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Abstract. Gait analysis was calculated in eighteen healthy male adults (mean age 26.33 ± 4.40 years, body mass 74.66 ± 5.62 kg) wearing a smart shirt based on body-worn accelerometer. This approximation relating the inverted pendulum model to a fractal approach of walking, where an approximation of using the golden ratio φ is seen in our case nearby the golden ratio (φ = 1.61). Our results demonstrated that the inverted pendulum model and walking speed are affected by anthropometric characteristics with $p < 0.001$. As a result, smart clothing based on body-worn accelerometer revealed to be an innovative and useful device to monitoring gait and in particular ideal gait approximation in a non-intrusive way and ecological approach in different environments.

Keywords: Golden ratio · Walking speed · Spatio-temporal gait parameters · Gait · Smart clothing · Wearable sensors

1 Introduction

Nowadays wearable biomedical sensors are able to monitoring gait analysis in non-intrusive way and ecological approach over an extensive period of time [1].

In fact, wearable inertial sensors system (IMUs) can be used to continuously assess gait during everyday activities in different environments [2].

In particular, wearable-based motion capture systems such IMUs placed on the lower limb are able to calculate the kinematics of the subject's walking but their use is time-consuming and it requires a long procedure for placing them on the body and successively extracting and processing gait analysis parameters. Indeed, IMUs some time reveal to be uncomfortable due to straps that affect the user's comfort, range of motion and performance.

Smart garment or "intelligent garment" based on body-worn accelerometer (trunk accelerometry) demonstrate to be comfortable and 'fit for purpose' for the identified user solving the previous problems [3–5].

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This technology enables the rehabilitation specialist to investigate indoor and outdoor gait performance with patient-specific measuring protocols and end-user interface adapted to the user's needs.

Spatiotemporal gait measurements are important parameters for distinguishing pathological and health walk, in preventing overload injuries and in monitoring the rehabilitation pathway [6, 7].

They can also be used for analyzing what we call the golden gait approximation, relating the inverted pendulum model to a fractal approach of walking, where an approximation of 1.61 ratio is seen between spatio-temporal parameters such as stance and swing of gait cycle [7–10].

$$\varphi = \frac{1+\sqrt{5}}{2} = \text{stance/swing} = 1.618\ldots \qquad (1)$$

In fact, every gait cycle (0.98 to 1.07 s duration [11]) is composed of these two phases the stance and the swing that corresponds when the foot advances in overground and in air respectively [12]. Each phase is divided by ulterior sub-phases such as initial contact, loading response, mid-stance, terminal stance and pre-swing for the stance phase and initial, mid and terminal swing for the swing phase [12].

Between these phases, the golden ratio can be verified as an expression of gait harmony in natural walking defining the "golden" gait.

The golden ratio, "phi" indeed is present in nature, math, physics, and sometimes deliberately used in design [13–16]. Iosa et al. [8–10] restated this as a well-known expression of consecutive Fibonacci terms:

$$\varphi = \text{Gait cycle/stance} = 1 + \frac{1}{1+\frac{1}{1+\frac{1}{1+\cdots}}} \qquad (2)$$

And using the previous relation (2) Iosa et al. [8] defined additional relations describing the slow, fast and comfortable walking.

In these relations, the equilibrium between stability (stance/swing) and advancement (double support/swing) describes "a golden gait" [8].

Starting from these assumptions, this paper aims to present a method to detect spatio-temporal parameter such as stance and swing and correlating them to the gait ratio approximation.

This is achieved in for monitoring gait analyses in eighteen male subject's volunteers that wore a smart t-shirt based on body-worn accelerometer (trunk accelerometry).

2 Materials and Methods

2.1 Participants

Eighteen healthy male adults participated as volunteers to the study (mean age 26.33 ± 4.40 years, body mass 74.66 ± 5.62 kg) signing the informed after ethical committee approval.

2.2 Protocol and Measurements

The subject wore a washable smart t-shirt intended for monitoring the heart rate activity and trunk body acceleration. The smart shirt presents two textrodes embedded into the cloth and a smart unit connected by two fasteners (nickel free material). The device is supported by a mobile app designed by Politecnico di Milano, (Department of Design SensibiLab, Lecco, Italy) for collecting and managing data related to 3D accelerations (Anterior-Posterior, Medio-Lateral and Vertical) and the ECG potential in real-time [5].

Anthropometric measurements such as stature, outside leg length, chest-feet length were collected before the acquisition started (Table 1).

Table 1. Anthropometric data (cm)

Variable	Mean	SE mean	SD	Variance	CV	Minimum	Maximum
Stature	180.28	0.44	6.51	42.40	3.61	171.00	192.00
Leg length	93.94	0.35	5.14	26.39	5.47	84.00	105.00
Chest-feet length	130.94	0.38	5.67	32.12	4.33	122.50	143.00

Three different acquisitions of the subjects walking for 5 m were acquired with a speed (between 1.30 m/s and 1.55 m/s).

Two optical bars constituted of 96 LEDs (Optogait, Microgait, Italy) delimited the five meters' walkway and were used as a reference system for speed, Fig. 1.

Fig. 1. Setup of measurements

Experiments outside the speed range previously described were excluded.

A total of 12 steps for each subject were collected. Spatiotemporal parameters such as gait phases, speed and cadence were processed and calculated in Matlab and Excel.

In particular, the step length was estimated using the following formula

$$S\_anth = C * H \tag{3}$$

where H is the height (stature) and C is a coefficient depending on gender [17, 18].

While gait phases were identified using the vertical acceleration extrapolated from the smart shirt and successively elaborated in Matlab and in Excel according to Auvinet et al. [19].

3 Results and Discussion

Spatiotemporal parameters such as gait cycle and phases, cadence, step length and, speed were calculated using the vertical acceleration and anthropometric data of the subjects that wore the smart shirt.

Figure 2 below describes an example of the vertical accelerometric component of one stride according to Auvinet et al. [19].

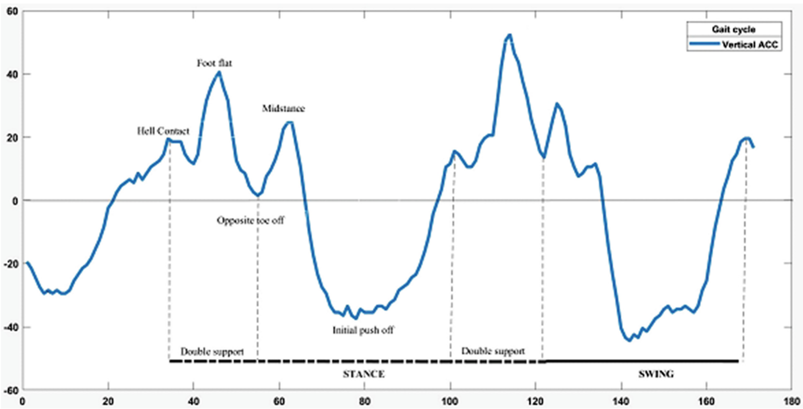

Fig. 2. Example of identification of the gait cycle and related gait phases using the vertical acceleration in one subject that wore the smart shirt

Walking speed, stance and swing phases were measured in the 18 subjects. Results are shown in Table 2.

Average walking speed was 1.374 m/s with a mean percentage of stance as 60.30 and of swing 39.70. These results are in accordance with the literature [12, 19–21].

In particular, the average speed demonstrates that the average population walked at fast and not a comfortable speed considering the relation calculated in previous studies [8–10].

Table 2. Spatiotemporal gait parameters calculated using the smart shirt (ST = stance, SW = swing, speed (m/s), %ST = percent of stance, %SW = percent of swing).

Variable	Mean	SE mean	SD	Variance	CV	Min	Max
ST	0.65	0.00236	0.03	0.001	5.31	0.54	0.74
SW	0.43	0.00217	0.03	0.001	7.41	0.32	0.52
%ST	60.29	0.141	2.07	4.32	3.45	55.11	67.93
%SW	39.70	0.141	2.07	4.32	5.24	32.06	44.88
Speed	1.37	0.00704	0.10	0.010	7.53	0.14	1.57

Anthropometric data were correlated (pairwise Pearson) with speed to understand how the speed was influenced by anthropometric characteristics as shown in Table 3.

Speed resulted to be correlated with step length, chest feet length and leg length with $p < 0.0010$.

Table 3. Pairwise Pearson correlations between anthropometric data, step length and speed.

Sample 1	Sample 2	Correlation	95% CI for ρ	p-value
Leg length	Stature	0.865	(0.827, 0.895)	0.0001
Chest-feet length	Stature	0.885	(0.852, 0.911)	0.0001
Speed	Stature	0.230	(0.100, 0.353)	0.0010
Chest-feet length	Leg length	0.741	(0.674, 0.796)	0.0001
Step length	Leg length	0.865	(0.827, 0.895)	0.0001
Speed	Leg length	0.174	(0.042, 0.301)	0.0101
Step length	Chest-feet length	0.885	(0.852, 0.911)	0.0001
Speed	Chest-feet length	0.220	(0.090, 0.344)	0.0010
Speed	Step length	0.230	(0.100, 0.353)	0.0010

These results demonstrated the influence of these variables on the inverted pendulum model [7, 22] suggesting to relate it to a fractal approach of walking, where an approximation of using the golden ratio φ is seen, as a 1.61 ratio [8–10] between gait cycle and stance, stance/swing or swing/double support (DS).

In addition, three gait ratios describing our population were calculated and shown in Table 4. The ratio between the gait cycle and the stance reveals to be nearby an approximation of the golden ratio ($\varphi = 1.61$).

While according with Iosa et al. [8] the other two ratio reveals if the population preferred the advancement (SW/ST), the stability (SW/DS) or a balance between the two is analyzed in Fig. 3.

Table 4. Gait ratios

Variable	Mean	SE mean	SD	Variance	CV	Minimum	Maximum	Range
GC/ST	1.66	0.003	0.056	0.003	3.39	1.47	1.814	0.34
ST/SW	1.52	0.009	0.138	0.019	9.05	1.22	2.11	0.89
SW/DS	2.70	0.755	11.10	123.21	410.87	1.00	164.97	163.97

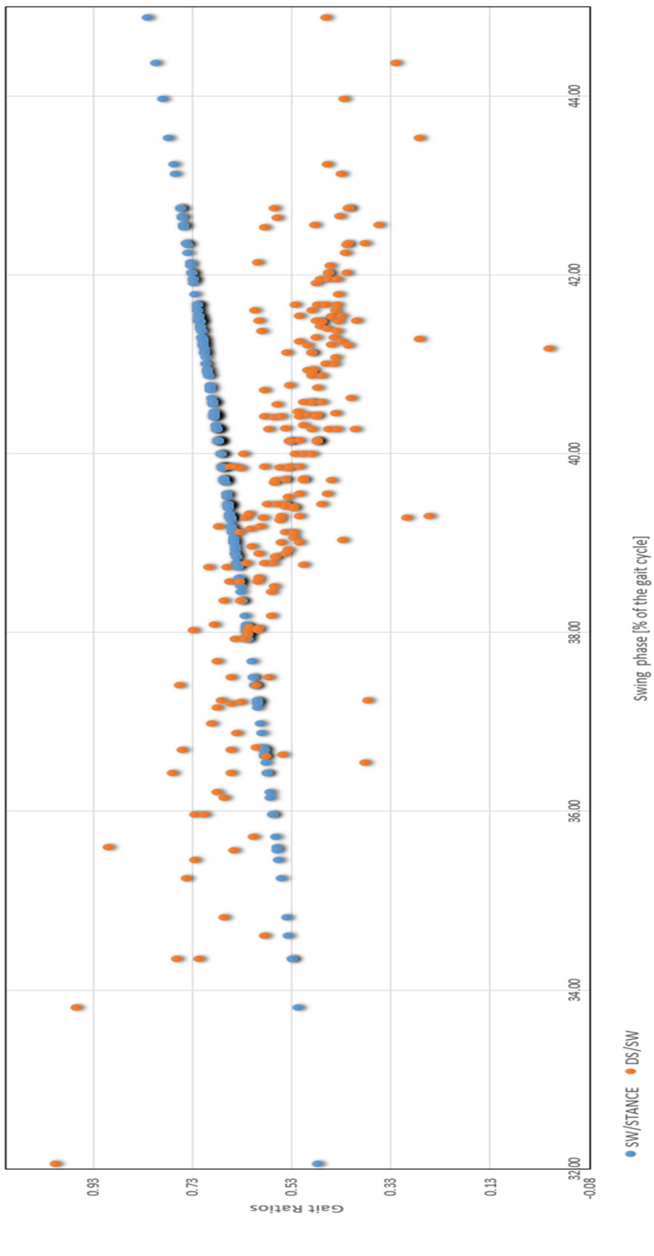

Fig. 3. Describes the golden equilibrium as intercept between stability (SW/DS) and advancement (SW/ST) for the entire population.

Analyzing Fig. 3, it is possible to see the behavior characteristics of the entire population, for example, if they preferred fast (stance = 60%, [8]), slow (stance 66.6%, [8]) or comfortable walking (stance = 62.5%, [8]). Also, considering the intercept between advancement (SW/ST) and stability (SW/DS), it is possible calculating the equilibrium point between the two as it was also described by Iosa et al. [8], that in our case is around 38%.

4 Conclusion

This study permits us to verify the use of smart clothing based on trunk accelerometer as an innovative way of monitoring gait analysis in an ecological approach in different environments.

Our results demonstrated that the inverted pendulum model and walking speed are affected by anthropometric characteristics with $p < 0.001$ where the ratio between the gait cycle and the stance reveals to be nearby an approximation of the golden ratio ($\varphi = 1.61$).

Future perspective will be addressed to exploring the use of smart clothing for monitoring running parameters.

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