Does gait harmony represent a convergence point between different biomechanical features of human gait?

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Introduction

Among primates, humans are recognized to be anatomically and physiologically specialized for economical walking with minimal energy expenditure. The energy cost strongly depends on walking speed, but is also related to balance control, an important aspect of bi-pedal locomotion for which effective mobility must be balanced by dynamic stability. Very recently, the relationship between anthropometric golden proportions and the golden ratio in gait has been demonstrated (Iosa et al., 2013).
Our hypothesis is that the gait harmony may represent a sort of convergence point (attractor) of different biomechanical determinants including gait speed, balance maintenance, and energy consumption.
The specific aims of this study were: i) to evaluate whether the gait ratios of ataxic patients are more distant from the golden ratio compared to those of healthy controls; and ii) to evaluate whether the deviation from the golden ratio is influenced by gait speed, gait variability, and energy consumption.

Methods

Partcipants. Twenty-eight patients affected by cerebellar ataxia (17 men, 11 women; mean age, 49.6±10.5 years; mean duration of disease, 13±6.4 years) were enrolled in the study. Seventeen patients had a diagnosis of autosomal dominant ataxia—spinocerebellar ataxia (SCA)—and there were 11 patients with SCA type 1, four patients with SCA type 2, and two patients with SCA type 3. The remaining 11 patients had sporadic adult onset ataxia of unknown etiology (SAOA).
Twenty-eight age- and gender-matched healthy adults (age of ataxic patients, 49.5±10.6 years; age of healthy controls, 49.6±7.1 years,) participated in the study as controls.
Instrumentation. Gait analysis was performed using an optoelectronic motion analysis system (SMART-DX 500 System, BTS, Milan, Italy). It consists of eight infra-red cameras (sample frequency of 300 Hz) used to detect the movement of 22 passive spherical markers covered with an aluminum powder reflective material (15 mm in diameter) placed over prominent bony landmarks, according to the recommendations of the International Society of Biomechanics and to Davis's protocol.
Data analysis. the following spatio-temporal gait parameters were calculated: stance (distance from first heel strike to toe off of the same limb), swing (distance from toe off to second heel strike of the same limb), and double support phase (time spent with both feet on the floor) duration within the stride, which were all expressed as a percentage of the stride duration, mean gait speed (GS, m/sec) and stride length (m). The total 100% of the stride duration was defined as the gait cycle.
Gait harmony measurements
The gait ratio was calculated according to a previously published method (Iosa et al., 2013). Specifically, for each subject we computed $\frac{gait\ cycle}{stance}$, $\frac{stance}{swing}$ and $\frac{swing}{double\ support}$ gait ratios for the right and left stride of each trial.

The mean ratios were computed among all the strides of all the trials for each subject. The ratios between these ratios and Φ were then calculated, in each subject's trial, according to the following formulas: and $\frac{\frac{gait\ cycle}{stance}-\Phi}{\Phi}$ $\frac{\frac{stance}{swing}-\Phi}{\Phi}$ $\frac{\frac{swing}{double\ support}-\Phi}{\Phi}$
Gait variability mesurements
The mean and standard deviation of all of the stride lengths were computed for each subject. To evaluate the within-subject variability of stride length, we calculated the coefficient of variation (CV) according to the following formula: $CV_{stride\ lengt\ h} = \frac{SD_{stride\ lengt\ h} * 100}{mean_{stride\ lengt\ h}}$
Energy consumption measurements
The total energy consumption (TEC) of the right and left step of each trial was calculated as the ratio between the total positive work of the body and its efficiency factor : $\mathrm{TEC} = \frac{\mathrm{W}^{+}_{\mathrm{ext}}}{0.21}$

$\mathrm{W}^{+}_{\mathrm{ext}}$ represents the positive work (sum of the positive increments over one step) produced by the total mechanical energy (Don et al. 2007). For each subject, was computed by considering the trajectory of the whole body center of mass (COM), which was determined using the so-called 'reconstructed pelvis method' (Ranavolo 2011). TEC was normalized to body weight and step length. In summary, the TEC represents an index of the total mechanical energy expenditure used to move the subject's body while walking. Higher values are indicative of greater energy expenditure.
Gait speed, gait variability, and energy consumption matching procedures
We compared the gait ratios of the patients and controls using the following matching procedures: i) not matched by any of GS, CV, and TEC (26 patients and controls); ii) matched only by GS (26 patients and controls); iii) matched by both GS and CV (17 patients and controls); iv) matched by both GS and TEC (19 patients and controls); v) matched by both CV and TEC (16 patients and controls); and vi) matched by all GS, CV, and TEC (20 patients and controls). Each matching procedure was performed for only those patients and controls whose means were statistically comparable

Statistical analysis
The statistical analysis was performed with SPSS 17.0 software (SPSS Inc. Chicago, IL, USA). *P* values <0.05 were considered statistically significant. The Shapiro-Wilk test for normal distribution was preliminarily executed. Mean and standard deviation within subjects were computed for all of the parameters and ratios considered.
Unpaired t-test or the Mann-Whitney test was used to detect any significant differences in GS, CV, TEC, and relative distances between ataxic patients and controls in both the matched and unmatched conditions.
Pearson correlation test was used to correlate each relative distance with the SARA total score.

Results

Patients with ataxia showed significantly higher values for all relative distance values than the healthy controls in both unmatched and matched conditions, with the exception of the CV and TEC matched condition and the GS, CV, and TEC matched condition (Table).
Figure 1 shows the relationship between the gait ratios and TEC values in patients and controls with both GS and CV matched with respect to the golden ratio. Figure 2 shows the relationship between gait ratios and CV values in patients and controls with both GS and TEC matched. These two figures reveal that the differences between the gait ratios and the golden ratio are greater for the ataxic patients than for the controls.
Significant positive correlations in the unmatched condition were found between the normalized distance and (GaR/GoR) values and the SARA total score (r=0.483, p=0.009; r=0.421, p=0.026, respectively), as shown in Figure 3.
However, when partial correlations were performed by considering as control parameter GS, CV, TEC, GS-CV, GS-TEC, CV-TEC-GS and CV-TEC, no significant correlations were found.

Gait ratios		Unmatched	Speed-matched	Speed/TEC -matched	Speed/CV-matched	CV/TEC	Speed/CV/ TEC
St/Sw	**Pts**	0.247±0.20	0.239±0.21	0.235±0.22	0.218±0.20	0.166±0.14	0.144±0.09
	Cs	0.075±0.03	0.126±0.07	0.113±0.06	0.121±0.06	0.106±0.04	0.129±0.06
	p-values	**<0.001**	**0.014**	**0.032**	ns	ns	ns
	Cohen's D	1.20	0.72	0.76	0.66	0.58	0.19
Cd/St	**Pts**	0.069±0.04	0.065±0.04	0.063±0.04	0.062±0.03	0.051±0.03	0.050±0.02
	Cs	0.029±0.01	0.041±0.02	0.038±0.01	0.040±0.01	0.040±0.01	0.045±0.01
	p-values	**<0.001**	**0.011**	**0.025**	**0.040**	ns	ns
	Cohen's D	1.37	0.76	0.86	0.98	0.49	0.32
Sw/Dbs	**Pts**	0.409±0.31	0.330±0.23	0.329±0.26	0.300±0.20	0.231±0.13	0.351±0.36
	Cs	0.226±0.14	0.213±0.09	0.195±0.09	0.205±0.08	0.309±0.17	0.284±0.14
	p-values	**0.011**	**0.022**	**0.044**	ns	ns	ns
	Cohen's D	0.76	0.67	0.69	0.62	0.52	0.24

Figure 1.

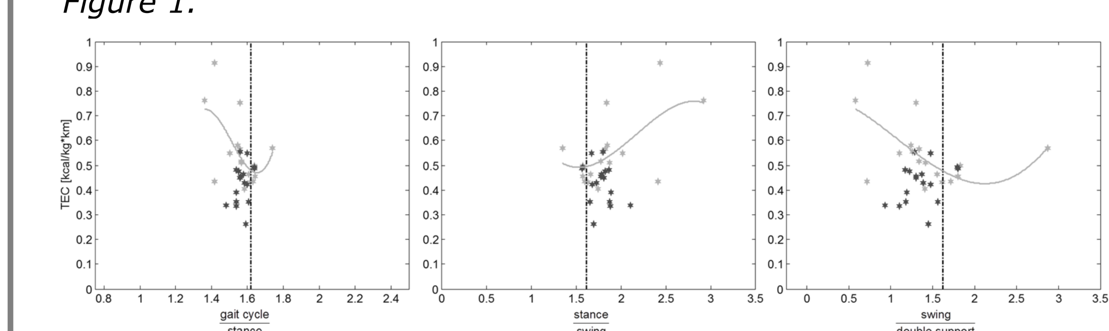


Figure 2

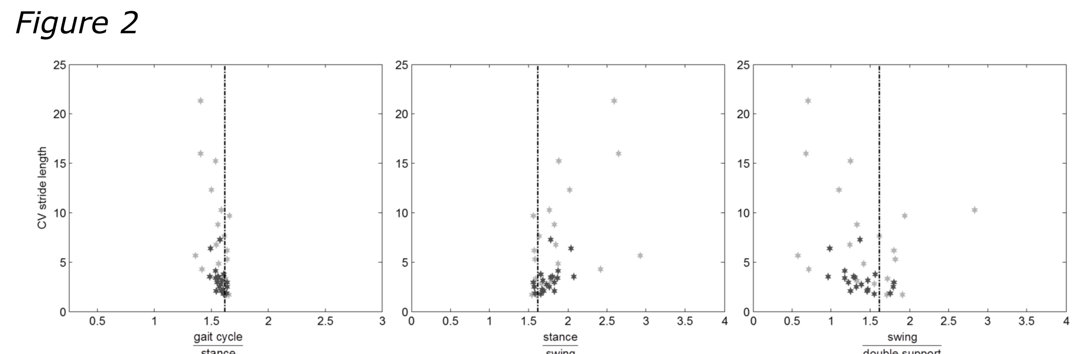
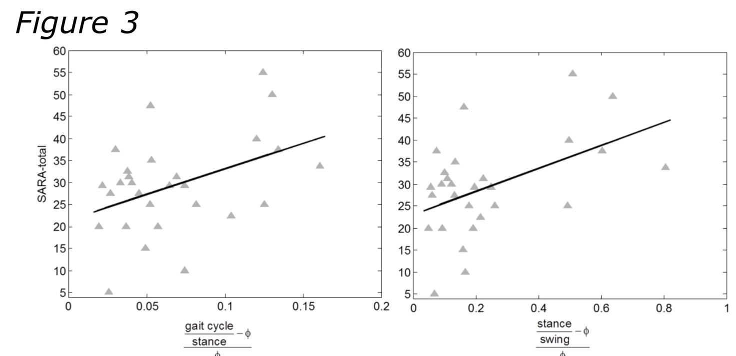


Figure 3



Discussion and conclusions

Ataxic patients showed gait ratio values that were more distant from the golden ratio values than those of healthy controls. Such differences in gait ratio values were related to both gait variability and energy consumption.
Our findings suggest that the harmony of the human gait may be not limited to an aesthetical aspect, but may have a functional significance and may be the result of complex relationships among several biomechanical determinants including balance-related gait variability and energy consumption.

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