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Kinematics reduction applied to the comparison of highly-pronated, normal and highly-supinated feet during walking

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ABSTRACT

Background: Kinematic analysis could help to study how variations in the static foot posture affect lower limb biomechanical function. The analysis of foot kinematics is complex because it involves managing the time-dependent joint angles in different joints and in all three planes of motion. But it could be simplified if joint angles are coordinated.

Methods: The kinematics of the ankle, midtarsal and metatarsophalangeal joints were registered in 20 highly-pronated, 30 normal and 20 highly-supinated subjects (assessed by the Foot Posture Index – FPI) as they walked barefoot. Coordination for each sample was analysed through principal component analysis applied to the dorsiflexion, abduction and inversion angles measured. Finally, a systematic comparison among the samples was performed through a set of ANOVAs applied to the reduced variables corresponding to the factors found.

Results: Three principal components (coordination patterns) accounted for about 70% of the variance of the joint angles, and were affected by the FPI. The main coordination in normal feet was the supination movement, while in highly-supinated and highly-pronated feet it was the flexion coordination of all foot joints, which could work against adaptation in cases of varying terrain. The original joint angles were reduced to three factors, and the ANOVAs applied to them showed that highly-pronated feet presented a delayed propulsion peak and smaller ranges of motion during propulsion regarding all factors, and that highly-supinated feet require more pronation time to fully support the foot during walking.

Significance: The coordination patterns of normal feet might be considered the normal patterns used for an efficient gait, and may help in planning surgical procedures and designing foot prostheses or orthotics. Dimensional reduction makes it possible to perform more systematic kinematic analyses, which have revealed that highly-pronated feet are in poorer propulsive condition, and this in turn may make them more prone to injury.

1. Introduction

Variations in the static foot posture (pronated or supinated vs. neutral feet) have been associated with an improper biomechanical function of the lower limb [1,2]. It is particularly interesting to analyse their effect on the foot kinematics during walking. However, a rigorous analysis is difficult because of the simultaneous management of the time-dependent angles in the different foot joints, and in all three planes of motion. Therefore, previous comparative studies [3–6] have focused on certain specific parameters such as peak angle, contact angle or range of motion (ROM). These analyses reported contradictory data. While some studies observed a decreased ankle ROM of pronated feet in the sagittal plane [5,6] and increased in the frontal plane [5,7,8], others found no significant differences in any motion plane [9,10]. At the midtarsal joint, one study observed a decrease in the ROM for pronated feet in the transverse plane and a greater plantar-flexion peak at push-off [3], whereas others found no significant differences in any motion plane [9,11]. At the metatarsophalangeal joint, one study observed a reduction in the ROM in the sagittal plane for pronated feet [5].

Differences in kinematics results among studies may be due to the reference postures used [4] but also to differences in quantifying the static foot posture or in the samples considered (age, sex, etc.). There are different methods available for quantifying the static foot posture [12], the foot posture index (FPI) being reported as more reliable than others to estimate the foot dynamic function [13,14].

Although walking is a complex task, various studies using principal component analysis (PCA) [15–18] have shown that kinematic co-ordination exists between hip, knee and ankle, i.e. there is a correlation

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between joint angles. Differences in kinematic coordination have been used to detect dysfunctions (e.g. to compare healthy and medial knee-osteoarthritic gait [18]), because coordination is a consequence of mechanical (connections of tendons, fascia) and neurological (innervation of a single cortical motor neuron in several spinal motor neuron pools) couplings. This coordination has been studied using lower limb models with the foot treated as a rigid segment, and thus coordination of foot joint angles during walking has not been approached to date.

The aim of this work was to prove the existence of kinematic coordination of the main foot joints – ankle, midtarsal (MT) and metatarsophalangeal (MP) joints – during walking, and to analyse the effect of FPI on this coordination. We hypothesize from previous studies on the lower limb [15–18] that feet with different FPI use different coordination patterns during walking, which could affect operation of the lower limb. Furthermore, this paper proposes a systematic comparison of the kinematics of the foot joints through dimensional reduction by using PCA.

2. Material and methods

2.1. Experiment description

Seventy adult male subjects, recruited from university communities, participated in the experiment, approved by the Ethics Committee of the Universitat Jaume I (Castellón, Spain). The same instructor (a podiatrist) classified all participants' feet using the FPI as described in [19]: 30 subjects with normal FPI (FPI + 2 ± 1.48, age 27.1 ± 3.8 years, weight 78.2 ± 13.9 kg, height 178 ± 5.9 cm), 20 subjects with highly-supinated FPI (FPI -8 ± 1.85, age 29 ± 9.1 years, weight 79 ± 8.5 kg, height 181 ± 8.8 cm) and 20 subjects with highly-pronated FPI (FPI + 11.65 ± 0.67, age 29.6 ± 7.39 years, weight 80.68 ± 19.38 kg, height 178.7 ± 6.7 cm). The participants reported no history of neuromuscular problems, diabetes or foot or ankle surgery, and did not use orthotics or report pain in the lower extremity. Their age was controlled to avoid kinematic alterations due to joint degeneration by ageing and they were duly informed and gave written consent to participate in the experiment.

Each subject was asked to walk barefoot at a comfortable self-selected speed along a 7-m walkway, stepping with the right foot on a pressure platform located halfway along it. The subjects were told to look forwards as they walked to avoid platform targeting, and repeated the activity until five valid trials were obtained, discarding those in which the subject did not step on the pressure platform with the right foot.

2.2. Data acquisition

In each of the trials, the kinematics of the ankle, MT and MP joints during the stance phase were recorded using the model proposed in [20] (Fig. 1), which adapted that presented in [21]. Twenty reflective markers were tracked with an eight infrared camera motion analysis system (Vicon® Motion Systems Ltd., Oxford, UK), at a 100 Hz sampling rate. The 3D coordinates of the markers, at each instant, were used to obtain the position and orientation of each segment [22]. Joint angles were calculated from the upright standing static reference posture,

Fig. 1. Markers used in the experiment to record the kinematics of foot joints.

using a Cardan's rotation sequence between distal and proximal segments [23]: 1-dorsiflexion/plantarflexion, 2-abduction/adduction, and 3-inversion/eversion. Dorsiflexion, abduction and inversion were considered positive. All kinematic data were low-pass filtered with a 4th-order Butterworth filter, with cutoff frequency of 10 Hz. Contact pressures of the right foot were recorded at a 100 Hz sampling rate with a Podoprint pressure platform (Namrol Group, Barcelona, Spain) synchronized with the infrared camera system, and were used to identify the initial and final time instants of the stance phase. Joint angles recorded were presented as a percentage of the stance phase during the gait cycle (0–100).

2.3. Data analysis

i) Kinematic coordination of foot joints in feet with different FPI: PCA was applied to each FPI sample to identify kinematic coordination in each case, after checking the appropriateness of the PCA through Bartlett test of sphericity. In brief, PCA [15,24] finds linear combinations of correlated variables to describe most of the data variation with a small number of new uncorrelated variables called principal components (PCs). Each of these PCs is a vector containing the loadings of each original variable (i.e. the weight by which each original variable should be multiplied to obtain the new variable), so that it represents a coordination pattern [15,24].

For each FPI sample, a PCA was applied to the nine joint angles measured in all the records (150 records for normal feet – 5 trials × 30 subjects – and 100 records for highly-pronated and highly-supinated feet – 5 trials × 20 subjects), each record containing the entire kinematic time series recorded. First, joint angles were normalized (mean = 0, standard deviation = 1) to make angles with different ranges of motion comparable [25]. The correlation matrix was then computed, after which the eigenvalues (variance explained) and eigenvectors (principal components) were calculated. Finally, Varimax rotation [25] was performed to simplify the interpretation of the PCs, which maximizes the sum of the variances of the squared loadings, so that any given PC comprises just a few variables with very high loadings on this PC, while the remaining variables have near-zero loadings. The resulting rotated PCs with eigenvalues greater than 1 were used to interpret the kinematic coordination in each FPI sample. The variance explained by the resulting PCs in each PCA was considered an indicator of how well the measured motion fitted the coordination represented by the PCs obtained.

ii) Differences in the kinematics of feet with different FPI through dimensional reduction: A new set of reduced variables (RVs) was considered, corresponding to the PCs found for the normal FPI sample, after having computed the variance these PCs explained for the data of highly-pronated and highly-supinated feet. Then, for each trial of each subject (with normal, highly-pronated or highly-supinated FPI) the values of the new RVs were calculated at each time step of the stance phase. For each FPI sample, plots of the RVs throughout the stance phase were performed with means and 95% confidence intervals from all of the repetitions and participants. A set of parameters describing these curves (start, end and peak values) was proposed for the kinematic comparison of feet with different FPI (Table 2). The values of these parameters were calculated for each subject in each of the five trials, with the median absolute deviation (MAD) method for detecting outliers [26,27] (threshold 5xMAD). Finally, a set of ANOVAs were applied to these parameters as dependent variables with FPI (normal, highly-pronated or highly-supinated) as factor, in order to identify which parameters are affected by the FPI (Bonferroni correction was applied to the significance level to compensate for the number of samples simultaneously compared).

3. Results

i) Kinematic coordination of foot joints in feet with different FPI: the

Table 1
Loadings of resulting PCs in the PCA performed on each sample. For easier interpretation, loadings greater than 0.3 (weak) and 0.5 (strong) are highlighted in light and dark grey, respectively.

Joint	Angle	Loadings								
		Normal feet			Highly-supinated feet			Highly-pronated feet		
		N-PC1	N-PC2	N-PC3	S-PC1	S-PC2	S-PC3	P-PC1	P-PC2	P-PC3
Ankle	Abduction	-0.817	0.028	0.167	-0.063	-0.855	-0.164	-0.185	-0.838	0.260
	Inversion	0.802	-0.344	0.033	-0.170	0.869	0.090	-0.179	0.922	0.006
	Dorsiflexion	-0.095	0.873	0.034	0.819	-0.149	0.135	0.775	0.035	0.252
MT	Abduction	-0.645	0.460	-0.427	0.645	-0.596	-0.192	0.546	-0.585	0.414
	Inversion	0.611	0.202	0.229	-0.023	0.685	-0.206	-0.346	0.103	-0.511
	Dorsiflexion	-0.017	0.277	-0.734	0.871	0.131	-0.168	0.793	-0.166	0.071
MP	Abduction	0.073	-0.583	0.590	-0.727	-0.002	0.441	-0.780	0.130	0.259
	Inversion	0.098	0.187	0.701	-0.140	0.021	0.894	-0.130	-0.148	0.838
	Dorsiflexion	0.661	-0.523	0.269	-0.535	0.394	0.366	-0.478	0.671	-0.088
Variance explained (%)		40.20	16.23	11.71	40.21	21.79	10.32	39.86	19.10	11.41

Bartlett test of sphericity confirmed the appropriateness of the PCA (significance level < 1.0E-05 for each sample). Table 1 shows the results of the PCAs performed on the joint angles in the three samples. Three PCs were obtained in all cases, explaining about 70% of data variance in each case. For subjects with normal FPI, the first PC (N-PC1) explained far more variance and corresponded to a coordinated movement of adduction and inversion of ankle and MT joints, together with dorsiflexion of the MP joint; the second PC (N-PC2) involved a coordination of ankle dorsiflexion with some eversion, MT abduction, and adduction and plantarflexion of the MP joint; and the third PC (N-PC3) corresponded to MT plantarflexion with some adduction, coordinated with inversion and abduction of the MP joint. The first and second PCs obtained for highly-supinated and highly-pronated feet were similar to those obtained for normal FPI, but they were interchanged in order and variance explained. The first PC of highly-supinated feet (S-PC1) incorporated MT dorsiflexion at the expense of the loss of MT plantarflexion in the third PC (S-PC3). This was also observed for highly-pronated feet, which incorporated a slight MT eversion in the first PC (P-PC1) at the expense of the loss of MT inversion in the second PC (P-PC2). The third PC showed more variations among samples, and explained only about 10% of data variance. This PC did not include ankle joint angles, included MP inversion in all cases, and only included significant sagittal motion (at MT) in normal feet.

ii) Differences in the kinematics of feet with different FPI through dimensional reduction: The original nine foot joint angles were reduced to three RVs corresponding to the PCs found for the normal FPI sample, which were checked to explain 62.7% and 68.8% of variance of the data for highly-pronated and highly-supinated feet, respectively. Fig. 2 shows means and 95% confidence intervals of these RVs from all the repetitions and participants in each sample. The curve profiles were similar, but presented some differences in the specific values of the RVs and time delays. For a systematic comparison of the curves of the participants with different FPI, a total of 20 parameters, listed in Table 2, were chosen as descriptors of these curves.

Table 3 shows the results of the ANOVAs performed to identify the effect of the FPI on these descriptor parameters. Regarding the RV corresponding to first PC (RV-1st PC), significantly higher RV values were observed for normal feet when compared to highly-supinated feet throughout the whole stance phase, but no significant differences were observed in the range or in the stance times; the propulsion peak for highly-pronated feet was significantly smaller and delayed than that for normal feet. Comparison of the RV corresponding to the second PC (RV-2nd PC) did not show any significant difference between normal and highly-supinated feet, while a significantly higher final value was observed for highly-pronated feet when compared to normal ones, together with a smaller range and a delay in propulsion peak. Finally, comparison of the RV corresponding to the third PC (RV-3rd PC) identified a significantly higher initial value for highly-supinated feet compared to normal ones; highly-pronated feet showed significantly smaller initial and final values than normal feet, and also a smaller range and a delay in the propulsion peak.

4. Discussion

The present study has shown that subjects use a reduced number of coordination patterns during gait. The main coordination in normal FPI sample contains the well-known relationship between adduction and inversion in ankle and MT joints (supination) [28], which is coordinated with dorsiflexion of the MP joint. The second coordination relates ankle dorsiflexion to some ankle eversion, MT abduction, and MP adduction and plantarflexion. And finally, the third coordination relates MT plantarflexion mainly to MP inversion and abduction. These coordinations might be considered as the normal patterns used for an efficient gait and may help better comprehend the functioning of the foot joints during gait, thus helping surgeons plan their operations to allow proper kinematic behaviour, and also designers of foot prostheses and orthotics.

The kinematics of subjects with normal FPI during the stance phase can be described from the plots of their corresponding factor scores (RVs, Fig. 2). During the initial contact phase (0–20% of stance phase) the ankle and MT joints pronate (RV-1st PC) while the ankle plantarflexes (RV-2nd PC) to allow the foot to land on the floor, and MT

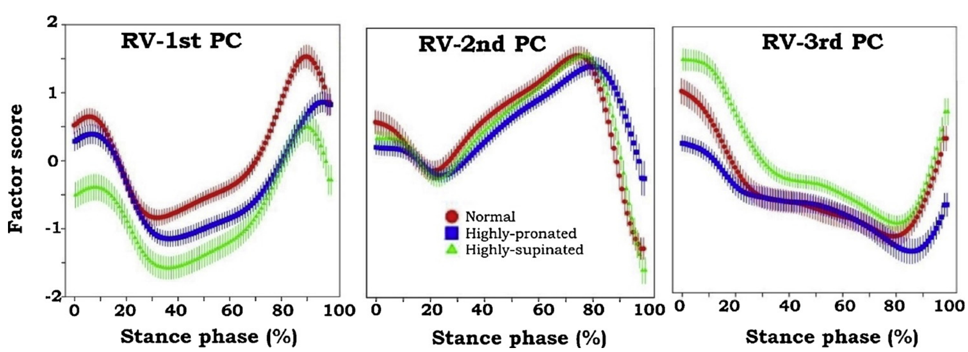

Fig. 2. Plots of the RVs (mean values and 95% CI from all repetitions and participants) during the stance phase of gait for normal, highly-pronated and highly-supinated feet.

Table 2
List of identified descriptive parameters of the RV curves.

RVs	Descriptive parameters
1st PC	Initial value, Final value, Range, Maximal value (0%–25%) and associated stance time, Minimal value (0%–100%) and associated stance time, Maximal value (50%–100%) and associated stance time
2nd PC	Initial value, Final value, Range, Maximal value (50%–100%) and associated stance time, Minimal value (0%–50%) and associated stance time
3rd PC	Initial value, Final value, Range, Minimal value (50%–100%) and associated stance time

Table 3
Summary of the results from the ANOVAs performed to identify the effect of FPI on the descriptor parameters of the RVs. Significant differences after applying Bonferroni correction have been underlined (sig. ≤0.017). Tukey post-hoc results are also summarized. Foot types: normal (1), highly-pronated (2), and highly-supinated (3).

Reduced Variable	Descriptor parameter	Sig.	Post-hoc (Tukey)	
			Foot type	Sig.
RV-1st PC	Initial value	<u>0.000</u>	1-3	0.000
			2-3	0.003
	Final value	<u>0.000</u>	1-3	0.001
			2-3	0.001
	Range	0.045		
	Max. (0-25) Value	<u>0.000</u>	1-3	0.000
			2-3	0.006
	Max. (0-25) Stance time	0.343		
	Max. (50-100) Value	<u>0.000</u>	1-2	0.047
			1-3	0.000
	Max. (50-100) Stance time	<u>0.000</u>	1-2	0.000
			2-3	0.000
	Min. (0-100) Value	<u>0.002</u>	1-3	0.002
			2-3	0.045
	Min. (0-100) Stance time	0.674		
RV-2nd PC	Initial value	0.357		
	Final value	<u>0.000</u>	1-2	0.000
			2-3	0.000
	Range	<u>0.000</u>	1-2	0.001
			2-3	0.000
	Max. (50-100) Value	0.932		
	Max. (50-100) Stance time	<u>0.003</u>	1-2	0.002
	Min. (0-50) Value	0.989		
	Min. (0-50) Stance time	0.928		
RV-3rd PC	Initial value	<u>0.000</u>	1-2	0.005
			1-3	0.014
			2-3	0.000
	Final value	<u>0.000</u>	1-2	0.001
			2-3	0.000
	Range	<u>0.007</u>	1-2	0.050
			2-3	0.006
	Min. (50-100) Value	0.068		
	Min. (50-100) Stance time	<u>0.017</u>	1-2	0.015

dorsiflexes as MP everts and adducts (RV-3rd PC). Subsequently, once the foot has landed on the floor, the midstance phase (20–70% of stance phase) is characterized by a supination of both the ankle and MT joints (RV-1st PC) and dorsiflexion of the ankle (RV-2nd PC), while the MT joint keeps dorsiflexing and the MP joint keeps everting and adducting (RV-3rd PC), but to a lesser extent than during the contact phase. Finally, in the propulsion phase (70–100% of the stance phase) the ankle and the MT joints supinate to a higher extent until the onset of the swing phase, after which they both pronate (RV-1st PC), and the ankle clearly plantarflexes (RV-2nd PC) together with the MT joint at the same time that the MP inverts and abducts (RV-3rd PC).

Subjects with highly-supinated and highly-pronated feet also use three main coordination patterns during gait, like normal FPI subjects, but with some notable differences. The two main coordinations are similar but interchanged in order, revealing that highly-supinated and highly-pronated feet make less use of the supination movement. The main coordination incorporates dorsiflexion of the MT joint at the cost of the third coordination not presenting plantarflexion of that joint. Therefore, the main coordination includes flexion in all three foot joints considered, revealing a lower degree of independence of movements in the sagittal plane in highly-supinated and highly-pronated feet than in normal ones. This could work against adaptation of gait in cases of varying terrain, which will generate joint instability, thereby increasing the joint sprain risk factor. The third coordination is the most variable between samples, but in all cases correlates the MP inversion with other movements of MP and MT joints, excluding sagittal motion except in normal feet.

The original nine foot joint angles were reduced to three RVs corresponding to the PCs found for the normal FPI sample. This has made it possible to perform a systematic analysis of the differences between the three FPI samples, by analysing 20 descriptive parameters. The ANOVAs allowed significant differences to be detected in the three RVs, especially in the first one (RV-1st PC): the coordinated supination movement. Highly-supinated feet presented significantly larger values for all parameters corresponding to RV-1st PC, except for the range and the time parameters. These results are in agreement with [6], and they are compatible with an offset (see Fig. 2), which could arise from differences in the reference postures adopted. The reference posture for highly-supinated feet is expected to have higher supination than that of subjects with normal feet, so that for the same postures they would yield lower supination values. Highly-supinated feet also show significantly higher RV-3rd PC values during the contact phase, and so the MT joints use a higher ROM in the sagittal plane, which may be responsible for the appearance of plantar fasciitis in highly-supinated feet.

Highly-pronated feet present differences during the propulsion phase compared to normal feet regarding all RVs, with a delayed propulsion peak and smaller ranges of motion, which is in agreement with the higher incidence of hallux limitus in these feet. Highly-supinated feet require more pronation time to fully support the foot during walking, which is in agreement with the longer time required to reach the eversion peak in the MT joint reported for high-arched feet in [9]. Results are also in agreement with the decreased ankle ROM of pronated feet in the sagittal plane reported in some studies [5,6] and the decrease in the ROM at the MT joint observed for pronated feet in the transverse plane [3]. The smaller ROM used during the propulsion phase in highly-pronated feet, with a significantly reduced final plantarflexion angle, might be related to the shorter length of the triceps surae muscle reported in [24], an aspect to be studied in future work. In any case, highly-pronated feet are clearly in poorer propulsive conditions, which may make them more liable to suffer injuries.

The results of this study are restricted to walking, and there could be other differences between normal, highly-supinated and highly-pronated feet in other activities. Results are also limited to the populations considered. Future research should study the correlations between the parameters in which significant differences have been found and the appearance of pathologies such as hallux abductus valgus or plantar fasciitis.

5. Conclusion

This study has proved the existence of kinematic coordination of foot joints during walking, and found evidence that these coordination patterns are affected by the FPI. Patterns from normal feet might be considered as the normal patterns used for an efficient gait and may help in planning surgery to allow proper kinematic behaviour and in designing foot prostheses and orthotics. Highly-supinated and highly-pronated feet make less use of the supination movement, and present a lower degree of independence of movements in the sagittal plane, which could work against adaptation of gait in cases of varying terrain, thus increasing the joint sprain risk factor. Furthermore, dimensional reduction has made it possible to perform a systematic analysis of the differences between the kinematics of normal, highly-supinated and highly-pronated feet, revealing that highly-pronated feet are clearly in poorer propulsive conditions, which may make them prone to injury.

Conflict of interest statement

Nothing to declare.

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