{\text{R-K-Abd/Add}}$ (°)	1.0	0.9	0.7	0.7	1.2	1.3	1.1	1.2
	$\Delta\theta_{\text{R-K-Int/Ext}}$ (°)	0.6	1.2	2.8	2.1	3.3	2.7	2.8	2.8
Right ankle	$\Delta\theta_{\text{R-A-Plt/Drs}}$ (°)	0.3	0.5	0.6	0.7	0.8	0.5	0.6	0.6
	$\Delta\theta_{\text{R-A-Int/Ext}}$ (°)	1.1	0.9	1.0	1.1	2.0	1.4	2.1	1.4
	$\Delta\theta_{\text{R-A-Inv/Eve}}$ (°)	1.2	1.4	1.4	1.5	1.9	1.7	2.4	2.1
Left hip	$\Delta\theta_{\text{L-H-F/E}}$ (°)	0.3	0.3	0.3	0.3	0.5	0.8	0.6	0.4
	$\Delta\theta_{\text{L-H-Abd/Add}}$ (°)	<0.3	<0.3	<0.3	<0.3	<0.3	1.0	<0.3	<0.3
	$\Delta\theta_{\text{L-H-Int/Ext}}$ (°)	0.5	0.6	0.7	0.5	1.3	1.3	1.3	1.2
Left knee	$\Delta\theta_{\text{L-K-F/E}}$ (°)	0.4	0.3	0.4	<0.3	0.5	0.4	0.7	0.4
	$\Delta\theta_{\text{L-K-Abd/Add}}$ (°)	0.3	0.4	0.6	0.4	0.9	0.8	0.7	0.6
	$\Delta\theta^{x}_{L-K-\text{Int/Ext}}$ (°)	0.8	0.7	1.2	0.6	1.7	1.7	1.3	1.4
Left ankle	$\Delta\theta_{\text{L-A-Plt/Drs}}$ (°)	0.3	0.3	0.3	0.3	0.5	0.4	0.5	0.6
	$\Delta\theta_{\text{L-A-Int/Ext}}$ (°)	1.3	1.2	1.1	1.1	1.8	1.5	1.7	1.4
	$\Delta\theta_{\text{L-A-Inv/Eve}}$ (°)	0.9	0.8	0.7	0.7	1.2	1.2	1.6	1.4

4. Conclusions

This paper presented a methodology to evaluate the effects that a set of calibration procedures, diversified for both acquisition volumes and duration, can have on calculating distances and angles starting from trajectory data measured by a stereophotogrammetric system. The inaccuracy of the estimated distances, angles and joint kinematics was found to be higher in dynamic than in static conditions, but still negligible in both conditions and not dependent on the performed calibration procedure. Between the two investigated systems, the one with the highest performances was also the one that led to the highest inaccuracies. This apparent paradox was indeed explained by the different aperture of the camera lenses. These findings led to the conclusion that successful calibration procedures of different durations and performed in different volumes did not affect the metrological performance of the investigated systems.

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