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CHARACTERISTICS OF AUTOCORRELATION STRUCTURE OF LOWER EXTREMITY FUNCTIONAL LATERALITY IN DISTURBED AND UNDISTURBED BIPEDAL UPRIGHT STANCE

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ABSTRACT
Purpose. It is posited that functional laterality is influenced by the generation and conduction of neural signals and therefore associated with sensorimotor control. The question arises if symmetry or asymmetry in sensorimotor processing affects the development of symmetric or asymmetric motor programs in the lower extremities. The purpose of the study was to examine the mechanisms of the human mobility moto-control – the process of maintaining body balance in a standing position through an appropriate course of distribution of ground reaction forces in a time frame, in a situation requiring lower extremity movement symmetry. **Methods.** The autocorrelation function was calculated for ground reaction forces (in the three orthogonal axes) registered during 45 s of bipedal upright stance in two conditions (eyes open and closed). **Results.** Minor albeit significant deficiencies in postural muscle control were revealed as a function of time, as evidenced in the decay of the autocorrelation function to zero (T_0) between the right and left foot for the mediolateral ground reaction force signal. However, the results attest to symmetrical sensorimotor control between both feet. **Conclusions.** Motor actions (postural corrections) performed in long-duration tasks may have less of an effect on sensorimotor control than those applied in shorter duration projections. ANOVA and correlation analysis (across all variables) of the right and left foot T_0 indicate considerable symmetry in the control of force magnitude and direction during upright standing.

Key words: symmetry, asymmetry, foot, force, balance, autocorrelation function

Introduction

While the external human body presents nearly identical reflection symmetry, even casual observation shows that there is a preference to use one side more than the other in even simple motor tasks [1]. Contemporary investigation on this neurophysiological phenomenon termed functional laterality has focused primarily on the relationships between functional and structural laterality and various aspects of motor performance [2–4]. However, while the literature is extensive, the multitude of available studies – with the overwhelming majority concentrating on the upper extremities – results partly from disparate findings across a wide range of protocols and methods assessing the magnitude [5, 6] and direction of lateralization. There is a paucity of research on lower limb laterality, particularly during movement activity in the context of measurements of ground reaction force (GRF) asymmetry.

Carlsson [7], Greengard et al. [8], and Kandel [9] have postulated that functional laterality is influenced in part by the generation and conduction of signals in the central nervous system and therefore constitutes a function of sensorimotor control. Nonetheless, little has been done to address this aspect and it is unknown if such symmetry or asymmetry in sensorimotor processing translates into the development of symmetric or asymmetric motor programs for both lower extremities.

One of the core motor processes involves the preservation of upright balance. This is because an erect vertical posture is inherently unstable and requires continual corrective action to negate falling [10]. As with all motor tasks, this process involves accumulating information from both the external environment and internal sensorimotor systems, processing it, and storing in various centres of the central nervous system [11]. This information is developed to form movement programs that overlap with intrinsic (proprioception and kinesthesia) and extrinsic (visual and auditory input) feedback and are then used to activate appropriate distal and proximal postural muscles. In the upright position, the interaction of these muscular corrections can be quantified by changes in the forces exerted by both feet on the ground [12, 13]. Measurable by GRFs, it can be assumed the magnitude of the relationship between the neurally-activated postural muscles and their respective body segments across time [14]. The resultant foot-ground reaction forces can be referenced in the three orthogonal axes in the Cartesian plane. While the vertical component of a GRF reflects upward thrust, the horizontal force components in the anteroposterior and mediolateral directions can be treated as the forces resulting from corrective actions. In recording the force development as a function of time (non-linear in nature), probability theory can be applied to determine the descriptive characteristics of the time series.

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One mathematical tool that is particularly valuable in time series analysis is the autocorrelation function, which can aid in trend estimation with the use of stationary or non-stationary time series data. If the time series data exhibit a trend, the autocorrelation function plot shows a slow decay pattern to the value of 0, whereas lack of predictable structure (randomness) in the time series will show a rapid decay in the autocorrelation function to 0. Therefore, the slower the decrease in the autocorrelation function, the less random the changes of the process as a function of time. In GRFs calculation, this would allow to deduce that the observed changes are primarily the result of internal control and not a random process.

It is posited that functional laterality is influenced by the generation and conduction of neural signals and therefore associated with sensorimotor control. The question arises if symmetry or asymmetry in sensorimotor processing affects the development of symmetric or asymmetric motor programs in the lower extremities. Therefore, there is a practical question contained in the description of the research purpose. The aim of the work was to examine the mechanisms of the human mobility moto-control – the process of maintaining body balance in a standing position through an appropriate course of distribution of GRFs in a time frame, in a situation requiring lower extremity movement symmetry. An additional objective was to analyse and describe changes in the process of maintaining body balance in conditions with and without visual feedback.

Therefore, to facilitate the understanding of the research problem complexity, a few support questions need to be asked:

1. What are the differences in motor behaviour based on T_0 when analysed as a time series of consecutive intervals (15-s)?

2. What are the associations of the mechanisms responsible for maintaining upright balance as evaluated by autocorrelation analysis within the entire duration of the standing task (45 s) and when analysed across consecutive time intervals (15-s)?

These questions lead to formulating the research problem: Is the mechanism of human behaviour – the moto-control of maintaining body balance in an upright position, with a symmetrical involvement of the lower extremities, evaluated by a proper distribution of GRFs for each of them – determined by a specified time interval throughout the course of the trial?

We postulated that the interpretation of such intermediate parameters can contribute to identifying the control mechanisms of postural response, particularly in regard to the occurrence of functional laterality.

Material and methods

Participants

An age-homogeneous sample of 102 university students (54 females and 48 males) was recruited. The mean age was 21.1 ± 1.1 years, height: 173 cm ± 0.10 cm, and body mass: 68.1 ± 13.1 kg. All individuals provided their written informed consent to participate in the study, and ethical approval was obtained. All procedures were performed at the Biomechanics Laboratory of the Opole University of Technology.

Measures

The study protocol involved measuring the GRF during two trials of bipedal upright stance over a period of 45 s. GRF data were synchronously collected on two 600 × 400 mm piezoelectric force platforms (type 9286B; Kistler Instruments AG, Winterthur, Switzerland) placed under each foot (Figure 1). Four tri-axial force sensors located in the corners of each platform quantified the GRF signal components in the mediolateral (F_x), anteroposterior (F_y), and vertical (F_z) directions at the sampling frequency of 480 Hz (measurement range, 10–20 kN). The force platforms were calibrated before usage and integrated with the BTS Smart optoelectric system (BTS Bioengineering, USA) to register the force-time characteristics.

Procedures

The first trial was performed in undisturbed conditions (eyes open), the second one with eyes closed. The net forces were normalized to the participants' body mass and expressed for the right and left foot. The autocorrelations from the ground force data were calculated with an algorithm [15] where $x(t)$ at time t and after time $t + \tau$ across the total observation period T is:

$$Rx(\tau) = lim_{T \to \infty} \tau 1/T \int_0 x(t)x(t+\tau)dt$$

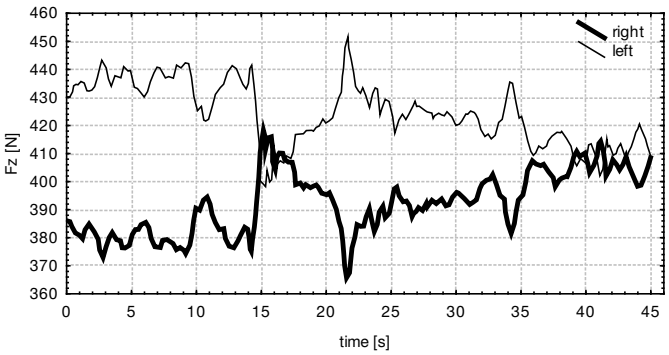

Figure 1. Exemplary plot of vertical ground reaction force (F_z) synchronized between the right and left foot force platforms

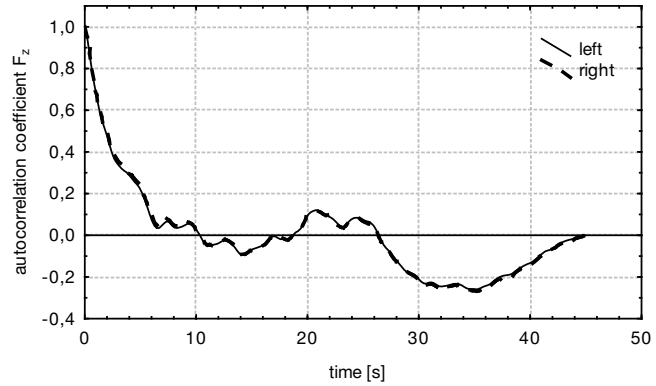

Figure 2. Exemplary plot of the autocorrelation function for right and left foot vertical ground reaction force (F_z) during the 45-s quiet standing task

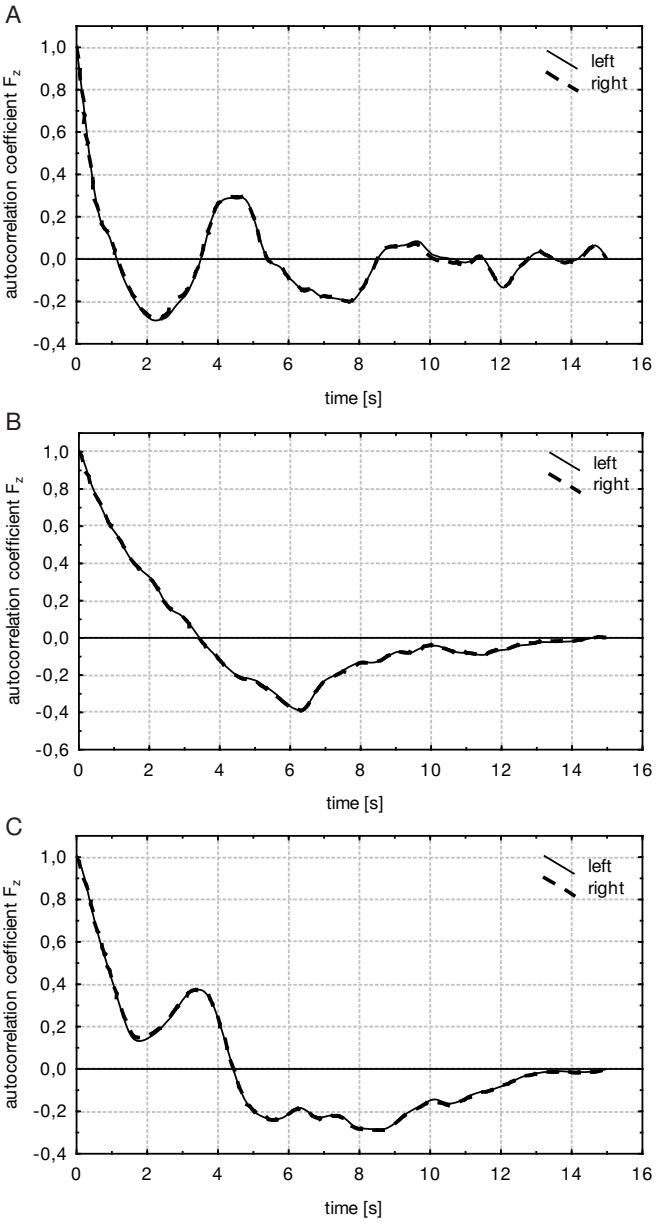

Figure 3. Exemplary plots of the autocorrelation function across the consecutive 15-s intervals: 0–15 s (A), 16–30 s (B), and 31–45 s (C)

The f(t) signal was defined as the continuous cross-correlation with itself but shifted by 1/48 s to represent the time delay of the signal. The parameter adopted to represent balance maintenance was the time elapsed from the moment of the initial observation, where the autocorrelation function was equal to 1, to the time when the value of 0 was reached (this time distance was herein adopted as T_0). T_0 was calculated for each 45-s trial duration (Figure 2) and also across three 15-s intervals: 0–15 s, 16–30 s, and 31–45 s (Figure 3).

Statistical analysis

Basic descriptive statistics were calculated (means ± standard deviations) for all measures. The distribution of the data set was screened for normality with the Shapiro-Wilk test. Repeated measures analysis of variance (ANOVA) was used to compare T_0 across the components of GRF in the total trial period and 15-s time intervals with regard to sex, visual condition, and right and left foot. Post-hoc analysis was performed with the least significant difference (LSD) test. Pearson's correlation coefficients were also determined to analyse the relationships among the variables. The significance level for all statistical procedures was set at $\alpha = 0.05$. Data processing was performed with the Statistica 9.0 software package.

Results

Testing the assumption of normality revealed the data to show a normal distribution. The ANOVA did not indicate any significant between-sex differences in T_0 for the right or left foot GRF. Hence, the data were analysed for the entire sample (n = 102) without considering sex as a factor.

T_0 in the total trial period (45 s) was approximately 3–4 times greater than that in any of the 15-s intervals. The difference was observed regardless of the GRF component (F_x, F_y, F_z) in both conditions (eyes open or closed) and feet (right or left) (Table 1).

The ANOVA revealed a significant difference in T_0 between the extracted time intervals in the anteroposterior and mediolateral components of GRF, as well as between the right and left foot in the mediolateral GRF. There were no significant interaction effects (Table 2).

Post-hoc comparisons of T_0 values among the 15-s intervals in the eyes closed condition revealed a decreasing trend across time in all the three GRF components for both right and left foot. Here, significant differences were observed primarily between the second (16–30 s) and third (31–45 s) time intervals (Table 3). An identical direction of change in T_0 was noted in the eyes open condition for the mediolateral component of GRF. Also in this condition, T_0 in the vertical GRF initially decreased only to attain a slightly higher value in the third time interval albeit lower than that in the first time interval. This trend was statistically significant in both the right

Table 1. Descriptive statistics of T_0 across the components of ground reaction force in the 45-s quiet standing task and three extracted 15-s intervals, in eyes open and closed conditions, for the right and left foot

	Force direction	Foot	Time intervals							
			0–45 s		0–15 s		16–30 s		31–45 s	
			$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*	$\bar{x}$	*SD*
Eyes open	Vertical	Right	8.53	5.12	2.42	1.67	2.01	1.53	2.12	1.68
		Left	8.70	5.08	2.41	1.67	1.99	1.51	2.12	1.69
	Mediolateral	Right	9.39	5.00	2.78	1.70	2.63	1.64	2.32	1.54
		Left	9.92	4.99	2.99	1.62	2.86	1.52	2.45	1.50
	Anteroposterior	Right	9.80	4.77	2.40	1.70	2.46	1.61	2.23	1.42
		Left	9.55	4.91	2.57	1.71	2.34	1.53	2.18	1.43
Eyes closed	Vertical	Right	8.90	5.40	2.20	1.72	2.21	1.66	1.78	1.44
		Left	8.83	5.39	2.23	1.73	2.22	1.65	1.77	1.43
	Mediolateral	Right	9.49	4.89	2.71	1.61	2.71	1.59	2.23	1.24
		Left	9.66	4.85	3.10	1.50	2.97	1.53	2.45	1.32
	Anteroposterior	Right	8.95	4.76	2.42	1.63	2.27	1.54	2.15	1.55
		Left	8.87	4.67	2.38	1.58	2.24	1.62	2.02	1.46

Table 2. Main effects and interactions of the trial duration (45 s), condition (eyes open or closed), foot (right or left), and ground reaction force for T_0

Ground reaction force	Main effect						Interaction							
	Condition		Duration		Foot		Condition × duration		Condition × foot		Duration × foot		Condition × duration × foot	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Vertical	0.75	0.3875	3.26	**0.0403**	0.03	0.8719	1.60	0.2042	0.66	0.4195	0.48	0.6209	0.40	0.6728
Mediolateral	0.04	0.8403	9.91	**0.0001**	17.70	**0.0001**	0.13	0.8771	1.31	0.2559	1.01	0.3666	0.46	0.6294
Anteroposterior	0.83	0.3647	2.08	0.1279	0.27	0.6071	0.02	0.9779	0.66	0.4198	1.52	0.2214	1.19	0.3070

Significant differences ($p \leq 0.05$) are denoted in bold.

Table 3. The significance of post-hoc LSD comparisons of T_0 across the components of ground reaction force between the three 15-s intervals of 0–15 s (I), 16–30 s (II), and 31–45 s (III)

	Eyes open						Eyes closed					
	Left foot			Right foot			Left foot			Right foot		
	I–II	I–III	II–III	I–II	I–III	II–III	I–II	I–III	II–III	I–II	I–III	II–III
Vertical	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.6853	**0.0000**	**0.0000**	0.6485	**0.0000**	**0.0000**
Mediolateral	0.1206	**0.0000**	**0.0000**	0.0742	**0.0000**	**0.0002**	0.1125	**0.0000**	**0.0000**	0.9310	**0.0000**	**0.0000**
Anteroposterior	**0.0206**	**0.0001**	0.1222	0.5389	0.0872	**0.0206**	0.1714	**0.0004**	**0.0280**	0.1374	**0.0078**	0.2336

Significant differences ($p \leq 0.05$) are denoted in bold.

and left foot. In terms of T_0 in the anteroposterior GRF, the left foot value decreased over the intervals but the right foot T_0 increased in the second time interval and then decreased. The difference between the second and third time intervals was statistically significant (Table 3; Figure 4).

Post-hoc comparisons of T_0 in the three GRF components for the eyes closed and open conditions revealed significant differences between the right foot and left foot across all time intervals in the mediolateral GRF in the eyes closed condition. In the eyes open condition, significant differences were attained only between the first and second time interval (Table 4).

Significant correlations were revealed between the right and left foot T_0 in all the three force directions for each time period (total trial and each 15-s interval)

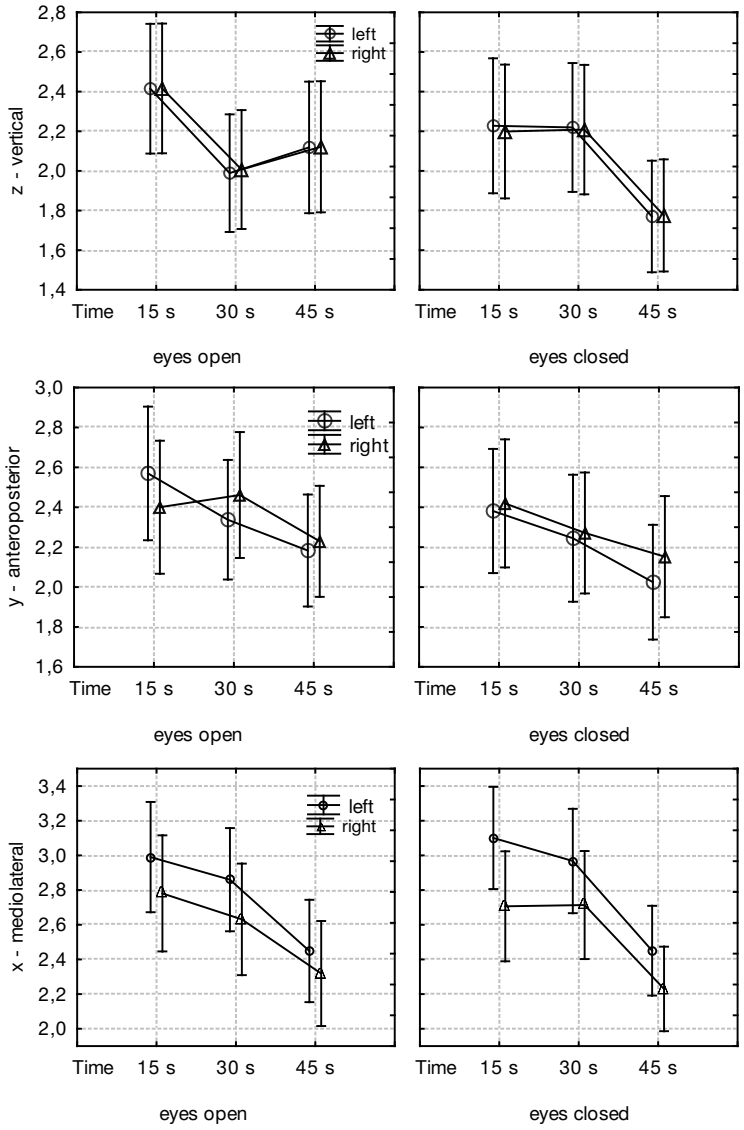

Figure 4. Means and confidence intervals (95% *CI*) of T_0 across the components of ground reaction force in eyes open and closed conditions

Table 4. The significance of post-hoc LSD comparisons of T_0 across the components of ground reaction force between the three 15-s time intervals in eyes open and closed conditions

	Eyes open			Eyes closed		
	0–15 s	16–30 s	31–45 s	0–15 s	16–30 s	31–45 s
Vertical	0.9415	0.3850	0.8811	0.1678	0.6024	0.7896
Mediolateral	0.0130	**0.0067**	0.1209	**0.0000**	**0.0027**	**0.0090**
Anteroposterior	0.0901	0.2144	0.6440	0.7001	0.7900	0.2001

Significant differences ($p \leq 0.05$) are denoted in bold.

Table 5. Correlations of T_0 across combined right and left foot ground reaction force components between the total trial period (45 s) and the three 15-s time intervals, in eyes open and closed conditions

Ground reaction force	Eyes open				Eyes closed			
	45 s	0–15 s	16–30 s	31–45 s	45 s	0–15 s	16–30 s	31–45 s
Vertical	0.948	0.988	0.967	0.999	0.992	0.995	0.997	0.982
Mediolateral	0.961	0.745	0.769	0.871	0.806	0.799	0.767	0.728
Anteroposterior	0.887	0.735	0.715	0.806	0.924	0.838	0.657	0.779

Significant differences ($p \leq 0.05$) are denoted in bold.

Table 6. Correlations of T_0 across the components of the right and left foot ground reaction force between the total trial period (45 s) and the three 15-s time intervals

Ground reaction force	Foot	Eyes open			Eyes closed		
		45 s / 0–15 s	45 s / 16–30 s	45 s / 31–45 s	45 s / 0–15 s	45 s / 16–30 s	45 s / 31–45 s
Vertical	Right	0.188	**0.400**	0.132	0.117	**0.457**	0.151
	Left	0.140	**0.403**	0.091	0.116	**0.473**	0.061
Mediolateral	Right	0.135	**0.229**	**0.214**	0.125	**0.364**	**0.221**
	Left	0.078	**0.281**	0.168	0.145	**0.279**	0.144
Anteroposterior	Right	0.189	**0.409**	0.005	0.024	**0.330**	0.106
	Left	0.177	**0.459**	0.068	0.023	**0.402**	0.113

Significant differences ($p \leq 0.05$) are denoted in bold.

in both the eyes open and closed conditions. The strongest correlation coefficients were found in the mediolateral GRF (Table 5).

The analysis of the correlative associations between T_0 in the total trial duration and the three 15-s intervals indicated a significant relationship only with the second interval (16–30 s) in both conditions (Table 6).

Discussion

The aim of the study was to examine the mechanisms of the human mobility moto-control – the process of maintaining body balance in a standing position through an appropriate course of distribution of GRFs in a time frame, in a situation requiring lower extremity movement symmetry.

In line with previous research [16, 17], the present study assumed that the maintenance of upright balance was guided by sensorimotor control mechanisms. Generally, these mechanisms are activated in the execution of a motor task by preprogrammed motor patterns [18]. It was hypothesized that the postural mechanics of upright stance might be statistically assessed by applying the autocorrelation function to determine the repeatability of balance maintenance measures as a function of time with regard to the motor primitive and motor control components. Such an approach could aid in clarifying the mechanisms underlying human motor control. At its core, the autocorrelation function can ascertain the dependencies of certain events (in this case, the magnitude of postural muscle correction forces) at a given moment in time from preceding and succeeding events. In this way, one can monitor the quality of postural control and therefore identify deficiencies that may affect daily living activities.

For the purposes of the study, the process of balance maintenance was considered within the time from the start of the trial, when the autocorrelation function was equal to 1, to the time when the value of 0 was reached (delineated as T_0). In this way, T_0 can serve as an indirect method of evaluating the sensorimotor control system via the forces exerted by the postural muscles to ensure a balanced stance. The autocorrelation function slowly decreasing to 0 would indicate that balance is well-coordinated (free of disturbance), whereas a rapid decay of T_0 would suggest uncoordinated balance, in which the right and left foot GRF would show large variation due to some unknown and/or random interference. To test this hypothesis, we included the deliberate application of a disturbed condition (eyes closed).

Comparisons of the autocorrelation function decrease to 0 across the various time intervals revealed very large differences between the total trial period (45 s) and the three extracted 15-s intervals. The T_0 in the 45-s trial was more than three times greater than the values reported in the literature for 10–15-s intervals of quiet standing [19] or the T_0 recorded in any of the 15-s intervals (Table 1). This may be explained by the fact that measures of force as a function of time predominantly show low-frequency trends of 0.1–0.2 Hz. These frequencies are not revealed in the 15-s intervals as they are omitted owing to the short measurement projection. However, this explanation does not translate into the sensorimotor control aspect of balance preservation.

The adopted 15-s interval, as understood in contemporary biomechanics via Bernstein's theory of movement behaviour [20], delineates that muscle movement in this time frame occurs in a closed-loop system of motor control by which the process of maintaining upright balance (understood as a motor program) is subject to adjustment in response to unpredictable and disruptive stimuli. It can be posited that relatively 'slow' T_0 reflects the effects of such disturbances on the activation and control of the mechanisms responsible for balance maintenance. In turn, rapidly changing autocorrelations imply that the balance process is dynamic and exceeds the confines of the sensorimotor control system; in the light of the accepted motor control theory, they indicate that balance maintenance has switched over to open-loop motor control. When we apply this finding with signal theory [21], it is possible that reduced T_0 values in the shorter time intervals are due to an influx of noise. Such

noise is therefore not revealed in the longer time intervals of upright stance as the low-frequency trend displaces the produced noise. Concomitantly, the noise present in the 15-s intervals prevents the identification of a trend. This noise may be extrapolated as the instability present in movements guided by open-loop motor control. In this case, it is likely that it represents the movements produced by various body segments interfering with the maintenance of stable upright stance. We are in agreement with the findings of Schmitt et al. [22] in that the open-loop control scheme of maintaining upright balance is primarily fulfilled by appropriately contracting the postural muscles. Kuczyński and Ostrowska [23] used the viscoelastic model to explain balance preservation in upright stance due to the properties of the musculoskeletal system. In this view, the body acts as a 'stiff beam' and is governed by Newton's first law of motion in regard to maintaining equilibrium [24].

In the present study, differences in T_0 between the right and left foot were adopted to assess motor laterality by controlling the plantar distribution of force. Generally, symmetry was observed in the plantar force distribution. The lack of significant between-foot differences in T_0 in the vertical and anteroposterior directions of force (Tables 1, 2, 4) attests to similar levels of right- and left-foot balance and sensorimotor control. While T_0 in the mediolateral GRF was significantly different, suggesting that this could be a sign of some inherent asymmetry in controlling upright stance between the right and left foot, this was undoubtedly a result of shifting body weight from one foot to the other as a matter of personal preference and comfort.

The significant differences observed in T_0 among the consecutive 15-s intervals exhibit an overall decreasing trend (Tables 1–3; Figure 4). This indicates that incidental muscle activity introduced indiscriminate changes in the magnitude of right and left foot GRF. In other words, the occurrence of incidental tension in the postural muscles acts as a form of interference that increases over time during upright stance.

Bearing in mind that the act of maintaining balance could be viewed as a stochastic process, we assume that the signal processing of related data (GRF as a function of time) must take into account associated noise characteristics. In line with Todorov [25], this noise can help explain (as much as any observed trends) the framework behind the optimal control theory of motor function. In situations where an individual (controller) directs the body, it is important to predict simultaneous and consecutive events (on the basis of immediate or past experience) in their motor behaviour. Following the significant findings of Singh et al. [26], in which balance is believed to be largely controlled by a closed-loop scheme, we attempted to register the time series of GRF in a relatively long-duration trial (45 s), although in the majority of studies, periods of 20–30 s had been adopted [27, 28]. This time interval was considered sufficient to reveal any underlying trends, proving that the slow decay of T_0 in the 45-s total trial period affirmed a low-frequency trend in balance maintenance. This trend in the present sample demonstrates that sensorimotor control is effective enough to preserve balance by generating and directing appropriate force by the feet onto the ground. In effect, these forces stabilized movement to such a degree that the entire body maintained a constant position and orientation. This was observed in both the eyes open and closed conditions.

Our analysis of the correlative associations among the variables revealed a significant correlation between T_0 values in the total trial period (45 s) and the second 15-s interval (16–30 s). We hypothesized that this dependency could be explained by the fact that individuals performing a long-duration task (in this case, quiet standing) treated the beginning of the trial as a 'warm-up'. Attention is focused on performance in the middle of the trial, whereas at its end it is possible that the onset of fatigue (and anticipation of the near trial ending) leads to the emergence of interference. This is apparent by way of the aforementioned significant declines in T_0, particularly between the second (16–30 s) and third (31–45 s) time intervals (Table 3; Figure 4). This finding suggests that clinical assessment of balance should be limited to a period of no longer than 20–30 s if the effects of fatigue and anticipation are to be negated.

It is hoped that the present approach of applying the autocorrelation function to characterize the time course of right and left foot GRF can lead to a greater understanding of the postural mechanisms responsible for maintaining upright stance and balance. Insight in movement symmetry and asymmetry as regulated by sensorimotor control strategies can aid in the development of effective methodologies in physical education and sports training, as well as the assessment of motor potential among individuals; it can also help diagnose injury and evaluate rehabilitation efficacy.

Conclusions

Significant differences were revealed in the autocorrelation function decrease to 0 (T_0) between the total trial period (45 s) and the extracted 15-s intervals. Motor actions (postural corrections) performed in long-duration tasks may have less of an effect on sensorimotor control than those considered in shorter duration projections. The analysis of T_0 – with reference to the right and left foot, including considerable symmetry in force magnitude and direction – indicated a decreasing trend across the consecutive 15-s intervals, primarily in the anteroposterior and mediolateral components of GRF for both conditions and in the vertical GRF for the eyes closed condition. This result suggests that the process of maintaining upright quiet stance, via optimal and uniform activation of control centres and the precise application of the desired net muscle force, is evidently

fatiguing, even in the sample of young and healthy adults. Finally, the experiment proved that the participants' 'motivation' for preserving upright stationary stance was strongest within this time interval and the assessments of balance should be limited to the period of no longer than 20–30 seconds.

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