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Balance Maintenance in the Upright Body Position: Analysis of Autocorrelation

by
Jacek Stodolka[1], Marian Golema[2], Juliusz Migasiewicz[3]

The present research aimed to analyze values of the autocorrelation function measured for different time values of ground reaction forces during stable upright standing. It was hypothesized that if recording of force in time depended on the quality and way of regulating force by the central nervous system (as a regulator), then the application of autocorrelation for time series in the analysis of force changes in time function would allow to determine regulator properties and its functioning. The study was performed on 82 subjects (students, athletes, senior and junior soccer players and subjects who suffered from lower limb injuries). The research was conducted with the use of two Kistler force plates and was based on measurements of ground reaction forces taken during a 15 s period of standing upright while relaxed. The results of the autocorrelation function were statistically analyzed. The research revealed a significant correlation between a derivative extreme and velocity of reaching the extreme by the autocorrelation function, described as gradient strength. Low correlation values (all statistically significant) were observed between time of the autocorrelation curve passing through 0 axis and time of reaching the first peak by the said function. Parameters computed on the basis of the autocorrelation function are a reliable means to evaluate the process of flow of stimuli in the nervous system. Significant correlations observed between the parameters of the autocorrelation function indicate that individual parameters provide similar properties of the central nervous system.

Key words: *lateralization, lower limbs, force, balance, autocorrelation.*

Introduction

Maintaining an upright position has entirely changed human life; with the upper limbs no longer required for support, they moved to manipulative function (Harcourt-Smith and Aiello, 2004; Thorpe et al., 2007). Supported at only two points, the body had to develop more efficient functioning of the central nervous system to participate in the performance of even the easiest daily activities (Brown et al., 1999; Lafond et al., 2009).

Such support creates a type of an inverted pendulum pivoted at the ankle joint (Arinstein and Gitterman, 2008; Fitzpatrick et al., 1996; Loram and Lakie, 2002; Van der Kooij et al., 2001) which causes difficulties in maintaining the upright position. Numerous scientists have attempted to solve this problem by developing a model of an inverted controlled pendulum. Winter et al. (1998) showed that the centre of pressure (COP) and centre of gravity (COG) oscillations for quiet standing fitted the equation of motion for an inverted pendulum. Gatev et al. (1999) observed that ankle mechanisms dominated in the sagittal plane with almost synchronous sway of body parts. Other authors have used more complex models to represent standing (Alsonso-Sanchez and Hochberg, 2000; Lauk et al., 1998; Nicholas et al., 1998; Van

[1] - *University School of Physical Education in Wroclaw, Department of Track and Field.*
[2] - *Opole University of Technology, Department of Biomechanics.*
[3] - *University School of Physical Education in Wroclaw, Department of Didactics of Sport.*

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Emmerik et al., 2013), or disputed the relevance of the ankle strategy and the inverted pendulum model in standing (Bloem et al., 2000). Similar model solutions have been proposed by several authors (Gustyn, 2012; Kuczyński and Ostrowska, 2006; Takada, 2013; Whittington et al., 2008; Yoshikawa et al., 2013) who formulated a hypothesis according to which the upright body position is maintained due to feet displacement at the point the ground reaction force vector (center of pressure – COP) is applied on the ground. Each displacement of the center of mass leads to a change of the center of pressure on the ground. The changes of the center of pressure are initiated by the central nervous system.

The upright body position is maintained and regulated by the central nervous system through information sent from nerve receptors (Bair et al., 2007; Haddad et al., 2012). Such information is related to the data received from the external and internal environment.

Information gathered by the receptors arrives at the central nervous system in the form of afferent impulses. Bursts of impulses are received and changed by lower sensory centers within the spinal cord and brain stem area and then transferred directly to higher and lower sensory centers located in the diencephalon and the cerebral cortex (Kandel at al., 2000).

Information delivered by the receptors to the central nervous system is used for comparison with a given motor task (in the closed regulating system) and corrected in the process of maintaining balance. This information may also be remembered and can become a basis for the development of new motor patterns in the nervous system. The frontal lobe of the cerebral cortex stores sensory information and activities related to long-term memory owing to numerous connections to the hippocampus located within the temporal lobe of the brain.

Sensory information from afferent neurons is processed and transferred to efferent neurons, which in turn send it to skeletal muscles. This process takes place at different levels of the central nervous system. Information collected while performing simple reflex actions is transferred from lower sensory centers to lower motor centers. Higher and lower sensory centers participate in complex reflexes (Fuller et al., 2011; Kandel et al.; Yeo et al., 2013).

The complex information processes observed in the central nervous system responsible for maintaining the upright body position are very difficult to test and explain. The ability to maintain body orientation in space, its position and balance in relation to the surrounding environment, relies on the visual, vestibular and proprioceptive sensory information (receptors located in the skin, muscles, tendons, and joints) processed by the brain. It results in pressure (force) placed by the foot on the ground, which can be measured by the use of different force plates (Clark et al., 2010; Griffiths, 2006; Hubbard et al., 2012; Robertson et al., 2004). So far it has been the only source of information about the process of maintaining the upright body position.

The only reliable method in the evaluation of the processes of regulating and maintaining the upright body position is recording of ground reaction forces in relation to time. Recording of ground reaction forces in time series constitutes a stochastic process. A basic tool used to analyze time series is the theory of probability. Time series can be treated as a signal. For many practical applications, the analyzed signal is compared to other signals, especially the time-delayed copy of itself. This comparison needs to be made for differing reciprocal signal positions in time function i.e. different values of one signal delay in relation to the other. This way autocorrelation of signal can be obtained (Pesaran and Pesaran 2010). As stated by Vetterli et al. (2014), it is a scalar product of a signal and a time-delayed copy of itself in time function considered as a phase shift. Autocorrelation determines similarity of signals on the basis of their values shifted in time. It is one of alternative manners to characterize signals in time (Vetterli et al., 2014). Autocorrelation can be calculated for any data and stationary and non-stationary time series. Computed for non-stationary time series autocorrelation reveals a relatively slow decline with an increase in s (distance on the time axis). In practice the autocorrelation curve passes through 0 over time. The quick decline of autocorrelation coefficient values determines the existence of unexpected changes (like interference) in a time series. The autocorrelation of a periodic function (natural frequency of time series) is itself periodic with the same period. The autocorrelation function can be used to determine the dependence of events in a time series (stochastic process) on those which took place in the past, present, or will take place in the future.

In the present study it was hypothesized that if recording of force in time depended on the quality and way of regulating force by the central nervous system (as a regulator), then the application of autocorrelation for time series in the analysis of force changes in time function would allow to determine properties of regulator and its functioning. Here the regulator is the central nervous system and its function in maintaining the upright body position.

This research aimed to analyze the autocorrelation curve computed from the time series of ground reaction forces measured in subjects standing in a stable, controlled and upright position.

The following research questions were formulated:

1. What are the values of the autocorrelation function parameters?
2. Do relationships exist between values of the individual parameters of the autocorrelation function?

Material and Methods

Eighty two physically active young subjects (51 men and 31 women) whose age ranged from 14 to 55 years of age (22.56 ± 1.81), body mass (78.73 ± 10.7 kg), and body height (181.69 ± 6.39 cm) volunteered to participate in this study. The subjects were selected purposely and the criterion was the participation in high performance sport and/or intensive physical activity. According to this criterion the participants were divided into several groups as follows: 1. track athletes – 17 participants (11 men and 6 women), 2. senior soccer players – 13 subjects (13 men), and 3. athletes - convalescents after lower limb injury – 10 subjects (5 men and 5 women). They were recruited from intercollegiate athletic teams and from collegiate sports clubs. The fourth group included youth soccer players (8 men and 10 women) who participated in regular soccer training. The last fifth group was composed of students, 24 subjects (14 men and 10 women), who participated in the Intercollegiate Sports League. Such a diversified group of subjects gave the researchers the opportunity to study a large number of autocorrelation function parameters. Before testing, all subjects were screened for their health conditions. All subjects and their parents (when necessary) signed an informed consent form. The study was approved by the Human Ethics Committee of the University School of Physical Education in Wroclaw. None of the participants had any physical or physiological limitations that could have affected the experiment results.

The research was conducted using two Kistler force plates (Kistler, Corp. 9286AA) with Bio Ware 4 software (Kistler Corp.) and additional equipment to measure ground reaction forces. The plates were installed side by side for corresponding positioning of the feet during standing. Such positioning enabled the measurement of ground reaction forces while standing. The recordings were time synchronized and both plates were calibrated. All tests were performed in the certified Laboratory of Biomechanical Analyses, University of Physical Education in Wroclaw (certificate no PN-EN ISO 9001:2001). Each subject performed relaxed standing for 15 s on the plates, during which ground reaction forces were measured. Before measurements were taken, the subject performed two trials in order to familiarize themselves with the procedure. The results of the force values measured over time were analyzed for: horizontal force in the left-right axis Fx (frontal plane); Fz vertical force (transverse plane); and horizontal force in the antero-posterior axis Fy (sagittal plane). Two time synchronized recordings were conducted for each force direction for the left and right lower limbs. An example of such a recording is presented in Figure 1. In total, there were 6 recordings of ground reaction forces in three directions collected for both limbs.

Time series were created by recordings of force in time. The time series described in this research were used to compute the autocorrelation function which is presented in Figure 2.

The parameters of the autocorrelation function were determined. The first parameter described time when the autocorrelation curve passed through 0. This parameter was described as time to obtain 0 (time zero). The second parameter referred to time in which the function reached its first peak and at which point it changed its direction (time extreme). The third parameter included the strength gradient. It determined mean velocity of the autocorrelation curve decline from 1 to a value on the autocorrelation scale in time extreme. Time extreme was the point where the curve changed its direction. A gradient was the quotient of the difference of values of the autocorrelation function (from Figure 1 – read to Figure 2) at the time of reaching the extreme. A derivative extreme was computed from the differential of the autocorrelation function.

The parameters of the autocorrelation curve were statistically analyzed. The following values were computed: arithmetical means, standard deviation and correlations between individual values of the parameters.

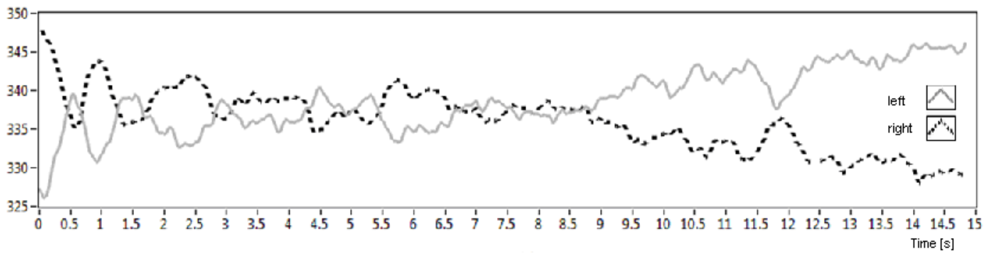

Figure 1

Exemplary recording of changes of force values in time in vertical direction for the right and left limb

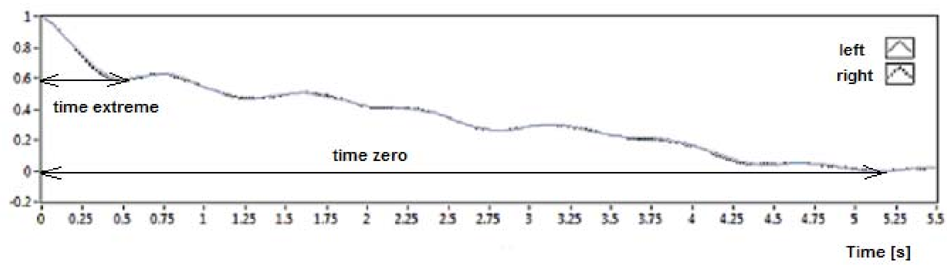

Figure 2

Autocorrelation time zero

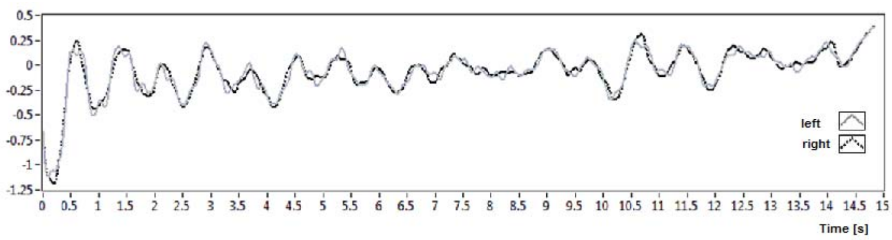

Figure 3

The derivative of the autocorrelation function

Table 1

Means and standard deviations of the autocorrelation function; N=82

Force vector	Lower limb	Time zero		Time extreme		Derivative extreme		Gradient strenght	
		Means	SD	Means	SD	Means	SD	Means	SD
left-right	right	2.549	1.666	1.997	1.986	-1.736	0.948	0.847	0.529
	left	2.842	1.541	2.137	1.819	-1.437	0.831	0.705	0.457
anterior-posterior	right	2.918	1.746	1.521	1.418	-1.481	0.693	0.811	0.401
	left	2.925	1.712	1.518	1.400	-1.485	0.697	0.815	0.407
up-down	right	3.081	1.655	1.513	1.597	-1.779	0.839	0.832	0.492
	left	3.126	1.652	1.648	1.733	-1.753	0.809	0.799	0.444

Table 2

Correlations observed between parameters of the autocorrelation function; probabilities p<0.05 are marked bold; N=82

Force vector	Lower limb	Time zero – time extreme	Time zero – derivative extreme	Time zero – gradient strenght	Time extreme – derivative extreme	Time extreme – gradient strenght	Derivative extreme – gradient strenght
left-right	right	**0.59**	**0.72**	**-0.73**	**0.67**	**-0.69**	**-0.91**
	left	**0.44**	**0.56**	**-0.52**	**0.67**	**-0.66**	**-0.92**
anterior-posterior	right	**0.32**	**0.63**	**-0.65**	**0.56**	**-0.62**	**-0.90**
	left	**0.32**	**0.62**	**-0.65**	**0.55**	**-0.61**	**-0.91**
up-down	right	**0.33**	**0.67**	**-0.66**	**0.54**	**-0.55**	**-0.89**
	left	**0.30**	**0.60**	**-0.53**	**0.58**	**-0.61**	**-0.86**

Results and Discussion

The results of arithmetical means and standard deviations computed for the values of autocorrelation parameters (Table 1) determined values of individual parameters. They also enabled the researchers to compare values of these parameters for the right and left limb and a direction of ground reaction forces.

The first parameter analyzed for the autocorrelation curve was time zero (the time needed by the curve to reach values from 1 to 0). A short time meant the lack of smoothness in regulating motor activity, as described in changes in value of force placed on the plates by the tested subject. Short-term interference may have occurred due to maintaining balance in a constant, unchangeable position. There was also interference in the dependence of events (activation of motor units) based on those which had taken and would take place. A long time needed by the autocorrelation function to reach 0 meant smoothness and calmness in maintaining balance in a stable, upright standing position. It may also indicate existence of low-frequency variability trends, which is swaying of very low frequency. Once again, they may point to dependence on events which have occurred, are occurring, or will occur.

Comparison of results of time needed by the curve of the right and left limb to pass through 0 revealed little and statistically non-significant differences. More significant differences were observed in a horizontal force in the left-right axis.

The second parameter analyzed was the time extreme, in which the curve reached its first peak (where it changed direction). It is a measure of the periodic factor and describes the natural frequency of regulation and movement systems. It is usually observed in a direction change of the ground reaction force.

On the basis of the results (Table 1), the natural frequency of change in the force direction can be determined by values of force put by a foot on the ground. The frequency of those changes ranged from 0.5 to 0.7 Hz in average. Furthermore, high standard deviation values may suggest great individual variability of those frequencies. There were no statistically significant differences between time in the change of force direction by the autocorrelation curve in the process of maintaining balance in the upright body position observed for the right and left foot. Significantly lower natural frequency of regulating and motor systems was observed in the horizontal force of the frontal plane.

The next parameter calculated on the basis of the autocorrelation curve was the maximum value of instantaneous peak velocity of function fall (described as a derivative extreme). This parameter was used to compute maximum instantaneous peak velocity of the autocorrelation drop from value 1 of the autocorrelation coefficient to 0. It may be assumed that this parameter indicated the amount of interference in motor coordination caused by unpredictable muscle spasms probably induced by the uncontrolled activation of motor units. Such activations were not taken into consideration in the process of performing motor activity (upright body position).

The comparison of maximum velocity of the autocorrelation drop of left and right limbs revealed significant differences in the horizontal force in the left-right axis induced by the left and right foot. However, there were no differences in the values of the derivative extreme in vertical and horizontal forces in the antero-posterior axis.

Gradient strength was the last of the considered parameters. It determines the velocity of the autocorrelation curve fall in reaching natural frequency of regulating and balance systems. The function of this parameter can be compared to the one of the derivative extreme with one difference: gradient strength determines the velocity in the system adjustment. The results (Table 1) indicated no differentiation in values of the discussed parameter – neither for the limbs or ground reaction force.

Each of the analyzed parameters of the autocorrelation function measured different properties for activity related to regulating and maintaining balance. The question to be posed is what is the difference in the parameters and what are the similarities? The point is which parameters are similar and which differ and affect other properties.

The comparison of correlation coefficients of individual values of autocorrelation parameters (Table 2) revealed a significant correlation between the derivative extreme and the gradient strength of the autocorrelation curve. Low correlation values (despite being statistically significant) were observed between the time the autocorrelation curve passed through the 0 axis and the time it reached the first extreme. Such a result is understandable as the value of time passing through 0 evaluates the smoothness of performing motor activity (standing) expressed by mutual dependence of events over time, those which took place, are taking place and will occur.

The time needed to reach the first extreme evaluated the process of adjustment, which is specific for each subject natural frequency of sending performance signals. It is worth noting that the present study has some limitations which could affect final conclusions and practical implications. A greater number of athletes from different sport disciplines would create greater statistical power, and above all, stronger application for sports training. Therefore, due to the small number (30) of professional athletes (soccer players and track athletes), we abandoned discussion about the difference in maintaining balance between the tested athletes and above average physically active subjects. By examining autocorrelation between the values of ground reaction forces in a time series, we tried to identify the pattern of repetition of the ground reaction force of the body in maintaining balance in the upright body position as a function of time (separate for each of the limbs, but simultaneously). This information appears to be extremely important due to the fact that on that basis we can predict what may happen in the next sequence of any sport movement structure. This is of particular importance in sports where the main task of training is to produce repetitive behaviors (simple or complex movements) of athletes, necessary to achieve the best performance. Another limitation may be that the proposal to use the autocorrelation function parameters to assess the behavior of the athlete in the described motor activity is based on the elusive and ambiguous term of "muscle memory" and the flow of nerve impulses in the human body. Despite these limitations the measurement of postural balance has numerous potential implications in sports training, medicine, and ergonomics.

Conclusions

Parameters computed on the basis of the autocorrelation function were a reliable means to evaluate the flow of stimuli in the central nervous system while maintaining the upright standing position. There were significant correlations observed between the values of parameters computed from the function values. It means that individual parameters determine similar values of the central nervous system as a regulator in the process of maintaining a balanced upright body position. From a practical viewpoint, the bilateral ground reaction force measurements are especially significant in sport performance which relies on balance and coordination, where the contribution of each limb separately in the process of balance control is of great significance (take-off in athletic jumping events, sprinting, throwing and kicking the ball in team sports and in martial arts: judo, boxing, wrestling). The second area of interest includes rehabilitation after injuries (lower limbs), where limb load asym¬metry may serve as a vertical measure of postural stability and can be used for the early diagnosis of potential decline in balance control.

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Corresponding author:

Jacek Stodolka
University School of Physical Education in Wroclaw, Department of Track and Field
Paderewskiego 35, 51-612 Wrocław, Poland
Phone: +48 71 347 3147; Mobile phone: +48 608 820 397
Fax: +48 71 347 3149
E-mail: jacek.stodolka@awf.wroc.pl