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Research paper

The connection between anthropometry and gait harmony unveiled through the lens of the golden ratio

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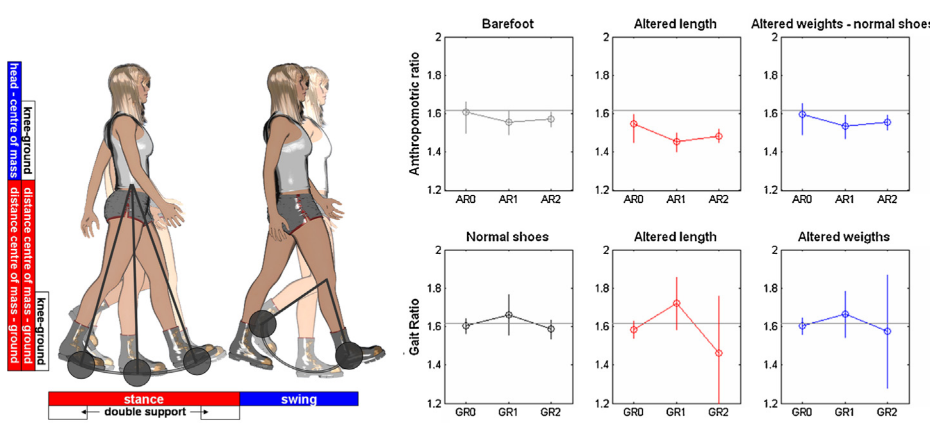
HIGHLIGHTS

- Human anthropometric measures and gait phases are both related to the golden ratio.
- The alteration of human anthropometric measures alter the gait phases.
- The alteration of mass of body segment does not affect the gait phases.
- Golden anthropometric ratios are reflected into golden gait ratios.

GRAPHICAL ABSTRACT



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ABSTRACT

In nature, many systems have a harmonic organization due to their fractal structure related to an irrational number called golden ratio. That is a constant proportion found in phases of human gait cycle, and is also found in the lengths of human body segments. In this study we tested if artificial alterations in anthropometric proportions may alter gait proportions. Twenty healthy subjects (29.15 ± 5.66 years) were enrolled in this study and asked to walk normally and with special shoes altering their anthropometric proportions. Further, to test if the relationship between gait phases and anthropometry could be due to the pendular mechanism of walking, subjects were also asked to walk with extra masses located on their shanks. Results showed that the artificial alteration of body segment proportions affected the gait ratio based on the proportion of time between stance and swing ($p = 0.015$). Conversely, no changes occurred during walking in weighted condition ($p = 0.394$). These results confirm the connection between anthropometric proportions and gait ratio, and suggest the idea that humans may have evolved into the actual anthropometric proportions for favoring a walking having a golden ratio based harmony, but research is required to verify this hypothesis.

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1. Introduction

Approximately twenty years ago, neuroscientists and clinicians started to be aware of the remarkable upsurge of interest in nonlinear dynamics and fractals theory used to explain the complexity of biological systems [1]. A fractal is an object or phenomenon composed of subunits and sub-subunits resembling the larger scale structure, a property known as self-similarity [2]. The simplest example of self-similarity is the irrational number $\phi = (1 + 5^{1/2})/2$ (Phi, about 1.6108), called golden ratio, extreme and mean ratio, or divine proportion [3].

Recently, the ratio between the duration of stance and that of swing phases of a gait cycle was found close to the ϕ value, implying for its property of self-similarity, that the following gait ratios: stride/stance, stance/swing, swing/double support, were not significantly different each other [4]. This may also be applied to units computed on larger scales, in accordance with fractal theory as shown in Fig. 1 that reports how also body anthropometry has proportions approximately close to ϕ [5]. This has implied that, in figurative arts, human body was often represented according to this proportion, particularly in sculptures and drawings [6,7]. Despite the fact that such an assumption has found its reasons in aesthetical studies rather than in anthropometric researches, a relationship between anthropometry and the ratio between stride and stance is conceivable.

The primary aim of this study is to verify the hypothesis that anthropometric proportions and gait phase proportions are strictly connected to each other. This hypothesis can be supported by the fact that gait ratios [4] and anthropometric proportions [5] were found both approximately equal to the golden ratio. However, the similarity of these two features does not mean that they are due to the same mechanism: for this reason we studied their possible connection testing if changing one of them may alter the other one. In particular, we tested if artificially altering the anthropometric proportions may alter the ratio between stance and swing, and hence the structure of walking in which each unit of gait cycle is in the same proportion with the relevant subunit (stride/stance, stance/swing, swing/double support are all approximately close to ϕ [4]).

Our primary hypothesis is that anthropometric ratios, found in proportion of ϕ, can be reflected into a gait ratio again in proportion of ϕ, analogously to the symmetry of the body that is reflected into the symmetry of movements during physiological walking.

If this connection exists, it could be related to the pendular mechanism of walking, an approximation proposed about two centuries ago [8]. In particular, the inverted pendulum model represents a basic mechanism of bipedal walking in which the center of mass of the body is considering vaulting over the stance leg in an arc [9]. An inverted pendulum is an unstable system, but considering an egocentric reference system, it can be easily transformed into a simple pendulum in which the foot vaulting under the body center of mass in an arc (as occurs when a subject walks on a treadmill, as shown in Fig. 2). Despite the simple pendulum is an ideal system and this model applied to walking was further criticized in favor of a force-driven harmonic oscillator [10], it is conceivable the closer movement is to that of a pendulum, the more energy can be recovered during walking [11]. It is the case, for example, of passive dynamic walking machines [12]. The fundamental property of a pendulum, known as principle of isochronisms, is that its period of oscillation depends solely on the length of the segment (and not on other parameters, such as its mass). This is another approximation, in fact this principle is appropriate only for a simple pendulum and only for small angles of oscillations. Conversely, human body is formed by different segments and some of them move through large ranges of motion during walking. Despite these differences, many studies, focused on the mechanical energy exchange and on the effect of leg length change, reported that walking is well approximated by a pendulum-like behavior for the stance leg and also by its corollary related to the swing leg [8,9,11,13–16].

To verify the hypothesis of a relationship between anthropometric and gait ratios, both related to the golden ratio, we tested if gait ratio may be changed by an artificial change in anthropometric proportions obtained with special shoes that increased the length of shank-foot compound in percentage more than the length of the whole lower limb. As control condition, we tested subjects applying an adjunctive mass to the center of mass of the same compound. Because of a change in mass does not alter the anthropometric ratio, we hypothesized a non significant effect on gait ratio.

2. Material and methods

2.1. Participants

Twenty healthy subjects participated to this study (on average: age = 29.15 ± 5.66 years, stature = 1.71 ± 0.089 m, mass = 68.80 ± 10.66 kg; gender: 11 males, 9 females). During upright standing, we measured stature, mass and distance from ground of L3 (that is in proximity to where the centre of mass of entire body moves during standing and walking [14,17]), lateral epicondyle of the femur, and head of fibula (on average: 171.3 ± 8.9 cm, 68.8 ± 10.7 kg, 106.6 ± 5.6 cm, 49.5 ± 3.0 cm, 44.2 ± 2.5 cm, respectively). From these measures, three anthropometric ratios (AR_0, AR_1, AR_2) theoretically close to the value of ϕ [5] are computed as shown in Fig. 1. Despite stature, mass and body segment lengths were significantly higher in males (t-test: $p = 0.002$, <0.001, 0.006, 0.046, 0.033, respectively for the above listed parameters), the investigated proportions between consecutive segments were not significantly different between males and females (t-test: $p = 0.752$, 0.704, 0.479, respectively for AR_0, AR_1, AR_2). This study was performed in accordance with the Declaration of Helsinki.

2.2. Protocol and measurements

Subjects were asked to stand on a strip of tape fixed on the ground (starting line) and to walk towards another strip placed on the ground at 8 m distance from the starting-line and parallel to it. All subjects performed the walking task in the three different conditions: normal walking, walking with extra masses located on shanks, and walking with special shoes with high soles for lengthening lower limbs, as described in detail below. All the tests were performed within a rectangular box formed by optoelectronic bars placed on the ground in our laboratory (Optogait®, Microgate, Italy; with inertial unit gyko located at the back in correspondence with L2–L3 spinous processes, sampling frequency = 100 Hz) [20]. Half of the electronic bars contained an infrared light emitter each 1.04 cm and the other half a receiver at the same distance. This optoelectronic system was used for measuring the gait spatio-temporal parameters in the central 4 m of walking pathway, for excluding from analysis accelerative part related to walking start and decelerative parts related to stop. All the data related to the steps performed in this central part during six trials were recorded by the optoelectronic system and further analyzed for each walking condition. Tests with special shoes and those with extra masses were performed in two different days; its sequence was randomized among subjects. First, subjects performed normal walking at self-selected speed. Then they were asked to walk slower than normal, and successively faster. After that, subjects wore special shoes or extra masses, and were asked to walk at self-selected speed. Because learning may occur with training [21,22], patients were also retested after a period of adaptation of 2, 4 and 6 min