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Harmony as a convergence attractor that minimizes the energy expenditure and variability in physiological gait and the loss of harmony in cerebellar ataxia

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ABSTRACT

Background: The harmony of the human gait was recently found to be related to the golden ratio value (ϕ). The ratio between the duration of the stance and that of the swing phases of a gait cycle was in fact found to be close to ϕ, which implies that, because of the fractal property of autosimilarity of that number, the gait ratios stride/stance, stance/swing, swing/double support, were not significantly different from one another. We studied a group of patients with cerebellar ataxia to investigate how the differences between their gait ratios and the golden ratio are related to efficiency and stability of their gait, assessed by energy expenditure and stride-to-stride variability, respectively.

Methods: The gait of 28 patients who were affected by degenerative cerebellar ataxia and of 28 healthy controls was studied using a stereophotogrammetric system. The above mentioned gait ratios, the energy expenditure estimated using the pelvis reconstructed method and the gait variability in terms of the stride length were computed, and their relationships were analyzed. Matching procedures have also been used to avoid multicollinearity biases.

Findings: The gait ratio values of the patients were farther from the controls (and hence from ϕ), even in speed matched conditions ($P = 0.011$, Cohen's D = 0.76), but not when the variability and energy expenditure were matched between the two groups (Cohen's D = 0.49). In patients with cerebellar ataxia, the farther the stance-swing ratio was from ϕ, the larger the total mechanical work ($R^2_{adj} = 0.64$). Further, a significant positive correlation was observed between the difference of the gait ratio from the golden ratio and the severity of the disease ($R = 0.421$, $P = 0.026$).

Interpretation: Harmony of gait appears to be a benchmark of physiological gait leading to physiological energy recovery and gait reliability. Neurorehabilitation of patients with ataxia might benefit from the restoration of harmony of their locomotor patterns.

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1. Introduction

Among primates, humans are considered to be anatomically and physiologically specialized for economical walking with minimal energy expenditure (Lovejoy, 1988; Foley and Elton, 1998). The energy cost of walking has historically been expressed as a function of the walking speed, and it was found to be minimal at a self-selected comfortable speed, usually in the range of 1.25–1.5 $m \cdot s^{-1}$ (4.5–5.4 $km \cdot h^{-1}$) (Cotes and Meade, 1960). In fact, the activity of the lower-limb muscles is minimal in this range of speeds (Neptune et al., 2008; Carrier et al., 2011), which reduces the total mechanical work that must be performed by the muscles during walking (Cavagna and Kaneko, 1977). In general, the mechanism of walking at a self-selected speed improves the utilization of the elastic energy storage and the mechanical efficiency related to the pendular mechanism of walking (Neptune et al., 2008). In fact, muscle activation intervenes in specific phases of the gait cycle to drive the intrinsic oscillations of the system to compensate for the small loss of energy (Lacquaniti et al., 2012). In addition, the duration of different gait phases, such as stance and swing, depends on the speed. However, large changes in the speed (up to 90%) imply small variations in the stance duration (approximately 4%) (Shemmel et al., 2007). The percentage duration of the stance is also quite invariable with respect to the ground inclination: on a terrain that is inclined by 42°, the stance varies from 60% (downward) to 64% (upward), and hence by only approximately 2% of the gait cycle around the theoretical value of 62% (Riener et al., 2002). Thus, despite being adjustable, the ratio between the stance (≈ 62%) and swing (≈ 38%) remains in a narrow range among different walking conditions, and this observation is highly reliable in healthy subjects who are walking at their comfortable speed (Perry, 1992).

Conversely, in pathological conditions, this gait ratio can be widely altered. A considerable amount of literature has identified the alteration of the proportion between stance and swing as a sign of pathological gait, as reported for stroke (stance duration approximately 70% of the gait cycle) (Kuan et al., 1999), cerebral palsy (70%) (Wang and Wang, 2012), Parkinson's disease (68%) (Peppe et al., 2007), and Huntington's disease (ranging from 59 to 70%) (Reynolds et al., 1999). However, although this proportion has been reported to be fundamental to classifying pathological vs. physiological gait, the reasons why it is such a reliable parameter of healthy human gait have been poorly investigated.

Recently, the value of this gait ratio has been noted to be close to ϕ (approximately 1.618034) in healthy subjects (Iosa et al., 2013), which is an irrational number called the golden ratio (Pacioli, 1509; Mario, 2002). The golden ratio has already been found in many physical, natural and human fractal structures that are self-organized with a larger-scale structure resembling a subunit structure, such as in some animals and plants, the solar system, architecture, certain musical rhythms, financial market patterns, and biological structures (e.g., DNA spirals) (Dunlap, 1997, Lidwell et al., 2003, and Yamagishi and Shimabukuro, 2008). In humans, harmonic proportions have been found in the physiological activity of the heart (Yetkin et al., 2013) and in anthropometry (Davis and Altevogt, 1979), as depicted in figurative arts (Hemenway, 2005). The golden ratio is an irrational number that is the solution of the problem already reported by Euclid in III century BCE to cut a given straight line so that the proportion between the shorter part to the longer one is the same as the longer part to the whole. When applied to gait cycle, the straight line is the stride, and the golden ratio is found when the proportion of the stance duration (the longer part of the stride) to the swing duration (the shorter part) is the same as that of the stride duration (the whole segment) to the stance duration (the longer part). This number has an intrinsic property of autosimilarity (being $1/\phi = 1 - \phi$), that implies the same proportionality between units and consecutive subunits of gait, resembling in each part the same whole structure. In fact, this property of ϕ provides the entire walking unit with a specific fractal autosimilar structure, as reported in the following formula (Iosa et al., 2016a):

$$\phi = \frac{1+\sqrt{5}}{2} = \frac{\text{swing}}{\text{double support}} = \frac{\text{stance}}{\text{swing}} = \frac{\text{stride}}{\text{stance}} = \frac{\text{stride + stance}}{\text{stride}} = \frac{2\ \text{strides+stance}}{\text{stride + stance}} = \ldots$$

Recently, a link between the functional gait ratio and anthropometric proportions, both of which physiologically approximate the golden ratio, has supported the idea of an inextricable association between the structures and functions that are involved in human walking, i.e., both are related to the pendular mechanisms of walking. This observation suggests the fascinating hypothesis that human anthropometry has phylogenetically evolved toward this proportion to favor the efficiency of walking (Iosa et al., 2016a). This fractal gait harmony is lost in patients with Parkinson's disease (PD) (Iosa et al., 2016b). This finding raises the question as to whether the harmony of the human gait could have a functional significance that is related to motor-control efficiency. The loss of gait harmony in PD was hypothesized to be related to alterations in internal cue production in the cerebellum-basal ganglia-spinal central pattern generator pathway (Rea, 2015; Iosa et al., 2016b). Conversely, alterations of the gait harmony observed in patients with cortical stroke were mainly due to a reduction in the walking speed and motor asymmetry but not directly due to damage in the cortical areas (Iosa et al., 2016c).

The above-described fractal gait harmony could represent a convergence point of the activity of the central nervous system (e.g., cerebellum-basal ganglia-spinal cord axis) and the musculoskeletal locomotor system. This convergence point could be an attractor, i.e., an equilibrium point, around which the locomotor system works in a stable and efficient manner (hence reducing the variability and energy expenditure). Furthermore, the discovery of the golden ratio as the physiological value of gait ratio, may allow to quantitatively assess the harmony of gait, characterizing healthy pattern and differentiating from that the pathological gait.

The hypothesis of this study is that subjects who walk with a gait ratio, i.e., the proportion between the stance and swing, that is close to the golden ratio could minimize the energy expenditure and gait variability. To test this hypothesis, we needed to measure the relationship between the gait ratio and both the energy expenditure and gait variability in healthy subjects and in patients in which gait is highly variable and poorly efficient. Hence, patients with cerebellar ataxia were the best candidates to test this hypothesis because of their damaged cerebella, which caused an impairment in the gait stability (low step-to-step reliability and low ability to maintain an upright dynamic balance during walking) (Iosa et al., 2014; Serrao et al., 2012; Nardone and Schieppati, 2012), which is strongly correlated with a history of falls (Schniepp et al., 2014) and an increase in energetic cost (Martino et al., 2014). Energetic cost of walking in patients with ataxia has been poorly investigated, despite many studies suggested a low gait efficiency in cerebellar ataxia because of typical prolonged muscle co-contraction (Mari et al., 2014) and abnormal trunk movements (Conte et al., 2014) that may affect the pendular mechanism of walking and hence reducing the energy recovery (Saunders et al., 1953).

Hence, the specific aims of this study were the following: i) to evaluate whether the gait ratios of the patients with cerebellar ataxia are different from the golden ratio and hence from the physiological harmonic structure of walking observed in healthy controls; ii) to evaluate by applying matching procedures, if the above difference may be due, or not, to the reduced speed at which the patients with ataxia walk in comparison to healthy subjects; and iii) to evaluate whether this change is related to the energy expenditure and gait variability in speed-matched conditions.