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Comparison of the rigidity and forefoot – Rearfoot kinematics from three forefoot tracking marker clusters during walking and weight-bearing foot pronation-supination

Fabrício Anicio Magalhães [a], Thales Rezende Souza [a,b], Vanessa Lara Araújo [a], Lílian Marques Oliveira [b], Letícia de Paula Silveira [b], Juliana de Melo Ocarino [a,b], Sérgio Teixeira Fonseca [a,b,*]

[a] Graduate Program in Rehabilitation Sciences, Universidade Federal de Minas Gerais, 6627 Antônio Carlos Avenue, Belo Horizonte, MG 31270-901, Brazil
[b] Department of Physical Therapy, Universidade Federal de Minas Gerais, 6627 Antônio Carlos Avenue, Belo Horizonte, MG 31270-901, Brazil

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ABSTRACT

Due to the relative motion among the foot rays, the present study aimed to compare the rigidity as well as the forefoot – rearfoot kinematics obtained from three forefoot tracking marker clusters during walking and foot pronation-supination (PROSUP). Nineteen healthy adults performed six walking trials and ten cycles of foot PROSUP movements recorded by an optoelectronic system. Rearfoot's and forefoot's coordinate system were equal for all setups, only the forefoot's tracking markers locations varied among them, which were: (1st) a typical cluster, focusing on the proximal forefoot, (2nd) a second typical cluster, focusing on the distal forefoot and outer metatarsals, and (3rd) a new cluster proposition, focusing on the distal forefoot and central metatarsals. Cluster rigidity was the normalized intra-markers residual, and forefoot – rearfoot angles were the forefoot motion relative to the rearfoot at the peak of each plane of motion. Repeated-measures ANOVA with pairwise comparisons ($\alpha = 0.05$) revealed that the 3rd cluster had the smallest residual ($p < 0.001$) in comparison with the other clusters for both walking and PROSUP. Differences between forefoot – rearfoot angles were found in the sagittal plane for walking ($p < 0.001$), but not for PROSUP ($p > 0.686$). In the frontal and transverse planes, all clusters showed different forefoot – rearfoot angles ($p < 0.001$) for both walking and PROSUP. The 1st cluster showed smaller ROM in the three planes during walking, and the 3rd cluster was the only that showed forefoot – rearfoot inversion during maximum pronation. Therefore, the new forefoot tracking marker cluster proposition (3rd cluster) captured different forefoot – rearfoot kinematics and can be recommended when the objective is to maximize the cluster rigidity.

1. Introduction

Methods commonly used in biomechanics use markers attached to the skin to track body segments. In six-degrees-of-freedom analyses, these segments are modeled as rigid bodies with no constraints among its parts, and a single explicit fixed coordinate system is associated to them (Cappozzo et al., 1995, 2005). However, segments such as the forefoot clearly have non-rigid behavior due to the mobility of the metatarsal bones (Nester et al., 2010; Okita et al., 2009; Wrbaskic and Dowling, 2007). This is noticeable during stance phase of gait, where the mobility of the medial longitudinal arch and the forefoot mediolateral spread improves the weight-bearing adaptability (Chan et al., 2019).

The conformity to the rigid-body assumption for the forefoot may depend on the location of the tracking markers used. One way to verify whether this assumption is appropriate for a given segment is by calculating its rigidity that can be estimated by the relative motion among all the tracking markers fixed to it. This method has been referred as segment residual in which the lesser the relative motion among markers, the greater its rigidity (Bruening et al., 2012b; Spoor and Veldpaus, 1980).

Bruening et al. (2012a,b) addressed the rigid body assumption for the forefoot when analyzing foot kinetics and kinematics of a multi-segmented foot model with the tracking markers at the 1st and 5th rays. However, the forefoot residual reported was almost

* Corresponding author at: Graduate Program in Rehabilitation Sciences, Universidade Federal de Minas Gerais, 6627 Antônio Carlos Avenue, Belo Horizonte, MG 31270-901, Brazil.

E-mail address: sfonseca@ufmg.br (S.T. Fonseca).

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three times higher than the residual found for the rearfoot and up to five times higher than the residual found for the marker cluster placed on the shank. This suggests that the forefoot tracking marker cluster used did not fully conform with the rigid-body assumption. Despite the multi-segmented nature of the foot, this assumption could be better achieved by using tracking markers placed on the central rays (2nd and 4th), where relative motion is more limited (Neumann, 2011; Okita et al., 2009).

In addition to the problem of rigidity assumption, different forefoot tracking marker clusters may provide different kinematic patterns, depending on which rays are being tracked and the location where the markers are being placed (Nester et al., 2010). Different forefoot tracking marker clusters have been proposed in the literature, which prioritize the motion of different forefoot parts (Leardini et al., 2019). For example, while some authors placed more markers on the metatarsal bases (Bruening et al., 2012b) others focused on the metatarsal heads (Leardini et al., 2007). These different placements may provide different kinematic angular measures.

Considering the existence of different forefoot tracking marker clusters, the choice of a specific cluster should be based on information about its conformity to the rigid-body assumption as well as about the kinematic data it provides. Therefore, the aims of the present study were to compare the relative motion among markers of three forefoot tracking marker clusters as well as to compare the values of joint angles of the forefoot relative to the rearfoot provided by these clusters during two situations: walking and weight-bearing foot pronation-supination. We hypothesize that (1) the new proposed maker cluster presents the lower forefoot residual and (2) each marker cluster may reveal different kinematics. This analysis may help researchers and clinicians choose a forefoot tracking marker cluster more appropriate to their objectives.

2. Methods

2.1. Participants

Six men and 13 women (24.3 ± 3.8 years old, 61.8 ± 10.7 kg and 166.0 ± 10.8 cm) participated in the present study after signing a consent form. They self-declared to be free of either orthopedic or neurological conditions in both lower limbs and lumbopelvic complex, and did not feel any discomfort or pain during data collection. This study was approved by the Institution's Ethics Committee.

2.2. Procedures and instrumentation

Kinematic data were acquired by an optoelectronic system (8 cameras Qualisys ProReflex, 120 Hz, Sweden) synchronized with two inline force plates (AMTI OR6-7-1000, 1200 Hz, USA) 2-mm apart from each other and positioned at the center of an 8 m walkway. An expert examiner attached 13 spherical 8-mm retroreflective markers onto left forefoot and rearfoot as seen in Fig. 1 and described in Table 1.

After marker placement, a 5-second static trial was carried out in relaxed standing position followed by three 5-second static trials in standing with the subtalar joint positioned in neutral position (Araujo et al., 2019). Soon after, the participants performed 10 cycles of slow foot pronation-supination (PROSUP). In standing position, they were oriented to move only left foot from the maximum pronation to the maximum supination and vice-versa, without taking off the ground the 1st and 5th metatarsal heads and the heel, keeping stationary the other lower limbs' joints as maximum as possible. Each PROSUP cycle was segmented from successive maximum supination angles. The PROSUP task was chosen because its motion is much simpler and controlled than walking, which facilitates understanding the kinematics obtained from each marker cluster. Also, it mimics the mid-stance phase of waking and may reveal important kinematic information about the orthostatic standing posture. The participants performed the PROSUP task in weight-bearing standing position and the movements were slow and well controlled. This procedure reduced the ground reaction force, which may have a small (or negligible) effect on the forefoot

Table 1
Markers description.

#	Marker	Description	Type
1	C1	Apex of calcaneal tuberosity	Anatomical/Tracking
2	C2	Superior apex of calcaneal body (Achilles tendon insertion)	Anatomical
3	CU	Inferior border of cuboid	Anatomical
4	NV	Superior prominence of navicular	Anatomical
5	ST	Sustentaculum tali of calcaneus	Anatomical/Tracking
6	PT	Peroneal tubercle	Anatomical/Tracking
7	B1	1st metatarsal base (medial aspect)	Anatomical/Tracking
8	B2	Between 2nd and 3rd metatarsal bases	Tracking
9	B5	5th metatarsal base (lateral aspect)	Anatomical/Tracking
10	H1	1st metatarsal head (medial aspect)	Anatomical/Tracking
11	H2	Between 2nd and 3rd metatarsal heads	Anatomical/Tracking
12	H4	4th metatarsal head	Tracking
13	H5	5th metatarsal head	Tracking

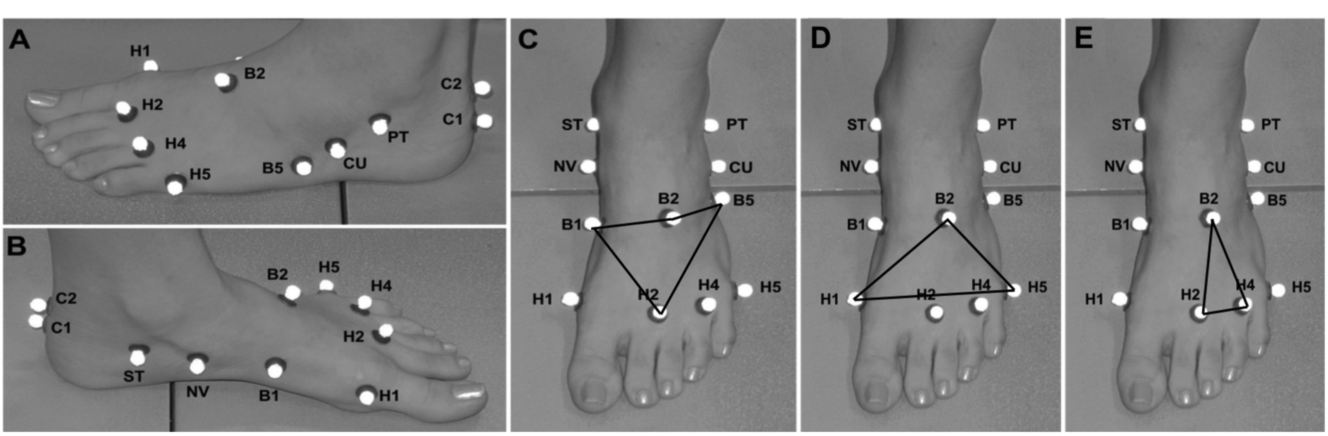

Fig. 1. Markers positioning. Lateral view (A), medial view (B), anterior-superior view displaying the cluster 1 (C), cluster 2 (D), and cluster 3 (E).

movements. It is worth to point out that foot PROSUP evolves the tridimensional movements of all foot segments but here only the forefoot – rearfoot motion was intentionally considered.

Following the PROSUP measurements, the participants were asked to walk at self-selected speed (1.15 ± 0.13 m/s), initially for familiarization and then to achieve six valid trials (i.e., trials with the participant stepping fully on the force plates without missing markers data). The participants were not asked to step on the force plate, to avoid interfering on his/her natural gait pattern. Force data were used to determine the beginning and end of the stance phase of walking.

2.3. Data processing

The data were processed with the Visual3D v5 (C-motion Inc., USA), using a 4th order Butterworth low-pass filter and cutoff frequencies of 6 Hz and 1 Hz for walking and PROSUP, respectively. The biomechanical model adopted was proposed by Bruening et al. (2012a,b), in which the rearfoot and forefoot were modeled as rigid segments with 6 degrees of freedom, as detailed in Table 2. This model is able to perform both kinematic and kinetic analyses (Bruening et al., 2012a,b). Rearfoot's and forefoot's coordinate system were the same for all clusters, only the forefoot's tracking markers locations varied among them. Three different marker clusters were used to track the forefoot movements, as seen in Fig. 1 and described in Table 2. The 1st cluster was the Bruening's original tracking marker cluster (Bruening et al., 2012a,b). The 2nd cluster was similar to the one proposed by Leardini et al. (Leardini et al., 2007) and has been widely used in the literature (Bishop et al., 2012; Deschamps et al., 2011). Finally, the 3rd cluster was hypothetically conceived as a variation of the 1st and 2nd clusters and was proposed to increase forefoot marker cluster rigidity, which could potentially obtain different forefoot – rearfoot kinematics and kinetics.

Forefoot – rearfoot angles were calculated as the relative motion between forefoot and rearfoot for the sagittal, frontal and transverse planes, by using the following Euler/Cardan rotation sequence: X (dorsiflexion/plantarflexion), Y (inversion/eversion) and Z (medial/lateral rotation). Its neutral position (0°) was defined as the mean angular position across the three static standing trials with the subtalar joint placed in neutral (Houck et al., 2008; Jenkyn and Nicol, 2007). For walking, minimum and maximum forefoot – rearfoot angles were computed during stance phase, whereas for PROSUP they were calculated at peak rearfoot eversion (foot pronation) and peak rearfoot inversion (foot supination). Moreover, forefoot – rearfoot range of motion were also considered for both walking and PROSUP. Note that there is relative motion between the anatomical forefoot and midfoot segments as well as between midfoot and rearfoot. However, according to the present purpose, only the relative motion between forefoot and rearfoot was considered.

Cluster rigidity was estimated by means of the segmental residual normalized by the average inter-markers distance, calculated on the Visual3D by using the goodness of fit (least squares fit method) of the tracking markers locations between a reference position (standing trial) and the evaluated task (dynamic trials) at each frame. This computation returns an averaged unitless value of all frames, which represents the relative motion among the markers due to equipment noise, soft tissue motion, and rigid body violations (C-motion, 2017; Chan et al., 2019).

Table 2
Biomechanical model description.

Segment	Features	Description
Rearfoot	Long Axis	Line connecting C1 to the center of the midfoot joint complex (midpoint between NV and CU)
	Sagittal plane	Plane defined by the longitudinal axis and the calcaneal bisection (line connecting C1 to C2)
	Tracking markers (all clusters)	C1, ST and PT
Forefoot	Long Axis	Line connecting the forefoot proximal center (midpoint between B5 and B1) to the forefoot distal center (vertical projection of H2 downward along the lab's vertical axis halfway to the floor)
	Transverse plane	Plane defined by B5, B1 and forefoot distal center
	Superoinferior axis	Axis perpendicular to the transverse plane
	Mediolateral axis	Axis orthogonal to the long and superoinferior axes
	Tracking markers (cluster 1)	B1, B2, B5 and H2
	Tracking markers (cluster 2)	B2, H1 and H5
	Tracking markers (cluster 3)	B2, H2 and H4

Cluster 1 is the Bruening's original tracking markers setup (Bruening et al., 2012a,b), cluster 2 is similar to the one proposed by Leardini et al. (2007) and cluster 3 is the new marker setup propositioned.

2.4. Statistical analyses

Repeated-measures analyses of variance (ANOVA) with one factor (marker cluster) and three levels (clusters 1, 2 and 3) were used to compare the residual and the forefoot – rearfoot angles among the clusters. Contrasts were used to locate specific differences when the ANOVA main effect was significant. Data reproducibility was computed through the intraclass correlation coefficient ($ICC_{3,1}$) between two random trials for each subject. The probability of type I error was set as $\alpha = 0.05$.

3. Results

Most $ICC_{3,1}$ values were above 0.75, showing the good to excellent data reproducibility (Table 3). Only the frontal plane range of motion during walking and PROSUP presented moderate reliability ($ICC_{3,1}$ bellow 0.75). There was no difference for the residual values between the 1st and 2nd clusters, whereas the residual of the 3rd cluster was smaller than those of the 1st and 2nd clusters ($p \leq 0.05$), for both walking and PROSUP (Tables 4 and 5).

During walking, differences were observed in the sagittal, frontal and transverse planes (Table 4). The 1st cluster had the lowest plantar flexion peaks and range of motion, while the 2nd cluster had the lowest dorsiflexion angle peak. The 1st cluster demonstrated the lowest frontal plane range of motion, whereas the 3rd cluster showed the highest inversion peak angle and the smallest eversion peak angle. The 1st cluster had the lowest range of motion in the transverse plane. Medial rotation angle was highest for the 2nd cluster, while the 3rd cluster showed highest lateral rotation angle (Fig. 2).

No differences were observed during PROSUP in the sagittal plane, while differences were found in the frontal and transverse planes (Table 5). In the frontal plane, the 3rd cluster was the only to show forefoot – rearfoot inversion (i.e., positive angle) during maximum pronation, and the 1st cluster had greater forefoot – rearfoot eversion than the 2nd cluster during maximum pronation. In addition, the 1st cluster showed the highest inversion peak angle during maximum supination. In the transverse plane, the 3rd cluster had the greatest medial and lateral rotation angles. In addition, the curves of the forefoot – rearfoot angles in the frontal

Table 3
Data reproducibility.

Task	Plane	Movement	$ICC_{3,1}$ (p)		
			Cluster 1	Cluster 2	Cluster 3
Walking	Sagittal	DF Peak	0.989 (p < 0.001)	0.975 (p < 0.001)	0.979 (p < 0.001)
		PF Peak	0.985 (p < 0.001)	0.982 (p < 0.001)	0.980 (p < 0.001)
		ROM	0.943 (p < 0.001)	0.965 (p < 0.001)	0.948 (p < 0.001)
	Frontal	IN Peak	0.986 (p < 0.001)	0.992 (p < 0.001)	0.987 (p < 0.001)
		EV Peak	0.987 (p < 0.001)	0.983 (p < 0.001)	0.987 (p < 0.001)
		ROM	0.741 (p < 0.001)	0.405 (p = 0.035)	0.859 (p < 0.001)
	Transverse	MR Peak	0.977 (p < 0.001)	0.985 (p < 0.001)	0.967 (p < 0.001)
		LR Peak	0.978 (p < 0.001)	0.985 (p < 0.001)	0.935 (p < 0.001)
		ROM	0.851 (p < 0.001)	0.942 (p < 0.001)	0.847 (p < 0.001)
Foot Pronation-Supination	Sagittal	Pronation	0.982 (p < 0.001)	0.985 (p < 0.001)	0.983 (p < 0.001)
		Supination	0.983 (p < 0.001)	0.965 (p < 0.001)	0.972 (p < 0.001)
		ROM	0.861 (p < 0.001)	0.880 (p < 0.001)	0.875 (p < 0.001)
	Frontal	Pronation	0.991 (p < 0.001)	0.992 (p < 0.001)	0.979 (p < 0.001)
		Supination	0.989 (p < 0.001)	0.985 (p < 0.001)	0.977 (p < 0.001)
		ROM	0.920 (p < 0.001)	0.879 (p < 0.001)	0.664 (p < 0.001)
	Transverse	Pronation	0.972 (p < 0.001)	0.960 (p < 0.001)	0.951 (p < 0.001)
		Supination	0.972 (p < 0.001)	0.960 (p < 0.001)	0.951 (p < 0.001)
		ROM	0.909 (p < 0.001)	0.989 (p < 0.001)	0.912 (p < 0.001)

$ICC_{3,1}$: intra-class correlation between two random trials for each subject. PF: plantar flexion. DF: dorsiflexion. EV: eversion. IN: inversion. LR: lateral rotation. MR: medial rotation. ROM: range of motion. p: p-value. Pronation and Supination refer to their maxima angular values.

Table 4
Comparative table among the three marker clusters for tracking the forefoot motion during walking.

Task	Plane	Variable	Mean (SD)			ANOVA		Contrasts		
			Cluster 1	Cluster 2	Cluster 3	p	F	C1 × C2	C1 × C3	C2 × C3
Walking	–	Residual	2.27E−2 (0.47E−2)	2.23E−2 (0.51E−2)	1.81E−2 (0.40E−2)	<0.001*	16.544	0.732	<0.001**	<0.001**
	Sagittal	DF Peak	8.88 (2.05)	6.83 (2.75)	8.55 (2.33)	<0.001*	24.377	<0.001**	0.166	<0.001**
	PF (−)/DF (+)	PF Peak	−5.16 (3.50)	−12.31 (4.06)	−10.62 (3.68)	<0.001*	105.879	<0.001**	<0.001**	0.006**
		ROM	14.04 (4.41)	19.14 (5.71)	19.18 (4.99)	<0.001*	54.282	<0.001**	<0.001**	0.947
	Frontal	IN Peak	0.88 (1.88)	2.61 (2.35)	6.82 (2.39)	<0.001*	119.756	<0.001**	<0.001**	<0.001**
	EV (−)/IN (+)	EV Peak	−4.86 (2.26)	−4.73 (2.95)	−2.16 (2.23)	<0.001*	16.259	0.808	0.001**	<0.001**
		ROM	3.97 (1.30)	7.35 (1.54)	8.98 (1.50)	<0.001*	87.984	<0.001**	<0.001**	0.001**
	Transverse	MR Peak	4.26 (2.45)	5.86 (3.40)	4.08 (3.56)	<0.001*	13.810	<0.001**	0.645	<0.001**
	LR (−)/MR (+)	LR Peak	−4.19 (1.92)	−4.37 (2.22)	−6.13 (3.30)	<0.001*	26.188	0.286	<0.001**	<0.001**
		ROM	8.45 (2.57)	10.23 (3.51)	10.21 (3.51)	<0.001*	14.236	<0.001**	<0.001**	0.964

*ANOVA main effect ($p \leq 0.05$). **Pairwise comparison ($p \leq 0.05$). C1: cluster 1. C2: cluster 2. C3: cluster 3. PF: plantar flexion. DF: dorsiflexion. EV: eversion. IN: inversion. LR: lateral rotation. MR: medial rotation. ROM: range of motion. Values in the sagittal, frontal and transverse planes refer to the forefoot – rearfoot angles in degrees.

Table 5
Comparative table among the three marker clusters for tracking the forefoot motion during foot pronation-supination.

Task	Plane	Variable	Mean (SD)			ANOVA		Contrasts		
			Cluster 1	Cluster 2	Cluster 3	p	F	C1 × C2	C1 × C3	C2 × C3
Foot Pronation-Supination	–	Residual	1.56E−2 (0.45E−2)	1.62E−2 (0.70E−2)	1.29E−2 (0.53E−2)	0.007*	7.805	0.627	0.001**	<0.001**
	Sagittal PF (−)/ DF (+)	Pronation	1.68 (1.56)	2.20 (3.05)	2.58 (2.42)	0.113	2.642	–	–	–
		Supination	−2.14 (2.24)	−1.96 (2.63)	−2.30 (2.44)	0.51	0.686	–	–	–
		ROM	3.83 (1.73)	4.47 (2.94)	4.92 (2.54)	0.081	3.022	–	–	–
	Frontal	Pronation	−3.69 (2.23)	−1.10 (2.68)	2.40 (2.73)	<0.001*	59.114	<0.001**	<0.001**	<0.001**
	EV (−)/IN (+)	Supination	1.93 (2.28)	−0.58 (1.36)	−0.39 (1.37)	<0.001*	29.200	<0.001**	<0.001**	0.497
		ROM	5.62 (2.84)	2.34 (2.32)	3.72 (1.97)	<0.001*	9.592	<0.001**	0.044**	0.055
	Transverse	Pronation	−3.80 (2.44)	−3.94 (3.01)	−6.77 (4.06)	<0.001*	47.787	0.563	<0.001**	<0.001**
	LR (−)/MR (+)	Supination	3.34 (2.95)	3.05 (3.03)	5.29 (4.01)	<0.001*	43.446	0.12	<0.001**	<0.001**
		ROM	7.14 (2.47)	6.99 (2.20)	12.06 (3.28)	<0.001*	153.234	0.538	<0.001**	<0.001**

*ANOVA main effect ($p \leq 0.05$). **Pairwise comparison ($p \leq 0.05$). C1: cluster 1. C2: cluster 2. C3: cluster 3. PF: plantar flexion. DF: dorsiflexion. EV: eversion. IN: inversion. LR: lateral rotation. MR: medial rotation. ROM: range of motion. Values in the sagittal, frontal and transverse planes refer to the forefoot - rearfoot angles in degrees. Pronation and Supination refer to their maxima angular values.

and transverse planes obtained from the different clusters showed visible differences (Fig. 2). These differences were in relation to the ranges of motion of the 3rd cluster (greater than the others) and to the opposite direction of movement in the frontal plane during PROSUP.

4. Discussion

The present study investigated the adequacy of three marker clusters in complying with the rigid body assumption through the segment residual analysis as well as for tracking the forefoot

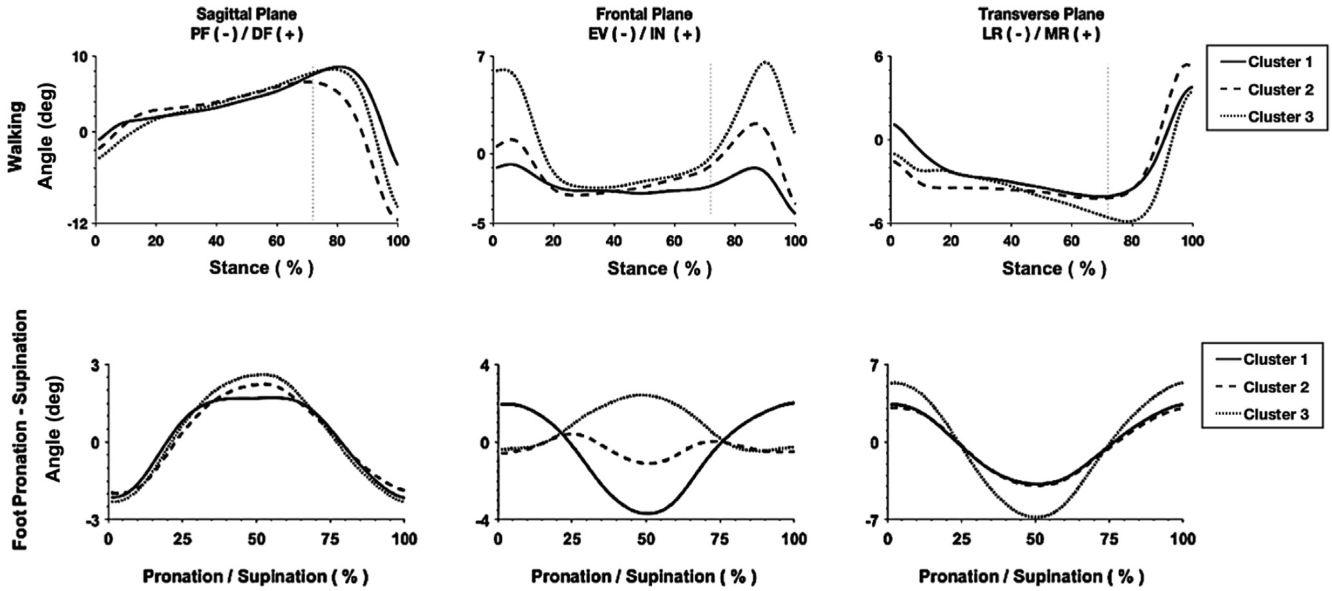

Fig. 2. Forefoot - rearfoot mean curves in the three planes of motion for walking (top plots) and foot pronation – supination (bottom plots). Y-axis: forefoot - rearfoot angles in degrees. X-axis: time relativized to 100% of cycles. PF: plantar flexion. DF: dorsiflexion. EV: eversion. IN: inversion. LR: lateral rotation. MR: medial rotation. deg: degrees. Stance refers to the whole stance phase of walking. In the top plots, the dotted vertical lines in about 70% represent the heel off. Pronation – supination cycles were considered from successive maximum supination angles. Maximum supination at 0% and 100%. Maximum pronation at 50%.

motion during walking and foot PROSUP motions. Segment residual analysis demonstrated that the 3rd cluster had the least amount of motion among the marker clusters. In addition, the investigated clusters provided divergent kinematic information. Pairwise comparisons among the clusters revealed significantly differences among them for most variables. Since each marker cluster represents different forefoot portions, the existence of relative motion among forefoot's rays may explain the differences found. Researchers should be aware that different marker clusters may provide different information about foot motion.

The proposed marker cluster (3rd) had the lowest segment residual values for both walking and PROSUP. Since it was located in the central portion of the forefoot (2nd and 4th metatarsals), avoiding the rays with the greatest quasi-independent motion (1st and 5th metatarsals) (Okita et al., 2009), the 3rd cluster is able to track the forefoot's less flexible portion. The results obtained with the 3rd cluster were similar to the ones reported by Bruening et al. (2012a,b) for the rearfoot and shank segments, which had the least violation of the rigid body assumption, similar to the finding of Chan et al. (2019). Placing markers near to the metatarsal-phalangeal joints (i.e. metatarsal heads) may produce greater soft tissue artifact. By avoiding this issue, the 3rd cluster demonstrated the smallest residual error. Therefore, the 3rd cluster for tracking the forefoot motion is recommended when the objective is to maximize marker cluster rigidity.

Forefoot – rearfoot kinematic analysis revealed, in general, similar angle curves shapes produced by the three marker clusters (Fig. 2). The exception was for the angles in the frontal plane during PROSUP, in which the 1st and 2nd clusters showed forefoot – rearfoot eversion during foot pronation and forefoot – rearfoot inversion during foot supination while the 3rd cluster showed an opposite pattern. In addition, during walking, although the general angle curve shapes in the frontal plane were similar, there were clear differences in amplitudes. Differences in markers location altered the tracked foot movements and, therefore, this issue will be discussed in detail.

The 1st cluster is characterized by three markers on metatarsal bases. In this case, tracking is restricted mostly to the forefoot's proximal portion, which seems to be more similar to the rearfoot motion due to their anatomical proximity. In this way, the relative motion between forefoot and rearfoot was attenuated, which may explain the smaller ROM found in all the three planes during walking. Moreover, this may also explain the smaller medial and lateral rotations during PROSUP of the 1st cluster compared to 3rd cluster. However, even if this 1st cluster showed the smallest ROM in the frontal plane during walking, it presented higher forefoot – rearfoot eversion and inversion angles during PROSUP in comparison to the 2nd cluster. The large lowering and raising of the 1st metatarsal base marker (observed through the navicular bone) during PROSUP, respectively, may have led to this specific result.

Since the participants were told to always keep the metatarsal heads in contact with the ground during PROSUP, the distal part of the forefoot was horizontally constrained and moved less. For this reason, the forefoot – rearfoot motion tended to be greater for the 2nd cluster in comparison with the 1st cluster, except in the frontal and transverse planes. It should be noted that the 2nd tracking marker cluster were placed in the 1st and 5th metatarsal heads, which are those with greater mobility. These rays are relatively independent between themselves, and may have displacements in opposite directions, which might justify the eversion shown by the 2nd cluster during pronation. During walking, all ROM were greater than those recorded with the 1st cluster. In the sagittal plane, the 2nd cluster captured less dorsiflexion than the 1st cluster, which may be a consequence of the absence of a 1st metatarsal base marker in the 2nd cluster.

Similar to the 2nd cluster, the 3rd cluster had more distal markers on metatarsals. But, these markers were more central (2nd and 4th metatarsal heads), which have less relative motion (Okita et al., 2009). This feature allowed the forefoot segment to behave more similar to a rigid body, probably with less influence from the larger and opposite motions of the 1st and 5th metatarsi. The greater number of distal markers compared to the 1st cluster may have allowed to track forefoot motion with less influence from proximal foot segments and tissues. Such characteristics may have contributed to the 3rd cluster to be the only cluster that showed forefoot – rearfoot inversion during maximum pronation in the PROSUP, which has been shown during weight-bearing forefoot – rearfoot motion (Hunt et al., 2001; Sarrafian, 1987; Souza et al., 2014). While the rearfoot is everting, the 3rd marker cluster seemed to track the more stable forefoot part, which does not depend on the 1st and 5th rays' motion. The same reasoning could explain its higher inversion peak and ROM in the frontal plane during walking. In addition, due to this same reason, its markers' location could explain the highest ROM observed in the transverse plane, during PROSUP and walking.

Kinematic models of the forefoot segments vary among authors. This includes variations in terms of the bones and sites tracked, since it is challenging to model a segment composed of five moving rays with relatively independent movements (Leardini et al., 2019; Okita et al., 2009; Rankine et al., 2008; Wolf et al., 2008). To compensate this problem, some authors divide the metatarsals into medial and lateral segments and report these motions separately (Cobb et al., 2016; Nester et al., 2014, 2010). Differently, we evaluated which marker cluster provides the appropriate measurement of forefoot motion relative to rearfoot, when the forefoot is treated as a single unit. Perhaps, an optimal marker cluster should cover the independent motions of the medial, central and lateral portions of the forefoot. For general purposes, the central portion of the forefoot may be more adequate to be tracked and more suitable for kinetic analysis. The information provided may help choosing a specific forefoot marker cluster according to the researcher's needs.

The present study had some limitations. Only young healthy subjects with body mass index (BMI) ranging from 18.67 to 25.61 kg/m^2 participated in the study. Other subjects with higher BMI may have more adipose tissue that could produce soft tissue artifacts and change forefoot residual values. The investigation of other tasks, like running, squatting and jumping, or the analysis of pathological populations should also be performed, to test whether the present findings may be generalized to other situations. In addition, the velocity and ROM during the PROSUP cycles were not entirely standardized among subjects, although verbal instructions were given to the participants to reach their highest ROM at slow and controlled speed. Finally, the forefoot segment residuals are influenced not only by rigid-body violation, but also by soft tissue artifact and equipment noise (Bruening et al., 2012b; Spoor and Veldpaus, 1980). Equipment noise was verified during each system calibration and only residuals lower than 1.2 mm for each camera was accepted. However, as the soft tissue artifact was not measured, the values of residual found in the present study are an indicator of forefoot marker cluster rigidity plus soft tissue artifact. Yet, it is important to note that, due to the repeated measure nature of the study, the comparisons among clusters are not influenced by these issues.

In conclusion, the three forefoot marker clusters resulted in different residuals ("rigidity") and forefoot – rearfoot angles during walking and controlled pronation/supination motions. When improving the forefoot marker cluster rigidity is aimed, which is common during kinematic and kinetic analyses, the 3rd marker cluster is recommended. Kinematic differences were observed in all planes, mainly in the frontal plane, where motion in opposite directions were observed during PROSUP. For example, the 3rd cluster was the only that showed inversion of the forefoot relative to rearfoot during maximum pronation (Lundgren et al., 2007; Mueller, 2005; Neumann, 2011; Souza et al., 2014). In addition, during walking, the amount of inversion was clearly greater for this cluster. Despite some small differences in amplitudes in the sagittal and transverse planes, the three clusters provided angle curves with similar shapes. Hence, the results of the present study may guide the proper choice of marker clusters for tracking the forefoot segment and, thus, the forefoot – rearfoot motion.

Declaration of Competing Interest

The authors report no conflicts of interest.

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