Comparison of Protocols for Walking and Running Kinematics Based on Skin Surface Markers and Rigid Clusters of Markers

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Key words
- biomechanics
- running
- walking
- kinematics
- lower extremity
- upper extremity

Abstract

The purpose of this study was to compare the two main types of marker sets for human body representation based on rigid clusters of markers and skin surface markers for measuring kinematics during walking and running. Velocity, body segment, and joint angle were considered in the comparison of both protocols. Six male athletes were studied during treadmill gait at 1.4 and 5.5 m/s and recorded with 8 high speed video cameras. The subjects used simultaneously both protocols in the same walking and running cycles, in order to compare the variability in the determination of the joint centers' positions and the joint angles calculated from each protocol. The three-way ANOVA results showed that the variability of the inter-markers distance in the skin surface protocol was higher than that in the rigid clusters of markers, as reported in the literature. However, no statistical differences between the protocols were found in the variability of the determination of the joint centers' positions. Therefore no advantage was verified to rigid cluster protocols even for the upper body segments. Another conclusion is that increases in velocity produced increases in variability of the joint centers' distances and increases in the maximum differences between the joint angles.

accepted after revision
June 19, 2009

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DOI 10.1055/s-0029-1234054
Published online:
July 23, 2009
Int J Sports Med 2009; 30: 827–833 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

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Introduction

Joint kinematics during walking and running are central issues in biomechanics since the beginning of pioneer works in this field. Consequently, critical problems in the determination of bony orientation derived from the external markers have been constantly pointed out in the literature [7].

The most common techniques of human body representation use two types of marker sets: 1) markers mounted on fixtures which are attached to the body segment, referred to, in the present study, as the rigid clusters of markers protocol [5,12], and 2) markers directly attached to the skin surface, referred to, in the present study, as the skin surface markers protocol [11,15]. These techniques have very different sensitivities to experimental uncertainties and present several limitations. The source of these critical problems is mainly the inaccuracy of recovering bone orientation during motion, when soft tissues artifacts are present [16]. The relative motion between markers of the same segments and global motion of the marker set relative to the bone are serious source of error in movement analysis [24]. In addition, the joint parameters sensitivity is related to the determination of anatomical landmark location and anatomical frames orientation [10].

In order to solve some of these problems, alternative techniques, like post-treatment, have been proved to be efficient for some of these issues. Optimization algorithms, for instance, are frequently used to solve system identification or movement prediction problems utilizing complex three-dimensional kinematics models. These methods adjust joint parameters or model degrees of freedom to fit a kinematic model to experimental movement data [21,24].

Since the calculation performed in the post-treatment techniques are influenced by the associated kinematic model parameters such as joint center positions and orientations, the choice between rigid cluster of markers or skin surface markers protocol becomes very important. This choice depends on the accuracy provided by each one, and is dependent upon the problem studied. Cappozzo et al. [6] showed that in slow movements such as gait, rigid clusters of markers protocols provide better results than skin surface markers protocol. This is due to the fact that the relative movement between the underlying bone and the markers mounted on fixtures is smaller than this same movement between the underlying bone and the markers located directly on the skin. However we hypothesized that during highly dynamic movement such as running, the vibration of the fixtures not only in the lower body but also in the upper body could cause more interference in the accuracy of the results than the skin markers.

Both kinds of protocols have been used to study walking and running [5,11], but it is not well known how increases in velocity can affect the determination of joint centers and joint angles obtained with the two types of protocols. Furthermore, it is also unclear if when considering the upper body segments, the results of rigid clusters of markers protocols established for lower limbs remain the best. We hypothesized that the higher the velocity the higher inaccuracy on the reconstruction regarding the joint centers and the joint angles.

As the rigid clusters of markers and skin surface markers are widely used to calculate the human motion, this study presents a comparison between these two kinds of marker sets according to velocities, body segments and joint angles. Both protocols were implemented simultaneously in each subject, in the same walking and running cycles, to compare the variability in the determination of the joint centers' positions and the joint angles calculated from each protocol.

Methods

Six male sprinters of national level were volunteers in this study. They trained around five times per week and run approximately 17 km per week. All of them were competitive runners in 200 and 400 m and the average characteristics were: age: 18 ± 2.4 yr; body mass: 68.0 ± 6.9 kg; height: 1.75 ± 0.07 m. They were informed about procedures and signed an informed consent (protocol n° 224/227). All sprinters were free of injuries at the time of the experiment.

Each sprinter walked and ran on the treadmill at two different velocities: 1.4 m/s and 5.5 m/s, for 10 and 20 s, respectively. Each one of them had a familiarization period on the treadmill of 5 min for each velocity. Then the fifth cycle of the right side of each task was chosen for all sprinters. One cycle of walking and one of running were analyzed for each sprinter.

The following segments were defined: foot, shank, thigh, pelvis, scapula, arm and forearm. For both protocols, retroreflective markers placed in the following locations were used to create the anatomical frame, during the static trial: Foot: first (**H1**), second (**H2**) and fifth (**H5**) metatarsal head and calcaneous (**CL**). Orientation: the frontal plane was the plane containing the markers **CL**, **H1** and **H2**. The sagittal plane was the plane perpendicular to the frontal plane and containing line connecting markers **CL** and **H5.** The transversal plane was the mutual plane perpendicular to the other two. Shank: medial (**MM**) and lateral malleolus (**LM**), head of the fibula (**HF**) and tibial tuberosity (**TT**). Orientation: the frontal plane was the plane containing points **MM**, **LM** and **HF**. The sagittal plane was the plane perpendicular to the frontal plane and containing line connecting points **TT** and midpoint between **MM** and **LM**. The transversal plane was the mutual plane perpendicular to the other two. The markers and the orientation of the thigh, pelvis, arm, forearm and scapula were done according to the ISB recommendation [26,27].

The hip and glenohumeral joint centers were calculated according to Bell et al. [3] and Meskers et al. [17], respectively. Ankle, knee, elbow and wrist joint centers were calculated as halfway between the lateral and medial markers of the respective joint [15].

For the dynamic trials, ten anatomical markers not used for tracking were removed and the anatomical orientation of the segments was obtained applying the Calibrated Anatomical System Technique [5], in which the anatomical landmarks are calibrated with respect to the corresponding arrays of tracking markers mounted on the subject's limbs.

The differences between the protocols are in the tracking markers. For the skin surface markers protocol, the following tracking markers were used: Tibial Tuberosity, Lateral Malleolus, Tibial Tubercle, Hip Joint Center, Greater Trochanter, Lateral Femoral Epicondyle, Glenohumeral Joint Center, Insertion of Deltoid, Lateral Humeral Epicondyle Radial and Ulnar Styloid (**Fig. 1b**). On the other hand, the tracking markers used for the rigid clusters markers protocol were mounted on fixtures (15 cm) attached to the bodies segments. Three markers were placed on each of the eight fixtures attached to the thighs, shanks, arms and forearms. **Fig. 1a** shows the markers locations in both protocols used simultaneously during the dynamic trial. **Fig. 1b** identifies the differences in the locations of the tracking markers in both protocols.

Despite the tracking markers being different for each protocol, the technical orientation of the segments in both protocols was calculated using the same methods: clusters which complied with the requirement that the distance between the three markers and the offset of any marker from the line joining the other two was as large as possible [6]. The longest principal axis of the cluster was oriented towards the relevant marker [9].

Three-dimensional joint rotation was calculated using Euler angles. The sequence of rotations was first flexion/extension (FL/EX) angles about the z axis of the proximal segment, abduction/adduction (AB/AD) angles about the floating axis, then internal/external rotation (IN/EX) angles about x axis of the distal segment.

Kinematic data were collected using 8 digital cameras (JVC, model GR-DVL9500, 120 Hz), which were placed around a treadmill (Pró-Fitness, Model AP 10.500). DVideo software was used for the calibration of the cameras, the synchronization of the registrations and the 3D reconstruction of the coordinates of the markers [2]. In order to compare the angles curves between walking and running, both 3D data were smoothed with a zero-phase forward and reverse 5th order Butterworth digital filter with a 6 Hz cut-off frequency [14,21].

To compare both protocols, four experimental variables were analyzed. The first one was the coefficient of variation for inter-marker distances. The means and the standard deviations of three inter-marker distances per segments for each protocol and for each velocity were calculated. Then three values of the coefficient of variation were obtained. Finally, the mean of these three values of coefficient of variation was calculated (**Table 1**). This variable analyzed the condition of rigidity provided by each protocol considering just the variability due to the relative movements among markers during the dynamic trial.

Although the relative motion between markers of the same segments can be evaluated by the first variable presented, the global motion of the markers relative to the segments can affect the calculation of the joint centers and consequently propagate uncertainties to local frames orientations. Because of that, a sec-

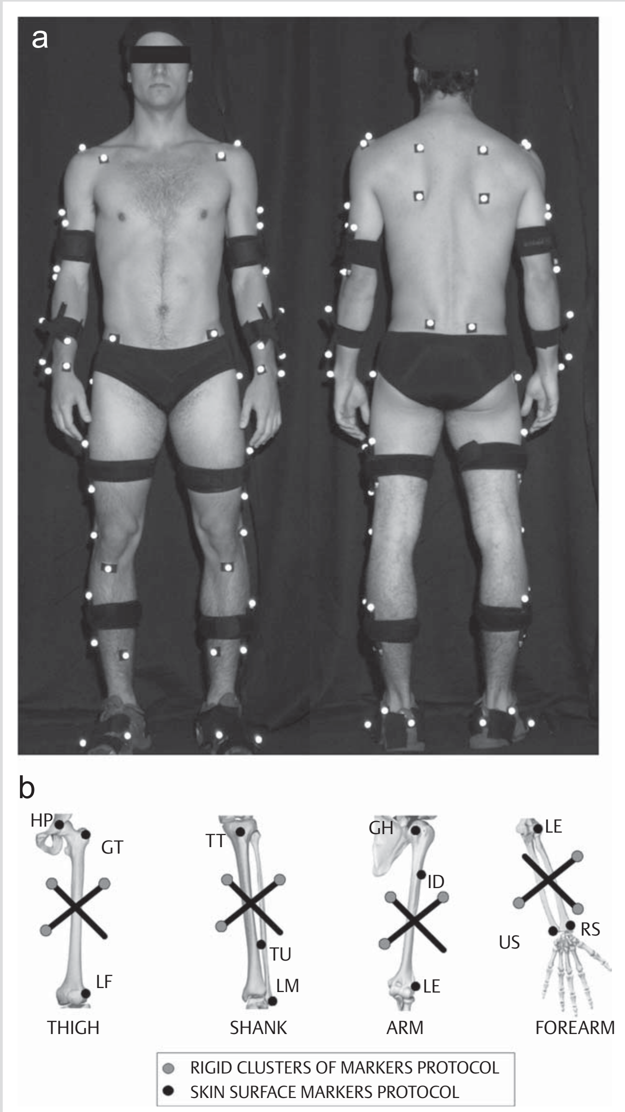

Fig. 1 **a**) Markers' locations in both protocols used simultaneously in the dynamic trial. **b**) Differences in the tracking markers' locations of both protocols. The abbreviation legend: Hip joint center (**HP**), the most lateral protrusion of the Greater Trochanter (**GT**), the most lateral prominence of the Lateral Femoral Epicondyle (**LF**), the most anterior border of the Tibial Tuberosity (**TT**), the lateral prominence of the Lateral Malleolus (**LM**), Tibial Tubercle (**TU**), Glenohumeral Joint Center (**GH**), Insertion of Deltoid (**ID**), the most lateral prominence of the Lateral Epicondyle (**LE**) and the most lateral prominence of the Radial (**RS**) and Ulnar (**US**) Styloid.

ond variable – the coefficient of variation for joint centers' distances – was calculated as well. The joint centers were estimated from the proximal segment reference frame for each protocol. For example, the knee joint center was estimated from the thigh reference frame.

The third variable calculated was the Pearson correlation coefficient between the rotation angles, allowing the comparison between the signals of each rotation angle obtained by each protocol. To complement the analysis, the fourth variable calculated was the maximum difference between the rotation angles of each protocol for each joint.

Three-way analysis of variance with repeated measured was used to compare the mean of four variables analyzed. The coefficient of variation for inter-marker distances and for joint cent-

Table 1 Mean values and statistical results of the coefficients of variation (CV, in percentage) for inter-marker distances per segment, and for joint centers' distances for each segment according to protocols, velocities and segments.

Segments	Means CV for inter-marker distances for RC (%)		Means CV for inter-marker distances for SS (%)		Segment Means (%)	Means CV for joint centers distances for RC (%)		Means CV for joint centers distances for SS (%)		Segment Means (%)
	Walking	Running	Walking	Running		Walking	Running	Walking	Running	
thigh	2.4 ±0.3	2.6 ±0.2	2.2 ±0.3	2.8 ±0.4	2.5±0.3	1.5±0.3	1.6±0.5	1.4±0.5	2.0±0.8	1.7±0.5
shank	2.3 ±0.2	2.6 ±0.3	2.0 ±0.3	2.9 ±0.4	2.5±0.4	1.9±0.8	2.5±0.9	1.8±0.5	2.2±0.9	2.1±0.8
arm	1.9 ±0.3	2.2 ±0.1	2.1 ±0.3	2.7 ±0.5	2.3±0.4	1.2±0.5	1.7±0.6	1.4±0.5	1.8±0.4	1.7±0.5
forearm	2.2 ±0.2	2.3 ±0.2	2.4 ±0.5	2.4 ±0.5	2.3±0.3	1.3±0.6	1.7±0.7	1.0±0.5	1.7±0.6	1.4±0.6
protocol means (%)	2.3±0.3		2.5±0.5			1.7±0.6		1.7±0.7		
	Statistical results					Statistical results				
Factors	**Mean±SD**		**F-values**	**p-values**		**Mean±SD**		**F-values**	**p-values**	
protocols	RC (2.3±0.3)<SS (2.5±0.5)		5.33	0.0223 *		RC (1.7±0.6)≡SS (1.7±0.7)		0.042	n.s.	
velocities	V1 (2.2±0.3)<V2 (2.6±0.4)		45.53	<0.001 *		V1 (1.4±0.6)<V2 (1.9±0.7)		32.68	<0.001 *	
segments	SH (2.5±0.4)>FA (2.3±0.3)		2.15	0.0414 *		SH (2.1±0.8)>TH (1.7±0.5)≡ AM (1.7±0.5)≡FA (1.4±0.6)		4.92	<0.001 *	

RC: rigid clusters of markers protocol; SS: skin surface markers protocol; V1: walking velocity equal to 1.4 m/s; V2: running velocity equal to 5.5 m/s; SH: shank; TH: thigh; AM: arm; FA: forearm
* Significant differences ($p<0.05$)

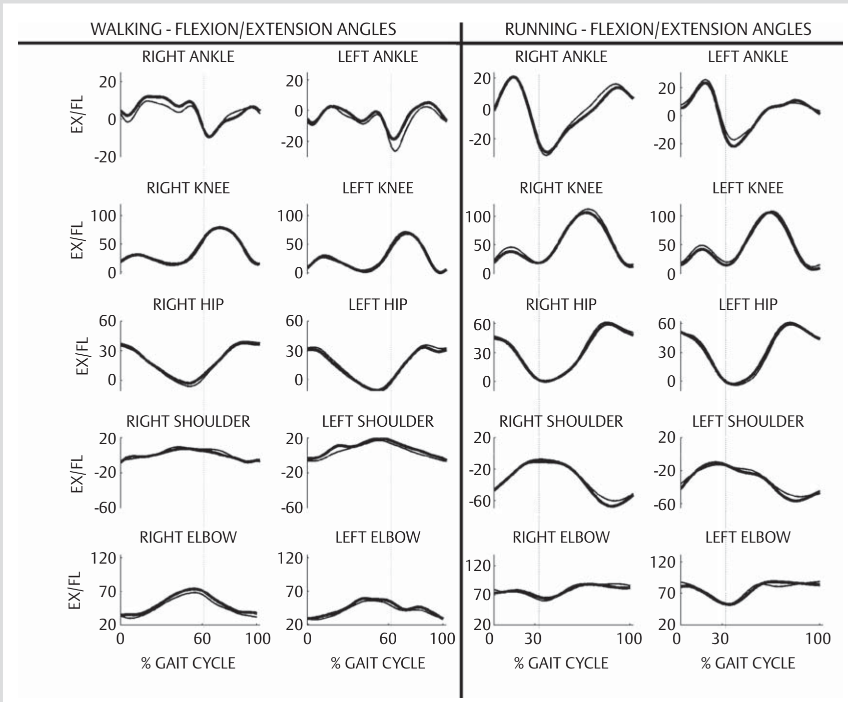

Fig. 2 The flexion/extension angles as calculated by two protocols (The thicker curves indicate the rigid clusters of markers protocol and the thinner curves, the skin surface markers protocol) and relative to only one complete gait cycle of a typical subject. The first and the second columns correspond to the velocity 1.4 m/s (walking) and the third and fourth columns correspond to the velocity 5.5 m/s (running). The ankles, knees, hips, shoulders and elbows were analyzed.

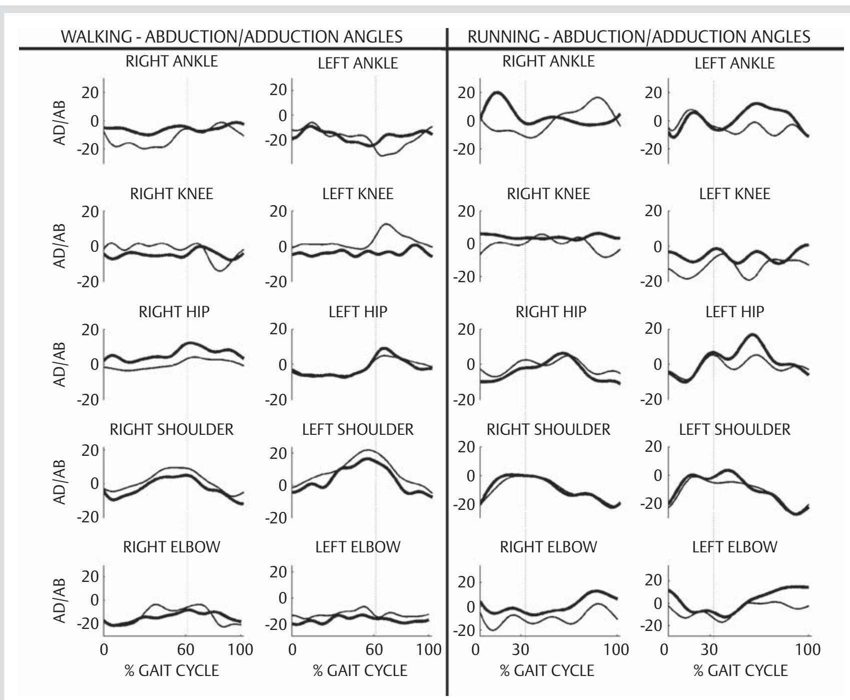

Fig. 3 The abduction/adduction angles as calculated by two protocols (The thicker curves indicate the rigid clusters of markers protocol and the thinner curves, the skin surface markers protocol) and relative to only one complete gait cycle of a typical subject. The first and the second columns correspond to the velocity 1.4 m/s (walking) and the third and fourth columns correspond to the velocity 5.5 m/s (running). The ankles, knees, hips, shoulders and elbows were analyzed.

ers distances were analyzed according to three factors: protocols (rigid cluster of markers protocol and skin surface markers protocol); velocities (1.4 m/s and 5.5 m/s) and the segments (thighs, shanks, arms and forearms). The Pearson correlation coefficient and the maximum difference between the rotation angles were analyzed according to three factors: velocities, rotation angles (AB/AD angles, IN/EX angles and FL/EX angles); and the joints (ankles, knees, hips, shoulders and elbows).

Where a significant effect was detected, Tukey's honestly significant difference criterion ($p<0.05$) was performed. Considering that the coefficient of variation and the Pearson correlation coefficient do not present a normal distribution, the $\sin^{-1}$ transformation and Fisher transformation were applied to the coefficients respectively, before using ANOVA.

Results

▶ **Tables 1** and **2** show the mean values and statistical results of four experimental variables.

The curves showed in ▶ **Figs. 2, 3** and **4** correspond to the FL/EX, AB/AD, IN/EX angles respectively, relative to only one complete gait cycle of a typical subject. Because the variability over repetitions is much smaller than that over protocols, a single repre-

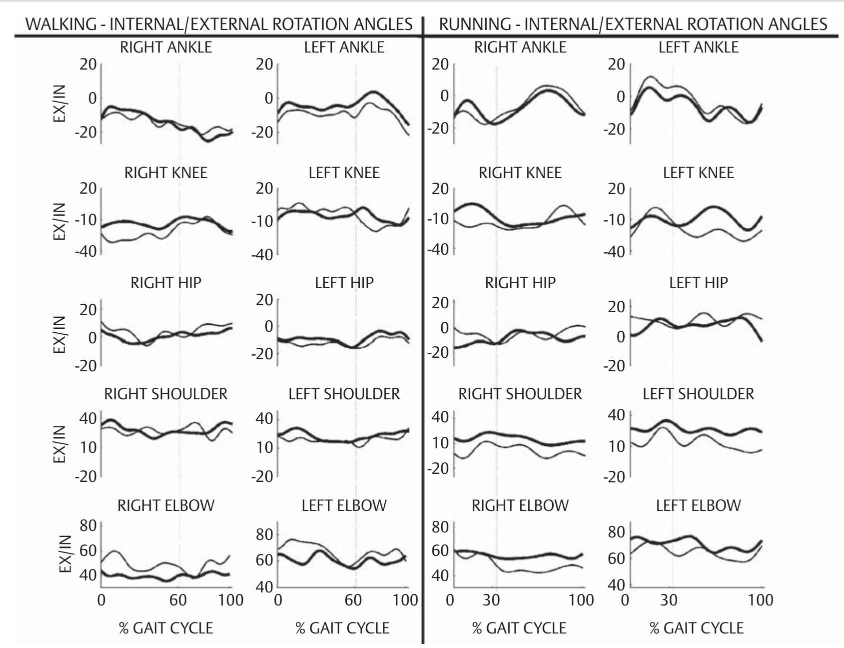

Fig. 4 The internal/external rotation angles as calculated by two protocols (The thicker curves indicate the rigid clusters of markers protocol and the thinner curves, the skin surface markers protocol) and relative to only one complete gait cycle of a typical subject. The first and the second columns correspond to the velocity 1.4 m/s (walking) and the third and fourth columns correspond to the velocity 5.5 m/s (running). The ankles, knees, hips, shoulders and elbows were analyzed.

sentative trial was reported [13]. The figures showed the angles in relation to the percentage of the cycle in both velocities for both protocols. The first and the second columns of each figure correspond to the velocity 1.4 m/s (walking) and the third and fourth columns correspond to the velocity 5.5 m/s (running). The ankles, knees, hips, shoulders and elbows were analyzed.

Discussion

The purpose of this study was to compare the two main types of marker sets for human body representation. In biomechanics studies, these protocols can differ according to location markers, anatomical and technical frame orientation. However, all of them have problems with soft tissue artifacts. Therefore, the results of this study can be applicable to all marker set using skin surface markers or rigid clusters of markers during walking and running.

The overall procedures were repeated in only six subjects. However, the analyses of the right and left legs and arms imply diverse experiments, involving two different protocols and two different velocities.

As expected, the coefficient of variation for inter-marker distances per segment showed that the variability of the distances in the skin surface protocol was higher than that in the rigid clusters of markers protocol (**Table 1**). This result confirms the affirmations made by Angeloni et al. [1] and Cappozzo et al. [7], showing that the skin markers were consistently subjected to larger displacement than markers mounted on the rigid clusters.

However, the present study did not find statistical differences between the protocols with regard to the variability of the determination of the joint centers' positions (**Table 1**). Such findings were against our preliminary hypothesis that the vibration of the fixtures could cause more interference in the accuracy of the results than the skin markers. These results show that although the variability of the distances among the tracking markers for each protocol were different, both protocols were similar when the global motion of the markers relative to the segment were calculated. It suggests that the calculation of the joint centers could propagate similar uncertainties to local frames orientations for both protocols. Other possible explanations could be that the present study analyzed high level athletes who had probably less fat tissue (the mean of their body mass index is 22.2 kg/m^2). The differences in body composition could explain why no difference between protocols was found even when analyzing gait. This result suggests that body composition can play an important role when external markers are used to determine segment orientation during motion. In future works, the effect of different body compositions on the results of motion analysis should be addressed.

Increases in velocity produced increases in variability. The variability of the joint centers' distances in walking was lower than that in running. It is important to point out that these results are just for the velocity factor. There was no interaction between velocities and protocols. Similar results were found by Reinschmidt et al. [22]. The author found that the skin artifact movement in the thigh and in the shank during the running was higher than the one during the walking.

Comparing body segments, the variability of the shank length was higher than that of the thigh, arm and forearm lengths. This result suggests that the proximity of the impact region of the shank on the ground had a more important effect on the variability of its length than that produced in the thigh length, despite its greater wobble mass.

The correlation coefficient between the AB/AD and between the IN/EX was lower than the ones between the FL/EX (**Table 2**) and the maximum differences between the AB/AD and between the IN/EX were higher than the ones between the FL/EX (**Table 2**). We noted, mainly in the frontal and transverse planes, substantial angular variabilities in both protocols. Similar results were also found by Ferrari et al. [13]. These authors also compared different protocols over the same gait cycles and they found that for the kinematics variables, correlations were

Table 2 Mean values and statistical results of the Pearson correlation coefficient (r) and maximum difference (md) between the rotation angles obtained by each protocol for each joint, according to velocities, rotation angles and joints.

Joint	Mean of the r between IN/EX		Mean of the r between AB/AD		Mean of the r between FL/EX		Mean of the md between IN/EX		Mean of the md between AB/AD		Mean of the md between FL/EX	
	Walking	Running	Walking	Running	Walking	Running	Walking	Running	Walking	Running	Walking	Running
ankle	0.93	0.93	0.37	0.46	0.97	0.99	7.6	9.8	17.2	22.0	3.8	5.8
knee	0.48	0.30	0.55	0.58	0.99	0.99	18.6	26.6	11.2	14.0	5.9	8.6
hip	0.48	0.44	0.91	0.87	0.99	0.99	11.8	15.7	6.9	8.6	4.3	5.6
shoulder	0.51	0.69	0.96	0.97	0.99	0.99	18.9	25.0	6.3	7.2	4.2	7.8
elbow	0.50	0.62	0.58	0.57	0.99	0.97	20.3	17.4	13.7	25.1	6.1	10.4
rotation angles means	0.65		0.78		0.99		17.2		13.2		6.3	

Factors	Statistical results (r)			Statistical results (md)		
	Mean	F-values	p-values	Mean	F-values	p-values
velocities	V1(0.91) = V2(0.92)	0.366	n. s.	V1 (10.5) < V2 (14.0)	48.43	< 0.001*
rotation Angles	FL/EX(0.99) > AB/AD(0.78) > IN/EX(0.65)	752.52	< 0.001*	FL/EX(6.3) < AB/AD (13.2) < IN/EX (17.2)	153.48	< 0.001*
joints	HP(0.94)≡SD(0.95) > AK(0.90)≡KN(0.90) > EL(0.84)	11.33	< 0.001*	HP(8.8) < SD(11.6) < KN(14.2)≡EL(15.5); HP≡AK(11.1) < EL ; AK≡SD; AK≡KN	10.78	< 0.001*

V1: walking velocity equal to 1.4 m/s; V2: running velocity equal to 5.5 m/s; HP: shank; SD: shoulder; AK: ankle; KN: knee; EL: elbow; FL/EX: flexion/extension angles; AB/AD: abduction/adduction angles; IN/EX: internal/external rotation angles

* Significant differences (p < 0.05)

smaller for rotations out-of-sagittal planes than for FL/EX. We believe this is a reflection of the difficulty in measuring the movements in these planes due the small range of motion compared to sagittal plane, resulting in small signal-to-noise ratios [8]. This reasoning agrees with the results of Leardini et al. [18] who assert that the AB/AD and IN/EX angles should be regarded with much more caution as the soft tissue artifact produces spurious effects with magnitudes comparable to the amount of motion actually occurring in the joints.

Good consistency between the protocols was observed for all joint FL/EX (▶ **Fig. 2**) in the walking and in the running and were in agreement with the findings in previous investigations [13, 19, 20]. Acceptable consistency was found for the AD/AB and IN/EX angles (▶ **Figs. 3, 4**) Due to the difficulties to measure the movements out-of-sagittal planes, the differences observed between the protocols were considered negligible (▶ **Table 2**). Very similar results were found for the other five subjects analyzed.

In conclusion, there was no advantage in the use of one protocol as compared to the other even for the upper body segments. In addition, increases in velocity produced increases in variability of the joint centers' distances and increases in the maximum differences between the joint angles.

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