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Stabilometric parameters are affected by anthropometry and foot placement

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Abstract

Objective. To recognize and quantify the influence of biomechanical factors, namely anthropometry and foot placement, on the more common measures of stabilometric performance, including new-generation stochastic parameters.

Design. Fifty normal-bodied young adults were selected in order to cover a sufficiently wide range of anthropometric properties. They were allowed to choose their preferred side-by-side foot position and their quiet stance was recorded with eyes open and closed by a force platform.

Background. Biomechanical factors are known to influence postural stability but their impact on stabilometric parameters has not been extensively explored yet.

Methods. Principal component analysis was used for feature selection among several biomechanical factors. A collection of 55 stabilometric parameters from the literature was estimated from the center-of-pressure time series. Linear relations between stabilometric parameters and selected biomechanical factors were investigated by robust regression techniques.

Results. The feature selection process returned height, weight, maximum foot width, base-of-support area, and foot opening angle as the relevant biomechanical variables. Only eleven out of the 55 stabilometric parameters were completely immune from a linear dependence on these variables. The remaining parameters showed a moderate to high dependence that was strengthened upon eye closure. For these parameters, a normalization procedure was proposed, to remove what can well be considered, in clinical investigations, a spurious source of between-subject variability.

Conclusion. Care should be taken when quantifying postural sway through stabilometric parameters. It is suggested as a good practice to include some anthropometric measurements in the experimental protocol, and to standardize or trace foot position.

Relevance

Although the role of anthropometry and foot placement has been investigated in specific studies, there are no studies in the literature that systematically explore the relationship between such BF and stabilometric parameters. This knowledge may contribute to better defining the experimental protocol and improving the functional evaluation of postural sway for clinical purposes, e.g. by removing through normalization the spurious effects of body properties and foot position on postural performance.

Keywords: Posture; Platform stabilometry; Normalization; Anthropometry; Base of support; Vision

1. Introduction

Platform stabilometry, sometimes referred to as static posturography, is a common technique aimed at quantifying the body sway of subjects in a standing position [1]. By means of a set of force transducers the ground-reaction vector and its point of application, the center of pressure (CoP), are recorded. Ground-reaction vector and CoP provide important insights into the process of controlling balance since they can be directly related to the motion of body center of mass [2].

Several measures have been proposed in the literature to describe the planar (2D) migration of CoP over the base of support or along the antero-posterior (AP) and medio-lateral (ML) directions. Parameters have been typically used that estimate the summary statistic

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properties of CoP displacement [3]. Recently, also model-based parameters have been used that postulate the time-scale dependence of CoP statistical properties [4–6].

All these measures have in common a fair to large variability, both between- and within-subjects, and this may be a limiting factor when wishing to determine whether a postural performance is abnormal or whether it is sensitive to a treatment or a therapy [5,7]. The inherent variability of all such measures in normal subjects has been largely debated [4,5,7,8]. Intra-subject variability has been partially explained by a learning effect that leads to an optimization of the energy expenditure by means of a progressive reduction in body sway over repeated trials [9]. The large inter-individual differences prevented from defining normative values for stabilometric parameters [1]. This is of course a major limitation for a test that may be well suited for routine use in clinical practice (e.g. for fall prevention in the elderly) as well as a simple tool for a first-level investigation of balance control state. For this reason it is important to cope with all the potential sources of spurious variability that may mask or overwhelm control-related information. To this aim, first, a significant role can be ascribed to inconsistencies in the measurement procedure (between experimental sessions within the same lab and, more so, between different laboratories) including, e.g., reproducibility of the experimental protocol, environmental conditions, random errors, signal processing. This is a relevant concern and a satisfactory solution will be established only once a standard procedure for stabilometric tests is proposed and widely accepted. A second source of variability is related to the intrinsic differences between subjects in terms of their biomechanics. Subject morphology together with joints and muscle function have been identified, in a systems approach, as the main biomechanical factors (BF) involved in balance control [10]. Body size and foot placement are known to influence postural stability [11–15] but their impact on stabilometric parameters has not been extensively explored yet.

The present paper moves from this latter concern and aims at investigating the influence of BF such as anthropometric and foot-placement measurements on stabilometric parameters, including new-generation stochastic parameters, during quiet standing. This enabled us to highlight which of the stabilometric parameters were robust and, on the contrary, which of them were more heavily dependent on differences in BF. This analysis was performed with eyes open (EO) and eyes closed (EC) in order to ascertain if the relation with BF was sensory-dependent. Finally, a normalization method is recommended to deal with the partial compensation of the undesired bias that BF may introduce to the estimate of stabilometric parameters.

2. Methods

2.1. Subjects

Fifty young adults (25 male and 25 female) gave informed consent before their inclusion in this study. Mean age was 25.7 years (SD: 2.8; range 21–30 years). All subjects were physically active and did not have any self-reported musculoskeletal or neurological disorders. Subjects were normal bodied, selected in order to cover a sufficiently wide range of anthropometric properties. The body mass index (BMI, see definition in Table 1) ranged between 17.8 and 31.0, corresponding to a classification in the range "underweight" to "overweight" in the scale proposed by the American Society of Obesity Surgery [16].

2.2. Biomechanical factors

Several measurements were taken on each subject, in order to estimate the size of the main body segments and the relative mass distribution. Body segments were identified by the following set of anatomical landmarks: left and right acromion, greater trochanter, lateral epicondyle, and lateral malleolus. After the anatomical landmarks were located by palpation according to the procedure proposed by Benedetti et al. [17], length of the shank, thigh, and trunk, and breadth of the shoulders were determined with a caliper. Moreover, the chest,

Table 1
Age and BF relative to the entire population (50 subjects) and to the two gender groups (25 subjects each)

	Mean (SD)			P^a
	Overall	Males	Females	
Age (years)	25.7 (2.8)	26.3 (3.0)	25.0 (2.5)	–
Height (cm)	170.2 (9.8)	176.3 (7.7)	164.2 (7.9)	**
Weight (kg)	65.6 (13.6)	74.8 (12.9)	56.5 (6.4)	**
BMI[b] (kg/m^2)	22.5 (3.1)	24.0 (3.4)	20.9 (1.8)	**
Shoulders (cm)	35.5 (3.3)	38.1 (2.1)	33.0 (2.2)	**
Trunk (cm)	51.1 (4.0)	52.9 (3.8)	49.2 (3.2)	**
Chest Ø (cm)	89.3 (7.3)	93.4 (7.6)	85.2 (4.0)	**
Waist Ø (cm)	74.1 (10.7)	80.2 (11.1)	67.9 (5.4)	**
Hip Ø (cm)	92.2 (7.0)	94.9 (7.8)	89.6 (5.0)	*
Thigh (cm)	43.5 (3.2)	44.3 (3.2)	42.7 (3.2)	–
Shank (cm)	38.4 (3.5)	40.6 (2.8)	36.3 (2.6)	**
FL (cm)	26.0 (1.9)	27.3 (1.3)	24.7 (1.3)	**
MFW (cm)	9.1 (0.9)	9.7 (0.9)	8.6 (0.6)	**
EFL (cm)	25.8 (1.8)	27.1 (1.4)	24.6 (1.3)	**
IMD (cm)	8.0 (3.6)	8.2 (3.4)	7.9 (3.7)	–
BTD (cm)	16.5 (4.6)	18.6 (4.2)	14.4 (4.0)	**
BoS (cm^2)	318.6 (100.1)	362.1 (91.5)	275.2 (90.2)	*
α (degree)	18.8 (8.1)	22.3 (8.2)	15.3 (6.5)	*

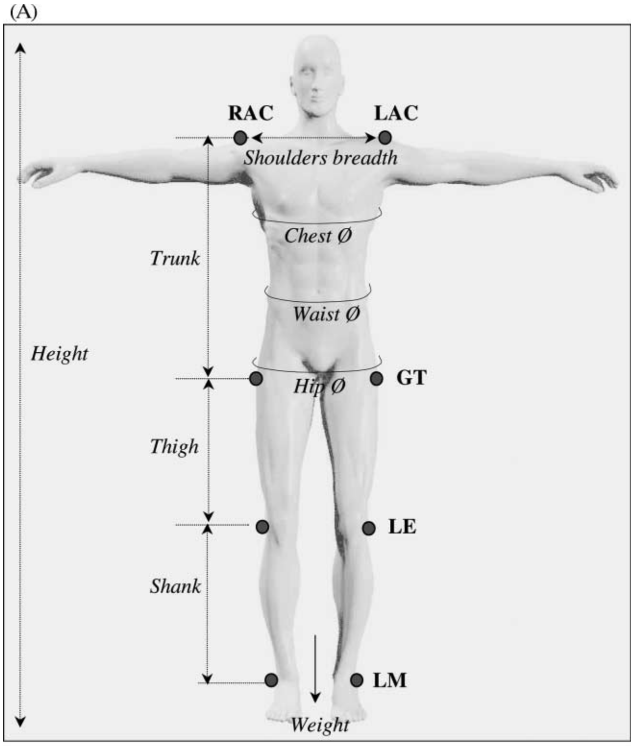
Results of two-sample t-test between BF of males and females are shown in the last column.

[a] $^*P < 0.01$; $^{**}P < 0.001$ (two-tail).

[b] BMI = weight (kg)/(height (m))^2.

waist and hip girth were measured. Body height was measured by a fixed wall height measure, and weight was computed from the vertical component of the ground reaction vector. The anatomical landmarks and anthropometric measurements mentioned so far are represented in Fig. 1A.

As part of the stabilometric experiment, before balance testing, subjects were requested to self-select a side-by-side feet position on the force platform and to stand quietly. All subjects were unshod and their foot size and placement were measured by means of footprints, traced on squared paper immediately prior to the acquisition. Foot anthropometry was assessed by foot length (FL), measured as the length of the segment joining the distal end of the great toe to midpoint of the heel, and by maximum foot width (MFW), defined as the widest aspect of the foot, perpendicular to the former line. Relative foot placement was measured by the big toe distance (BTD), the inter-malleolar distance (IMD), and the distance of big toes from the line joining the heel extremities (effective foot length, EFL).



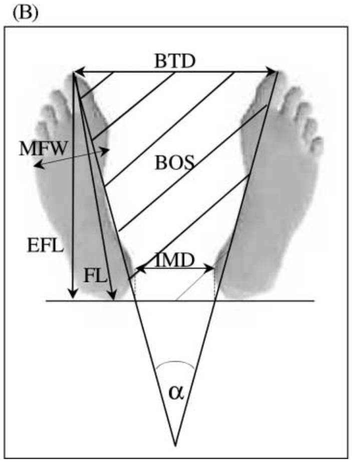


Fig. 1. BF—(A) anthropometric measurements and anatomical landmarks. LAC: left acromion; RAC: right acromion; GT: greater trochanter; LE: lateral epicondyle; LM: lateral malleolus. (B) Base of support measurements from the footprints. Foot anthropometry measures: foot length (FL) and maximum foot width (MFW). Foot position measures: big toe distance (BTD), inter-malleolar distance (IMD), effective foot length (EFL). Computed measures: base of support area (BoS) and feet opening angle (α).

By making some simplifying assumptions, an estimate of the base of support area (BoS) and of the feet-opening angle (α) was achieved with the following equations:

$$\mathrm{BoS} = \frac{\mathrm{BTD} + \mathrm{IMD}}{2}\mathrm{EFL} \tag{1}$$

$$\alpha = 2\,\mathrm{atan}\left(\frac{\mathrm{BTD} - \mathrm{IMD}}{2\mathrm{EFL}}\right) \tag{2}$$

Measurements taken from the base of support are represented in Fig. 1B. All the values of the BF obtained from the population under study are summarized in Table 1. Foot morphology and lower limb axial alignment were not assessed in the present protocol. They could be considered in future studies in order to establish their influence on overall body balancing.

2.3. Stabilometric test

Postural sway was measured for 50 s while subjects stood on a strain-gauge force platform (mod. 4060-08, Bertec Corporation, Columbus, OH, USA). They were instructed to maintain an upright standing position, with arms at their sides, EO with gaze straight ahead at a 2 m far achromatic target (a 5 cm diameter circle), or EC. Subjects' sway-in-stance was quantified in two trials for EO and two for EC. Between each trial the subjects were allowed to rest and sit down, but the foot position remained the same as the footprint for all the four trials. In order to avoid any kind of 'learning' or fatigue effect (see [9]), only the first valid trial in each condition was then retained in the analysis. The three force and three moment components were recorded from the force plate at 200 Hz. Subsequently, data were filtered at 8 Hz (by a 30th order low-pass FIR filter with zero-phase) and down-sampled at 20 Hz.

The outputs of the force platform allow to compute the CoP time series in AP and ML directions. A 2D representation of body balancing can be obtained by plotting the AP as a function of the ML CoP displacements. Representative curves are shown in Fig. 2.

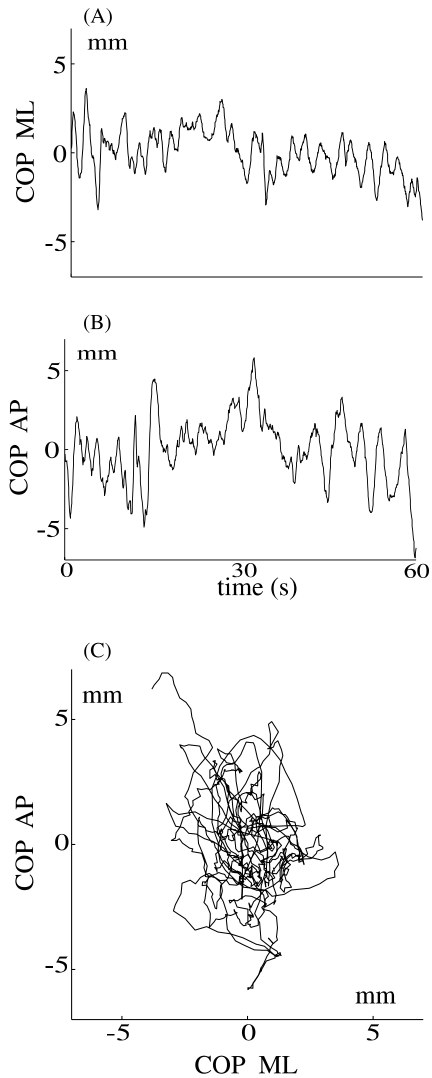


Fig. 2. Representative CoP displacement. (A) Mono-dimensional time series in ML direction. (B) Mono-dimensional time series in AP direction. (C) 2D CoP trajectory in the horizontal plane.

2.4. Postural parameters

Seventeen parameters were computed from each of the two components of CoP displacement, and from the 2D (distance) time series (see [3]). In addition, three measures of area and one estimate of principal sway direction were quantified from the joint use of AP and ML time series. This takes to a total of fifty-five parameters, of which thirty-seven can be classified as *summary statistic scores*, and eighteen come from *stochastic* property models of the CoP time series [5,6].

2.4.1. Summary statistic scores

This kind of parameter is the most commonly used in the clinical practice, being easy to use and computationally undemanding. The full list of the summary statistic scores computed throughout this paper is reported in the first section of Table 2 [3,18]. All these scores taken per se have some limitations since they are univariate descriptors of body sway and do not aim at evaluating the structural properties of CoP. In addition, it is unreasonable to think that the whole set of 37 parameters is needed to characterize the properties of body sway. Nonetheless, few authors have tried so far to select a subset of non-redundant and complementary features [3].

2.4.2. Stochastic parameters

CoP displacements during standing display a fractal behavior [19], entailing the presence of a relationship between the value of a statistical property and the time scale at which it is measured (*scaling relationship*). After Collins and De Luca [4], who characterized the fractal properties of CoP time series during quiet stance by a framework of Brownian motions, two modes of postural control are usually looked for in the range 0.01–10 s: open-loop (short term) and feedback (long term).

In the present study we consider a modification of the original Collins and De Luca technique, with improvements in the parameter estimation procedure that increased parameter reliability [5]. The four parameters of this model, computed after stabilogram diffusion analysis, can be estimated from the AP, ML, and 2D time series, for a total of twelve parameters. Moreover, we compute the two parameters from another model [6] that describes with continuity the transitions among the different scaling regimes found in CoP time series. Considering the parameters along each dimension, their total number is six.

The full list of the stochastic parameters is reported in the second section of Table 2.

2.5. Statistical analysis

The first step of the analysis aimed at identifying the more important sources of variation from the large number of BF that were measured. By means of principal component analysis (PCA) and multivariate procedures a subset of the original variables was selected, herein after named selected BF (SBF). Jolliffe [20] discusses several methods to reduce the number of variables in a data set while retaining most of the variability. We adopted the method outlined as follows:

- perform a PCA on the correlation matrix;
- retain the k most important factor scores, with k chosen by the rule of an eigenvalue cut-off of 1;
- the k factor scores are involved in a multivariate variable selection procedure [21] with the original variables as the independent variables, to find the best subset of the original variables that predicts the group of factor scores.

As a second step we investigated the presence of linear relationships between the stabilometric parameters

Table 2
Stabilometric parameters

Acronym	Description	EO Mean (SD)	Gender effect[a]	EC Mean (SD)	Gender effect[a]
Section I—summary statistic scores [3,20]					
Time-domain parameters					
MD	◆ Mean distance from center of CoP trajectory (mm)	4.1 (1.6)	–	4.6 (1.8)	–
RMS	◆ Root mean square of CoP time series (mm)	4.7 (1.8)	–	5.3 (2.0)	–
SP	◆ Sway path, total length of CoP trajectory (mm)	347 (93)	AP†	470 (141)	2D† AP*
RANGE	◆ Range of CoP displacement [mm]	23.7 (8.7)	–	28.0 (10.2)	–
MV	◆ Mean velocity (SP/T[b]) (mm/s)	6.9 (1.9)	AP†	9.4 (2.8)	2D† AP*
$\|90° - Mdir\|$	Angular deviation from AP sway (degree)	23.9 (23.6)	–	14.8 (13.7)	–
CCA	Area of the 95% confidence circle (mm^2)	227 (191)	–	287 (225)	–
CEA	Area of the 95% confidence ellipse [mm^2]	176 (132)	–	244 (199)	–
SA	Sway area, computed as the area included in CoP displacement per unit of time (mm^2/s)	9.1 (5.6)	–	13.9 (9.0)	–
MF	◆ Mean frequency, i.e. the number, per second, of loops that have to be run by the CoP, to cover a total trajectory equal to SP ($MF = SP/(2\pi^* MD^* T)^b$) (Hz)	0.30 (0.10)	-	0.35 (0.10)	2D* AP**
Frequency-domain parameters					
TP	◆ Total power (mm^2)	1192 (1009)	–	2160 (1383)	–
$f50$	◆ Median frequency, frequency below which the 50% of TP is present (Hz)	0.39 (0.10)	–	0.39 (0.08)	2D†
$f95$	◆ 95% power frequency, frequency below which the 95% of TP is present (Hz)	1.37 (0.31)	2D* AP**	1.40 (0.32)	2D** AP**
CF	◆ Centroidal frequency (Hz)	0.61 (0.13)	2D† AP*	0.60 (0.14)	2D** AP*
FD	◆ Frequency dispersion [–]	0.77 (0.05)	2D†	0.77 (0.04)	–
Section II—stochastic parameters [5,6]					
Hs	◆ Short-term scaling exponent (–)	0.85 (0.06)	–	0.88 (0.05)	–
Ks	◆ Short-term diffusion coefficient (mm^2)	1.42 (0.36)	–	1.76 (0.32)	–
Hl	◆ Long-term scaling exponent (–)	0.24 (0.11)	–	0.09 (0.11)	2D* AP†
Kl	◆ Long-term diffusion coefficient (mm^2)	1.0 (0.32)	–	1.41 (0.30)	–
K	◆ Diffusion coefficient (mm^2)	13.7 (9.9)	–	24.2 (15.4)	–
Δt_c	◆ Time lag corresponding to a pure random motion (s)	0.37 (0.26)	–	0.29 (0.24)	2D* AP**

Acronym, brief description, and values obtained from the 2D CoP time series of the entire population are presented for both the experimental conditions: EO and EC. All frequency-domain measures were calculated in the range 0.15–5.0 Hz. Results of two-sample t-test between values of the parameters in males and females are shown for both visual conditions. 2D, AP and ML denote whether the gender effect is not negligible along the corresponding component of CoP displacement.

◆ Parameters extracted also from the AP and ML time series.

[a] Two sample t-test between gender groups: $^{\dagger}P < 0.05$, $^{*}P < 0.01$, $^{**}P < 0.001$.

[b] Duration of the trial (in seconds).

and the SBF determined so far. This was done by means of maximum-likelihood robust regression techniques [22] that provide an alternative to least squares regression. These techniques work with less restrictive assumptions and down-weight the possible influence of outliers. Correlation was assumed significant when $P < 0.01$.

Differences between BF and stabilometric parameters in the two gender groups and in each visual condition were determined by using t-tests with parametric or non-parametric methods when appropriate. Differences were assumed significant when $P < 0.05$. All statistical procedures were performed with NCSS [23].

2.6. Normalization procedure

Normalization aims at removing the dependence of stabilometric parameters on SBF. The solution that we adopt here, originally proposed by O'Malley for temporal-distance parameters of gait [24], involves the removal of linear trends and has the advantage of retaining the original units. The estimated regression model is subtracted from the original values of the parameters and the mean value of original data is added, in order to keep the data in the same range.

3. Results

3.1. Anthropometric and foot placement measurements

The effect of gender on BF is documented in Table 1. All anthropometric measurements but 'Thigh' are significantly larger in males than females, corresponding to larger body size ($P < 0.001$, except 'Hip girth', $P < 0.01$). The choice of the relative foot placement, as indicated by the IMD, is on the contrary very similar in the two groups. The other base of support measurements also shows larger values in males though the high percent standard deviation (up to 50% of the mean values) within groups keeps $P > 0.001$ for both BoS and stance angle α.

3.2. Stabilometric parameters

The mean values and standard deviations (SD) of the stabilometric parameters in each visual condition are reported in Table 2, together with the results of the *t*-test comparisons between the two gender groups.

3.2.1. Summary statistic scores

Eye closure increases the greater part of the time-domain summary statistic scores and makes the sway direction more straight ahead, being the deviation from AP sway ($|90° - MDir|$) lower in EC than EO condition. Very few differences were found between the two gender groups with EO. Only sway path and mean velocity in the AP direction are slightly gender-sensitive ($P < 0.05$). In the EC condition both the 2D and the AP value of sway path, mean velocity, and mean frequency are gender-sensitive. Parameters estimated from the ML time series never differ between males and females.

Apart from EC total power that is almost twice the EO value, all the other EC frequency-domain parameters remain unchanged. In this domain the effect of gender is evident for nearly all 2D and AP parameters. Unlike time-domain parameters, this is true also in the EO condition.

3.2.2. Stochastic parameters

The effect of vision on the stochastic parameters is shown in the second section of Table 2. This is consistent with previous results [5,6] and shows that all the parameters but the short-term scaling exponent are affected by vision. A difference between genders appears only with EC involving the 2D and AP values of both the long-term scaling exponent from the piecewise linear model and the characteristic time-lag from the continuous model.

3.3. Feature selection

Principal Component Analysis allowed the four main factors to be identified that alone explained 84% of the total variance in the BF and that are a linear combination of the original variables. Hence, the four factor scores resulting from PCA could be replaced, after the multivariate variable selection procedure, by five of the original variables, namely 'height', 'weight', BoS, MFW and α. This defines the subset of SBF.

3.4. Regression analysis

Only nine out of the thirty-seven summary statistic scores and two out of the 18 stochastic parameters were immune from a linear dependence on SBF, both in EO and EC conditions, as shown in Tables 3 and 4. As a general remark it can be noted that eye closure introduces or strengthens the linear dependence of the majority of stabilometric parameters on SBF.

3.4.1. Time-domain parameters

Seven time-domain summary statistic scores are independent of SBF in both visual conditions. They include three 'distance' measures: mean distance, mean distance AP, and root mean square AP; two 'area' measures: areas of the 95% confidence circle and ellipse; the sway direction, and the frequency that ML sway would have if it traveled sinusoidally. Both sway path and mean velocity, along all the components, are strongly related to 'height' and 'weight', with r that is up to 0.7 ($P < 0.001$). Most of the ML parameters are affected by BoS with a negative correlation, i.e. any increases in the support area reflect in a decrease in the parameter. Only a subset of the ML parameters, with EC, is affected by MFW, although to a smaller degree than by BoS. The influence of α is quite marginal and plays a role only with EC. An increase in α is associated to a decrease in root mean square and an increase in AP mean frequency.

3.4.2. Frequency-domain parameters

Two frequency-domain summary statistic scores are independent of SBF in both visual conditions: median frequency and AP frequency dispersion. As regards the properties of power spectral densities, total power is only (positively) related to 'height', AP total power is related to 'height' and 'weight' in EC, and ML total power is (negatively) related to BoS and MFW, both with EO and EC. Median frequency and frequency

Table 3
Robust regression analysis

		Height						Weight						BoS						MFW						α					
		EO			EC			EO			EC			EO			EC			EO			EC			EO			EC		
		r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1
Time-domain parameters	MD																														
	MD_{AP}																														
	MD_{ML}	0.38*	-3.0	0.029	0.41*	-4.1	0.04							-0.47**	2.87	-0.003	-0.47**	3.32	-0.003				-0.36*	4.77	-0.31						
	RMS																												-0.37*	6.56	-0.07
	RMS_{AP}																														
	RMS_{ML}				0.42*	-5.2	0.05							-0.48**	3.64	-0.004	-0.48**	4.15	-0.01				-0.37*	6.08	-0.39						
	SP	0.48**	-334.3	3.99	0.59*	-673.7	6.67	0.43*	193.08	2.27	0.52**	203.4	4.05																		
	SP_{AP}	0.39*	-92.9	1.94	0.70**	-691.0	6.05	0.44*	137.68	1.51	0.67**	70.1	4.22																		
	SP_{ML}	0.47**	-239.4	2.53	0.37*	-277.4	2.95							-0.38*	252.85	-0.21	-0.39*	330.90	0.32												
	RANGE	0.37*	-23.8	0.27	0.38*	-26.2	0.31																								
	$RANGE_{AP}$				0.38*	-24.3	0.27																								
	$RANGE_{ML}$				0.36*	-18.6	0.19							-0.50**	20.30	-0.024	-0.52**	22.20	-0.26				-0.44*	34.52	-2.26						
	MV	0.48**	-6.7	0.079	0.59**	-13.5	0.13	0.43*	3.86	0.045	0.52**	4.1	0.08																		
	MV_{AP}	0.39*	-1.9	0.038	0.70**	-13.8	0.12	0.44*	2.75	0.03	0.67**	1.4	0.08																		
	MV_{ML}	0.47**	-4.8	0.050	0.37*	-5.5	0.06							-0.38*	5.06	-0.004	-0.39	6.62	-0.01												
	|90°-*MDir*|																														
	CCA																														
	CEA																														
	SA	0.36*	-18.9	0.157	0.49	-41.5	0.32																								
	MF																						0.41*	-0.02	0.04						
	MF_{AP}										0.47**	0.1	0.004				0.37*	0.24	0.0004										0.46**	0.26	0.01
	MF_{ML}																														
Frequency-domain parameters	TP	0.36*	-3120.8	24.22	0.46	-6263.0	47.90																								
	TP_{AP}				0.58	-16246.6	117				0.45**	-642.0	62.1																		
	TP_{ML}													-0.49**	2021.40	-3.45	-0.55**	3828.50	-6.90	-0.38*	3354.74	-267.80	-0.46**	6375.70	-531.8						
	f50																														
	$f50_{AP}$																			0.38*	0.15	0.02									
	$f50_{ML}$				0.48	-0.9	0.01							0.61**	0.16	0.001															
	f95	0.36*	-0.2	0.009	0.39	-0.4	0.01				0.60**	0.6	0.01	0.51**	0.98	0.001				0.36*	0.53	0.09	0.47**	0.11	0.14						
	$f95_{AP}$	0.62**	-1.4	0.016				0.59**	0.58	0.010	0.54**	0.5	0.01							0.66**	-0.44	0.18									
	$f95_{ML}$	0.44*	-0.6	0.010	0.43	-0.3	0.01							0.45*	0.83	0.001	0.42*	0.96	0.0008												
	CF										0.52**	0.3	0.004	0.55**	0.44	0.001							0.43*	0.10	0.05						
	CF_{AP}	0.54**	-0.4	0.006				0.58**	0.31	0.004										0.60**	-0.09	0.07	0.40*	0.14	0.04						
	CF_{ML}													0.61**	0.29	0.001															
	FD																			0.44*	0.61	0.02									
	FD_{AP}																														
	FD_{ML}													-0.48**	0.85	0.0003															

Summary statistic scores (time and frequency domain) vs anthropometric and foot placement measurements. When correlation is significant (at a P level of 0.01) the correlation coefficient, r, and its P value are reported. The corresponding parameters of the regression model are listed: a_0, offset; a_1, slope.
$^*P < 0.01$. $^{**}P < 0.001$.

Table 4
Robust regression analysis

Stochastic parameters	Height						Weight					
	EO			EC			EO			EC		
	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1
Hs												
Hs_{AP}												
Hs_{ML}												
Ks	**0.42***	-1.0	0.014	**0.55****	-0.9	0.02						
Ks_{AP}	**0.38***	-1.1	0.013	**0.59****	-1.4	0.02				**0.45****	0.9	0.01
Ks_{ML}	**0.36***	-1.3	0.014	**0.41***	-1.6	0.02						
Hl							**0.47****	0.03	0.003			
Hl_{AP}												
Hl_{ML}												
Kl				**0.58****	-1.4	0.02						
Kl_{AP}				**0.60****	-1.6	0.02				**0.44***	0.6	0.01
Kl_{ML}												
K				**0.52****	-85.5	0.63						
K_{AP}				**0.48****	-52.1	0.39				**0.41***	-1.0	0.23
K_{ML}												
Δt_c												
$\Delta t_{c\,AP}$												
$\Delta t_{c\,ML}$												

Stochastic parameters	BoS						MFW						α					
	EO			EC			EO			EC			EO			EC		
	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1	r	a_0	a_1
Hs	**-0.38***	0.92	-0.0002	**-0.47****	0.94	-0.0002	**-0.47****	1.09	-0.025	**-0.55****	1.08	-0.02						
Hs_{AP}							**-0.37***	1.06	-0.02	**-0.42***	1.06	-0.02						
Hs_{ML}	**-0.53****	0.96	-0.0002	**-0.57****	0.96	-0.0002	**-0.47****	1.07	-0.02	**-0.46***	1.07	-0.02						
Ks							**-0.37***	2.47	-0.11									
Ks_{AP}																		
Ks_{ML}	**-0.49****	1.60	-0.002	**-0.52****	1.92	-0.002	**-0.43***	2.46	-0.15	**-0.37***	2.54	-0.14						
Hl							**0.41***	-0.09	0.03									
Hl_{AP}										**-0.36***	0.46	-0.04				**-0.37***	0.18	-0.004
Hl_{ML}																		
Kl	**-0.49****	1.43	-0.001				**-0.42***	2.11	-0.12									
Kl_{AP}																		
Kl_{ML}				**-0.67****	1.66	-0.0026												
K																		
K_{AP}																		
K_{ML}				**-0.50****	14.44	-0.025				**-0.43***	24.78	-2.06						
Δt_c										**-0.36***	0.69	-0.05						
$\Delta t_{c\,AP}$										**-0.44***	1.02	-0.08						
$\Delta t_{c\,ML}$																		

Stochastic parameters *vs* anthropometric and foot placement measurements. When correlation is significant (at a P level of 0.01) the correlation coefficient, r, and its P value are reported. The corresponding parameters of the regression model are listed: a_0, offset; a_1, slope.

$^{*}P < 0.01$. $^{**}P < 0.001$.

dispersion, computed from 2D, AP, and ML components of CoP displacement, are only slightly associated with SBF. On the contrary, 95% power frequency and centroidal frequency, that estimate signal bandwidth and frequency distribution, are largely dependent on SBF with the only exception of α. The largest values of r, up to $r = 0.66$ ($P < 0.001$), are encountered in the AP components.

Unlike what happens in the time-domain, BoS and MFW influence also the 2D components of the majority of the parameters in the frequency-domain. Moreover, MFW plays a significant role also with EO. The frequency-domain parameters are positively correlated with all SBF, excluding total power and frequency dispersion with respect to base of support measurements.

3.4.3. Stochastic parameters

Table 4 shows the results of the robust regression analysis between SBF and the parameters estimated by Brownian motion modeling of the CoP path. The two stochastic parameters immune from linear correlation are both computed from the ML component. The short-term parameters of the piecewise linear approach [5] are well (negatively) related with base of support measurements (BoS and MFW). 'Height' reflects positively on the short-term diffusion coefficient along each component. The effects of 'weight' and α are fairly marginal. In the long-term the dependence on 'height' is completely absent with EO. Long-term scaling exponent is moderately linked to SBF even if its AP estimate is one of the few parameters that are affected by feet opening angle. It is common to the two scaling exponents the nearly absolute independence from 'height' and 'weight'.

As regards the parameters of the continuous approach [6] they are never prone to SBF dependence with EO. Only eye closure introduces a positive correlation between the diffusion coefficients (2D and AP) and 'height' and 'weight'. Similarly, a negative correlation is found between ML diffusion coefficient and time lags (2D and AP), and the BF BoS and MFW.

3.5. Normalization

An example of the correlation found between SBF and stabilometric parameters is shown in Fig. 3A. Here the scatter plot illustrates the high collinearity between 'height' and the EC values of mean velocity in the AP direction. The maximum-likelihood linear model is also shown and the goodness of fit is well evident ($r = 0.7$, $P < 0.001$). The detrending normalization [24] leads to new values of the stabilometric parameter where the effect of SBF is removed, as well documented by Fig. 3B.

4. Discussion

4.1. Selected biomechanical factors

The output of the feature selection process performed on the whole set of BF measured in this study shows that only few variables are needed to characterize the morphology and stance of subjects and should be primarily considered in any experimental acquisition protocols. Two of them are relevant parameters of any inverted pendulum models of the body ('height' and 'weight'). The remaining three describe the body interface with the ground, in particular its size and geometry (MFW, BoS, α). Hence, there is no evident redundancy between anthropometric properties and size and geometry of the base of support. Rather, they should be considered in conjunction. This result is consistent with the findings of Kirby et al. [14] and highlights the importance of measuring also foot position, in order to address all the major biomechanical characteristics of the body while standing.

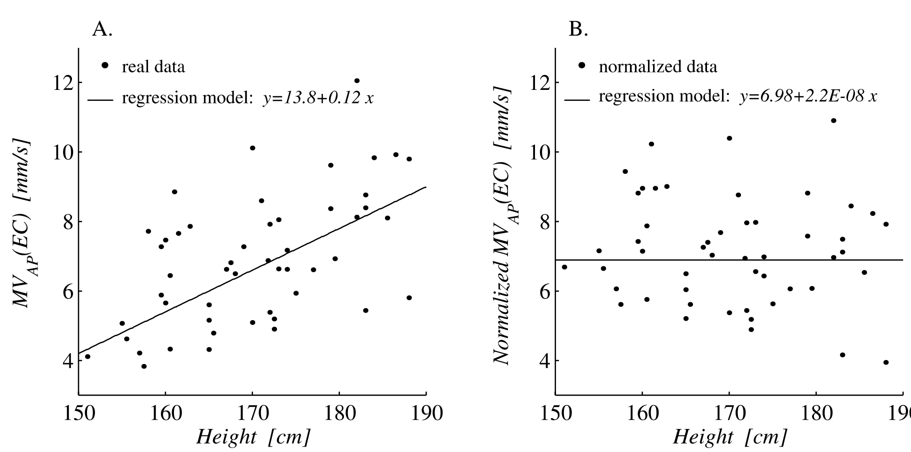


Fig. 3. Example of a stabilometric parameter that highly correlates with one of the selected BF. AP mean velocity recorded in EC condition vs height: (A) before normalization; (B) after normalization. $^{**}P < 0.001$.

4.2. Influence of biomechanical factors on stabilometric parameters

It is well evident from the results shown in Tables 3 and 4 that the selected BF affect most of the more commonly used stabilometric parameters, including new-generation stochastic parameters. In short, parameters could be classified as (see Table 2 for acronyms):

- 'heavily dependent' on SBF. Here the effect of SBF is detectable both with EO and EC and r mostly exceeds 0.45. In particular, we mention SP, MV, $f95$ and CF along all components, and MD, RMS, RANGE, and TP on the ML direction. Among the stochastic parameters we cite Kl and all the short-term parameters of the piecewise linear model [5] but Hs_{AP}. None of the parameters of the continuous model [6] lies in this group.
- 'moderately dependent' on SBF. There is some dependence on SBF but (1) only in one visual condition, or (2) there is a dependence on more than one SBF, with r always below 0.45. In this group we can include RANGE, $f50_{ML}$, $f95_{ML}$, CF_{ML}, FD_{ML}. Among the stochastic parameters we cite all the long-term parameters of the piecewise linear model [5] but Kl and Hl_{ML}, and all the components of K of the continuous model [6].
- 'almost independent' of SBF. (1) There is no dependence at all, or (2) there is a dependence but on only one SBF, with r always below 0.45. The parameters completely immune from SBF were already mentioned in the Results' section. In particular, the statistical models, which are used to estimate the area of the CoP path based on 95% confidence limits, can explain the robustness of CCA and CEA to SBF. We also mention here RMS, $RANGE_{AP}$, MF, $f50_{AP}$, and FD. It is worth noting that all the components of the characteristic time proposed in [6] lie in this group.

The regression analysis showed that the parameters quantifying the amount of the oscillation (as the sway path, mean velocity or RANGE) are strongly dependent on 'height' (and in part on 'weight'), and this correlation reinforces with EC. This influence propagates to the spectral properties of the CoP signals and is reflected by the values of the total power, and, among the stochastic parameters, by the diffusion coefficient of the short-term scaling region. According to the values of r, the planar component of CoP seems the more SBF-dependent with EO, whereas this primacy goes to the AP component with EC. Hence, for this kind of parameters the hypothesis of normalizing to 'height' should be seriously considered.

The negative correlation found between parameters quantifying the ML amount of the oscillation and base of support measurements can be explained taking into account the biomechanical properties of the body. In fact, the ankle joint mobility in the frontal plane is reduced with feet apart [14], enhancing the relative role of the AP component in body sway. The absence of correlation between the 2D composite parameters and the base of support measurements confirms that 2D measures should be preferred when the placement of the feet on the force plate is not constrained [3].

Interestingly, also the frequency-domain parameters describing the signal bandwidth correlate with BoS, but positively. This may be due to the need of more postural adjustments when BoS is small in order to avoid reaching stability limits. These adjustments are characterized by lower frequencies since they involve the slow motion of the center of mass [2]. It was shown in the literature that widening foot position changes the relationship of the body center of mass relative to the limits of stability of the feet, and increases the passive stability of the musculoskeletal system [25]. In particular, in response to horizontal translations of the support surface such an increase in biomechanical stiffness was associated to a decrease in active neural control [25]. Hence, the wider the stance the less the control activity.

Vision has a clear effect on the correlation between parameters and BF. This correlation is typically higher with EC than with EO, and can be interpreted as a major influence of body biomechanics on postural sway upon eyes closure. In this condition the inertial properties of the body, dependent on 'height' and 'weight', may become preponderant because of the removal of the visual afferent input to the postural control system. In fact, the loss of visual input has been shown to force, in most subjects, an increase in muscle stiffness [6].

A different result was obtained for parameters in the frequency-domain, whose correlation with base of support measurements is positive and frequently stronger with EO than EC. The contribution of the visual feedback to spectral properties makes most of these parameters linearly dependent on BoS and MFW. With this regard, the results obtained by Day et al. [15] emphasize the role of the proprioceptive input from the feet and the legs when stance width and geometry are altered. They suggested that stance widening acts to strengthen the coupling between ankles and hips and this increases the proprioceptive sensitivity to lateral motion. In this light, receptors in the head (including vision) become less important when BoS and MFW are larger and hence the biomechanical coupling comes to light.

Finally, two considerations can be made about stochastic parameters. The parameters derived more closely from the Collins and De Luca theory [5] are moderately correlated with selected BF. In particular, the short-term parameters are negatively correlated with base of support measurements (BoS and MFW). 'Height' and 'weight' influence the actual diffusion coefficients, especially with EC. Parameters from the continuous model [6] are totally robust to the influence of BF with EO, showing no correlation at all. In this light, these parameters seem to be sensitive only to the action of the postural control system and to the postural strategy used by the subjects. The correlation emerges with EC, when the diffusion coefficient behaves very similarly to the time-domain summary statistic scores. In fact it correlates positively with 'height' and 'weight' while its ML component correlates negatively with base of support measurements.

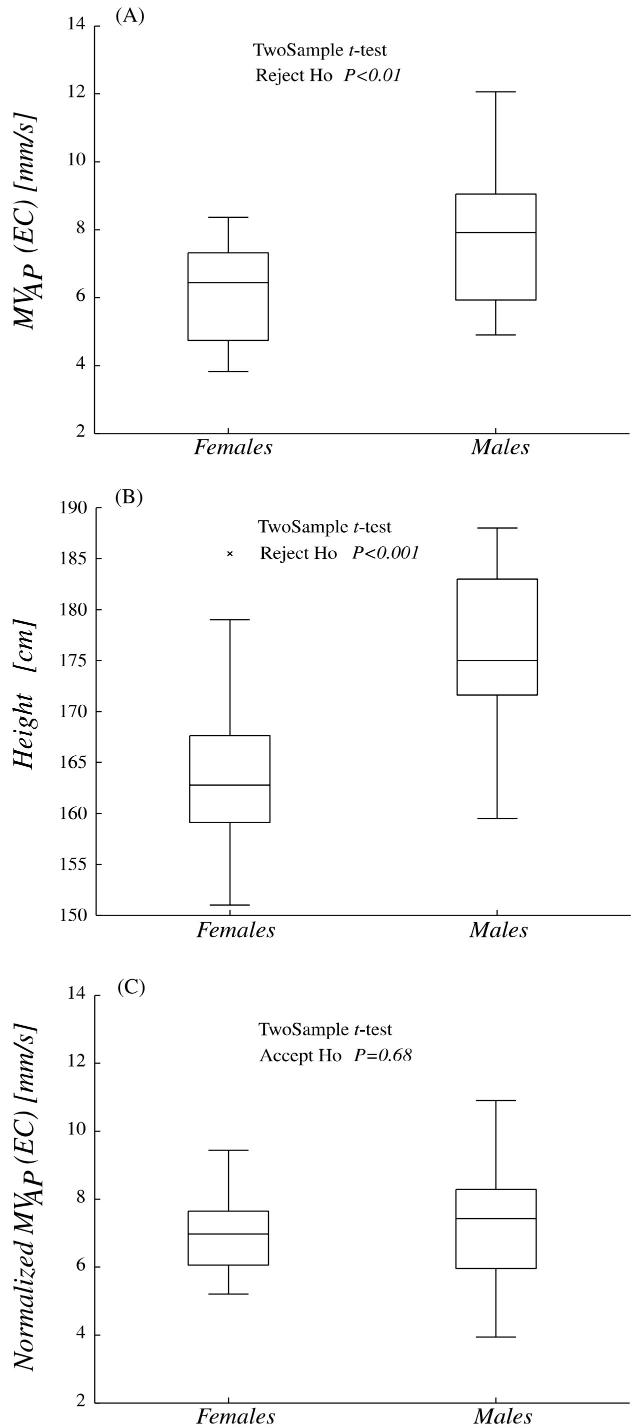


Fig. 4. Effect of normalization on the results of two sample *t*-test between the two gender groups. (A) AP mean velocity, EC condition, before normalization. (B) Height. (C) Same as in (A), after normalization: the significant difference between gender groups has vanished.

4.3. The relevance of normalization in the investigation of postural strategies

Fig. 3B reports the new set of values of the AP mean velocity after normalization. Some of the beneficial effects of such normalization procedure can be exploited by looking at the paradigmatic example of Fig. 4. Here (see Fig. 4A) the differences of the parameter found in males and females could be interpreted as a difference in the control strategy due to gender (mean velocity has been associated with the amount of the regulatory activity put into play by the postural control system [26]). Nevertheless, as shown in Table 1 and sketched in Fig. 4B, one should consider that 'height' is a major anthropometric determinant between genders. Normalization confirms that the result obtained previously was only due to the influence of such BF and to the lack of a scaling of the stabilometric parameter to body size (see Fig. 4C).

Hence, most of the effects of gender on the stabilometric parameters are, as a matter of fact, the fruits of difference in the biomechanical properties of the 'plant' rather than in the postural control system. This propagation of BF to stabilometric measures should be convincing of the opportunity to normalize these measures. Normalized values of the parameters that have been shown to be dependent on BF seem more suitable for further use in the analysis of postural strategies or for the quantification of postural performance across subjects.

5. Conclusion

The results reported in the present study show that care should be taken, in perspective, when quantifying postural sway through CoP-based measures. In fact here a non-trivial dependence with BF comes to light and it is suggested as a good norm to include some anthropometric measurements in any experimental protocols (e.g. height, weight, maximum foot width), and to standardize or control foot position. The linear dependence of CoP-based measures on the selected group of BF can explain up to 50% of variation of some parameters. For this reason the choice of a standardized foot placement and the measurement of the main anthropometric features could help in data interpretation and comparison among different subjects. Moreover, the regression equations identified might become informative about what we actually measure by these parameters. This remark involves also the stochastic parameters recently proposed in the literature, even if to different extents. Once more this is a confirmation that the control strategy they aim to describe cannot get rid of the physical properties of the body. Further investigation and a larger data-set would be necessary to better define the normalization procedures and extend them to different classes of subjects.

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