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COORDINATIVE PATTERNS AND GAIT STABILITY ACCESSED BY NONLINEAR DYNAMICS APPROACH: A PRELIMINARY STUDY

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Abstract: *The relationship between the trajectories of the pressure center (CoP) and the Mass Center (CoM) is determinant for the human stability during gait. To understand the relationship between these trajectories it is necessary to access the coordinating pattern that is maintained during the performance of this daily activity. Nonlinear dynamics and dynamical systems approaches and methodologies are increasingly being implemented in biomechanics and human movement coordination research. Therefore, the aim of this preliminary study was to investigate the coordinative patterns between the movements of the CoP and the CoM during the human gait, So that in the near future it is possible to propose a new gait stability criterion based on this approach. Using the kinematics and dynamometry, the CoP and CoM trajectories were calculated and then using the continuous relative phase method (CRP) the coordinative patterns of one subject were obtained in 3 gait attempts. The phenomena analyzed showed similarity of amplitude and in the temporal location. The variability of the coordinative patterns was also calculated and this variable inspires the continuity of the study with different samples.*

Keywords: Nonlinear dynamics, Coordination, Variability, Stability, Gait.

1. Introduction

Harmony is an essential feature of human gait warranting for efficient and smoothed movements during walking (Menz et al., 2003). Gait harmony has been defined as the capacity to transfer the symmetry of human body into alternated, synchronized, symmetric, coordinated and rhythmic movements (Menz et al., 2003).

When we examine the trajectories of the Center of Pressure (CoP) under the feet and the Center of Mass (CoM) of the total body, we see the challenge to the human control system to manage the relationship between these two points (Winter, 2009) (Fig. 1).

Relevant to identifying the nature of coordination changes is the distinction in the dynamical systems approach between order and control parameters (Turvey, 1990). Order parameters identify low-dimensional qualitative states (“macro states”) of the system dynamics, in which changes between states can be induced by manipulating an specific control parameter, such as frequency or velocity (Turvey, 1990). The relative phase between body segments has been identified as an order parameter because of its fundamental reflection of cooperativity between components in the system (“micro states”) (Van Emmerik and Van Wegen, 2000). Relative phase between component oscillators can identify different qualitative states of the system dynamics on which basis changes in coordinative patterns can be evaluated and discontinuous transitions are characterized by abrupt jumps between different coordinative modes (such as the transition from bipedal walking to running) (Hamill et al., 2005). Under a continuous scaling of a control parameter, preservation of the pattern is maintained for a wide range of control parameter values. However, when the pattern becomes unstable, these abrupt changes can occur for very small increments or decrements in the control parameter (nonlinearity) (Van Emmerik et al., 2004). Continuous phase transitions are more or less smooth and can occur over a larger interval of control

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parameter values. Critical in distinguishing these two types of transitions is the stability of the order parameter: In abrupt transitions, instability occurs before the transition point. This instability can be measured by means of critical fluctuations (increase in standard deviation) in relative phase or the relaxation time after a transient perturbation (Hamill et al., 2005).

Therefore, the objective of this preliminary study is to investigate the coordinative patterns between the movements of the Center of Pressure (CoP) and the Center of Mass (CoM) during the human gait, so that in the continuity of this study it is possible to propose a new criterion of gait stability.

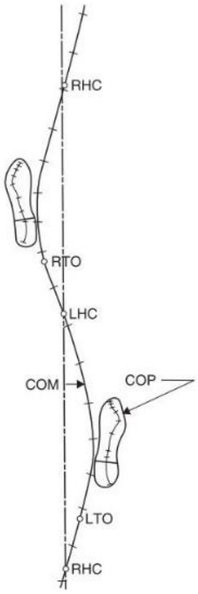

Fig. 1: Trajectories of the CoM and CoP. LTO – left toe off, LHC – left heel contact, RTO – right toe off, RHC –right heel contact. Note that the COM never passes within the base of support of either foot. Adapted from Winter (2009, pp. 291).

2. Methods

To collect the data was used 07 camera T10 with 250 fps (Vicon®) with kinematics software Vicon Nexus (Vicon®) and one force plate model OR6-6 (AMTI®). For the motion reconstruction, basic reflective markers (Vicon®) are fixed bilaterally according to the PluginGait model for whole body (Vicon®).

One young man (24 years, height of 170 cm and a body mass of 74 kg) performed 3 gait trials with a distance of 20 meters and at the chosen speed of the subject. The force plate was located 10 meters from the start of the gait and so that the subject performed the step with the dominant lower limb on the force plate. The analysis interval comprised the entire stance phase of the dominant lower limb (from the heel contact to the toe off over the force plate).

The data were processed and analyzed by specific routines developed in Matlab (Mathworks®, Inc.). The establishment of the optimal cut-off frequencies for signal filtering was performed using residual analysis (Winter, 2009), wherein the signal of the kinematic data was filtered with a recursive Butterworth lowpass 4th order with cutoff frequency of 6 Hz and the data of dynamometry with a recursive Butterworth lowpass 4th order with cutoff frequency of 95 Hz.

The medio-lateral displacement and velocity of the CoM were calculated from the position data from the reflective markers and the medio-lateral displacement and velocity of the CoP were calculated from the forces and moments obtained with the force plate using the function (Lafond, Duarte, & Prince, 2004)

$$CoP_x = \frac{-M_y + F_x \cdot Z_0}{F_z} + X_0 \,, \qquad (1)$$

where M is the moment, F the reaction force, x, y and z are the mediolateral, anteroposterior and vertical direction, respectively, and X_0, Z_0 are the offsets from the geometric center of the force platform.

For the phase graphics construction, first, the data of the CoM and CoP of each trial, were interpolated to 2500 points using Spline Cubic functions. The interpolation procedure was realized to standardize the different amount of samples of the files.

Phase graphics were constructed from the velocity as function of displacement, with the displacement in the horizontal axis and the velocity in vertical axis. Prior to calculating the phase angle *(φ)*, the data of displacement and velocity for each trial were normalized (Li et al., 1999).The goal of normalizing the data is to transform the phase graphics in such a way that both displacement of the signal and its first derivative are limited to the range between −1 and 1. First, normalization is accomplished for any input signal *y(t)* by the function

$$f(y(t_i)) = \frac{y(t_i)}{max(|y(t)|)}\,. \tag{2}$$

This technique limits the input signal of the function to either −1 or 1 depending on the maximum absolute value of *y(t)*. This method is used for velocity normalization because the zero value has qualitative meaning and, arguably, should be preserved. In other words, after normalization the zero value represents the zero value in the original signal. A second normalization technique is based on the function

$$g\big(y(t_i)\big) = 2\left(\frac{y(t_i)-min(y(t))}{max\big(y(t)\big)-min\big(y(t)\big)}\right) - 1\,. \tag{3}$$

This function transforms the original values *y(t)* in such a way that the minimum value of *g(y(t))* equals −1 and the maximum value of *g(y(t))* equals 1. Here the zero value is midway between the maximum and minimum and can, therefore, be arbitrary.

After normalization, the phase angle of the signal at time t_i is calculated based on the normalized phase graphic (Li et al., 1999)

$$\varphi(t_i) = \tan^{-1}\left(\frac{\dot{x}_{norm}(t_i)}{x_{norm}(t_i)}\right). \tag{4}$$

Finally, the continuous relative phase, CRP(*ti*), at time *ti* between two signals *x1(t)* and *x2(t)* is calculated as

$$\begin{aligned} CRP(t_i) &= \varphi_1(t_i) - \varphi_2(t_i) \\ &= \tan^{-1}\left(\frac{\dot{x}_{1,norm}(t_i)x_{2,norm}(t_i)-\dot{x}_{2,norm}(t_i)x_{1,norm}(t_i)}{x_{1,norm}(t_i)x_{2,norm}(t_i)+\dot{x}_{1,norm}(t_i)\dot{x}_{2,norm}(t_i)}\right). \end{aligned} \tag{5}$$

CRP was set in the range of -180 ° ≤ φ ≥ 180 °, as the difference between the phase angles of the CoP (φ_{CoP}) and of the CoM (φ_{CoM}) for each data sample. A larger phase angle of one point in relation to each other may be interpreted as that the same plays a slower movement or with lower amplitude, or a combination of both factors. From the CRP curves, were obtained the positive peak (maximum value), negative peak (minimum value), and the percentage time of the stance phase in which these values occurred. A CRP mean curve of the 3 trials was calculated (Fig. 3). The variability was calculated as the mean of the Standard Deviations (SD) of the CRP measures.

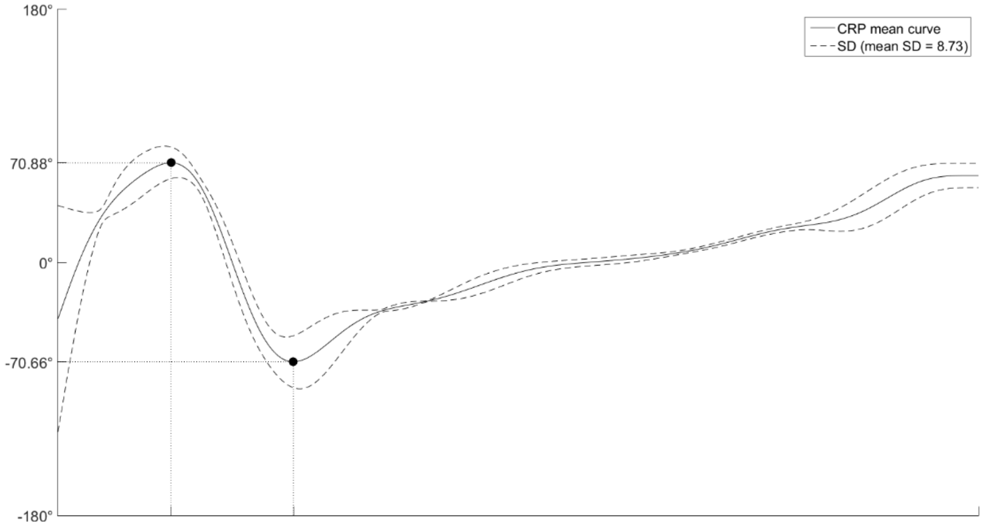

Fig. 2: CRP mean curve and Standart Deviation (SD); Positive Peak and Negative Peak, as well, the percentage time of the stance phase in which these values occurred.

3. Discussion and Conclusions

To discuss our results we can establish 3 hypotheses: 1. that the magnitudes of the anti-phase phenomena are similar in individuals without compromised stability; 2. that the anti-phase phenomena occur in specific moments in the stance phase of the gait in individuals without compromised stability; 3. that the variability of the coordinative patterns can be an index of stability.

The values of the positive peak (71.49 ° ± 10.89 °) and the negative peak (-72.43 ° ± 19.75 °) of the CRP curves are quite similar and lead us to accept the first hypothesis as true. Already the moment of occurrence of positive peaks (12.09 % ± 1 %) and negative peaks (25.47 % ± 1.2 %) appear to be repeated in the 3 trials, and still showing a very small variability, showing that these anti-phase phenomena have a temporal accuracy in the stance phase, and lead us to accept the second hypothesis as true.

According to Hamill et al. (2005), we can relate the increase of the standard deviation of the CRP curve with instability. However, as in this preliminary study we only have data from a subject without compromised stability, it is not possible to establish if this measure will have a higher value in subjects with an unstable gait, but we can verify a low value (± 8.7267 °) when we analyze this healthy individual in 3 trials. In this way, we can show the tendency to accept the third hypothesis as true and establish as objective of the continuity of this study to investigate a sample that possesses individuals who do not have compromised stability and individuals who have unstable gait, such as elderly fallers and individuals with Parkinson's disease.

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