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Smart Clothing for Monitoring Gait

Sofia SCATAGLINI[a,b,d,1], Guillaume ABRAN[c], Eddy ROOSENS[a,c], Damien VAN TIGGELEN[a], Robby HAELTERMAN[b] and Stijn VERWULGEN[d]
[a] *Military Hospital Queen Astrid, 1120 Brussels, Belgium*
[b] *Royal Military Academy, 1000 Brussels, Belgium*
[c] *Haute Ecole Libre de Bruxelles Ilya Prigogine 1070 Brussels, Belgium*
[d] *Department of Product Development, Faculty of Design Sciences, University of Antwerp, Antwerp, Belgium*

Abstract. This paper presents a method to calculate spatiotemporal parameters using a chest-worn accelerometer. Accuracy was compared with an optical system that consists of a walkway of transmitting and receiving bars (Microgait, Optogait, Bolzano, Italy). To this purpose, seventeen healthy male wore a smart shirt based worn accelerometer performing five meters of walkway delimited by five meters of optical bars OptoGait™ for three times. Spatiotemporal parameters such as gait cycle and gait phases were analysed and compared using the two systems. Smart shirt based on chest-worn accelerometer revealed to be a non-intrusive way of calculating gait cycle, phases and sub-phases. In addition, the inverted pendulum model based on chest body-worn accelerometer revealed to be a good model for calculating step length variation and consequently the speed. Our results, are in line with previous literature presenting an average of 60.24 % of stance phase, 39.75% of swing phase, a foot flat subphase of 17.60%, a terminal stance subphase of 21.42%, a pre-swing subphase of 10.65%, a step length of 0.74 m for an average speed of 1.37 m/s using the smart shirt.

Keywords. Smart Clothing, Gait Analysis, Monitoring, Spatio-Temporal Parameters, Human Kinematics, Biomechanical Modelling, DHM

1. Introduction

Monitoring and modeling physical functions in rehabilitation is becoming important to achieve/establish new and improved rehabilitation [1]. Instrumented gait analysis is commonly used to quantify and evaluate pathologies manifested by gait disorders [2-5]. Related to the lower body part, gait analysis is used to assess patients with affected physical activity [2-4].

This laboratory-based technique requires the use of a gold standard device, such as an optoelectronic system. Gold standard measurement devices are often costly, not intuitive, time-consuming and not suitable for outdoor use and evaluating subjects in an ecological context [6]. Nowadays smart clothing based on a body-worn accelerometer can respond to the problem [7]. This results in an intelligent garment that contains embedded sensors for monitoring bio-signals but also accelerometers or Inertial Measurement Unit (IMU) sensors for monitoring the subject's kinematics over an extensive period in a non-intrusive way and in an ecological approach [7-9].

[1] Corresponding Author, Email: sofia.scataglini@mil.be; sofia.scataglini@uantwerpen.be.

Previous studies demonstrated the use of wearable technology for measuring gait parameters [10-12] but few studies demonstrated the possibility to monitor gait using a smart cloth [13]. The majority of wearable devices are attached to shoes or to the body by straps, that revealed to be uncomfortable, limiting the wearer's movements and consequently his/her performance. Wearable technology integrated into a smart cloth can respond to user needs during daily activities, where monitor locomotion is essential [14].

Natural walking consists of consecutive gait cycles [2,3]. Each cycle is characterizing by two phases: the stance (60% of the gait cycle) where the foot remains in contact with the ground and the swing (40% of the gait cycle) where the foot is in the air (Figure 1).

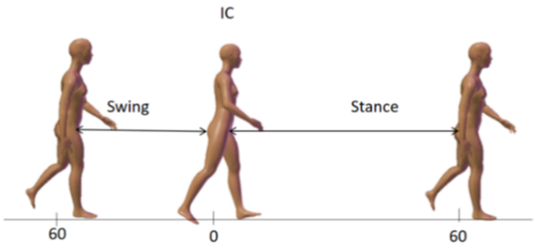

Figure 1. Gait cycle and phases. In order to show the concept, a dedicate DHM was created using MakeHuman and rigged in Blender with a BVH file of walking captured data acquired in one subject of this study [8].

Additionally, each phase is divided by sub-phases initial contact (IC), loading response (foot flat), mid-stance, terminal stance and pre-swing (toe-off) for the stance phase and initial, mid and terminal swing for swing [2,3,15] (Figure 2).

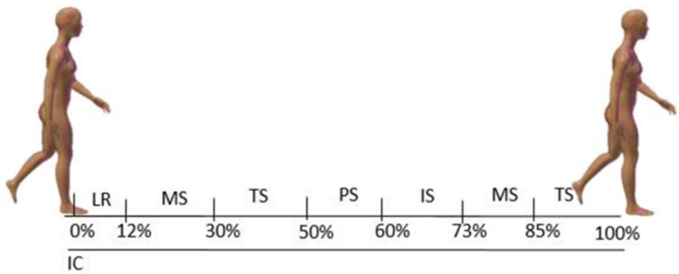

Figure 2. Gait cycle and the related sub-phases (IC=initial contact, MS=mid-stance, TS=terminal stance, PW=pre-swing, IS=initial swing, MS=mid-swing, TS=terminal swing).

Together with all the phases, there are other spatio-temporal parameters [2,3,15,16]: step length, cadence (step/min) and speed.

The step length (m) is the distance between the initial contact of one foot and the initial contact of the other foot [16]. The cadence (step/min) corresponds to the number of steps in a defined time; often expressed as a number of steps per minute [15]. The speed, also referred as the "sixth vital sign", can predict health status [17].

Starting from the previous assumptions, the objective of our research is to present a study that investigates the use of smart clothing for measuring spatio-temporal gait parameters in healthy individuals.

2. Methods

2.1 Participants

Seventeen healthy male volunteers participated in this study. Their anthropometric characteristics are summarized in Table 1. Subjects were instructed about the experiment and signed the informed consent. This study was also approved by the ethical committee (CE2019/32).

Table 1. Anthropometric characteristic of study population.

Anthropometric parameters	Mean (SD)	Minimum	Maximum
Age (years)	25.647 (6.123)	21	47
Stature (m)	1.807 (0.065)	1.71	1.92
Body mass (kg)	74.882 (7.398)	60	89
BMI (kg/m²)	22.873 (1.263)	20.047	24.915
Leg length (m)	0.94 (0.053)	0.84	1.05
Chest height (m)	1.31(5.992)	1.22	1.43

2.2 Protocol

Subjects were instructed to perform five meters of walkway delimited by five meters of optical bars OptoGait™ (Bolzano, Italy), wearing a smart t-shirt (Politecnico di Milano, SensibiLab, Lecco, Italy, Figure 3) for three times (Figure 4). To obtain a subject specific normal walking speed, subjects were first asked to perform a few laps without recording, to familiarize themselves with the environment and find their comfort speed [18].

Figure 3. Smart shirt realized by Politecnico di Milano (SensibiLab, Lecco, Italy).

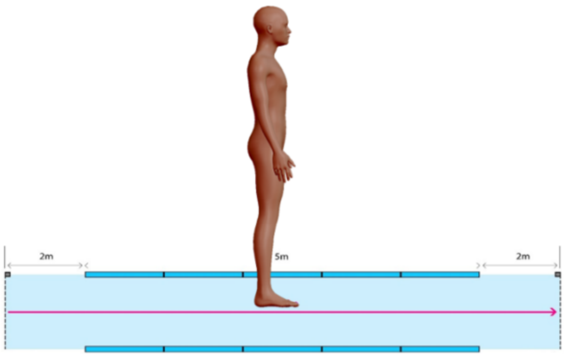

Figure 4. The five-meter walkway using the Optogait (OptoGait™, Microgait, Bolzano, Italy).

The five-meter walkway, OptoGait™ (Microgait, Bolzano, Italy) consists of five transmitting bars (each one contains 96 LEDs) and five receiving bars (each one contains 96 LEDs) communicating on an infrared frequency [19]. The smart shirt created by the (Politecnico di Milano, SensibiLab, Lecco, Italy) integrates two textrodes embedded into the cloth and a three-axial accelerometer, connected by two fasteners (nickel-free material). The t-shirt is connected with a dedicated App for collecting and managing data of tri-axial-acceleration (anterior-posterior, medio-lateral and vertical) and ECG recording in real-time [20-22].

Spatiotemporal parameters such as the time of the gait cycle (s), the duration of the swing and stance phase (s), the percentage of the swing phase, stance phase (%), the percentage of the loading response, flat foot, terminal stance and pre-oscillation (%), the percentage of the phase double contact (%), cadence, speed (m/s) and the gait to stance ratio were measured with the two devices and successively calculated. We have analysed 204 datasets (17 subjects x 3 trials of 4 steps each=204 datasets).

Spatio-temporal parameters using the OptoGait™ (Microgait, Bolzano, Italy) were automatically calculated by their software. In the smart shirt the vertical acceleration was used for calculating the gait cycle and their eight phases according to Auvinet et al. [23] (Figure 5).

Step length was calculated using two methods (SL_1 and SL_2).

The first one is represented by the product between the stature S and an anthropometric coefficient C, Eq.(1), [24-25].

$$SL1 = C*S \tag{1}$$

While the second method considers the pendulum model, according to Fusca et al. [12-25, 26], Eq.(2).

$$SL = 2\sqrt{2L * hCOM - hCOM^2} \tag{2}$$

In this equation, L is the length of the lower limb and hCOM is calculated by using the following formula based on the work of Fusca et al. [12]:

$$hCOM = 2 * Av * \left(\frac{T}{2\pi}\right)^2 \tag{3}$$

where in our case, Av is the maximum value of the vertical acceleration calculated at chest level and T is the period of the step.

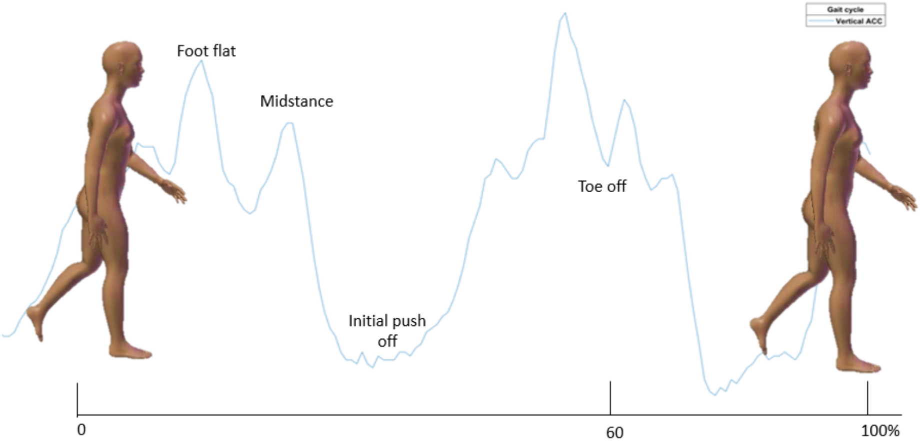

Figure 5. Gait phases identification using the vertical acceleration extrapolated by the smart shirt realized by Politecnico di Milano (SensibiLab, Lecco, Italy).

Introducing the Eq.(3) in the Eq.(2) with a quadratic relationship, SL2 can be determinate as follow:

$$SL2=\sqrt{SL} \quad (4)$$

While, two different speed (S_1, S_2) for the SL_1 and SL_2 respectively were calculated using the following formula:

$$S = \frac{2*K}{GC} \quad (5)$$

In this equation K is the step length and CG is the gait cycle duration.

3. Results and Discussions

Spatio-temporal parameters measured with the smart t-shirt and the OptoGait are shown in Table 2 and 3. In particular, the smart shirt showed to have a stance time of 0.653 ± 0.033 seconds, a swing time of 0.431± 0.027 seconds and an average time cycle of 1.085 ± 0.047 seconds according to the previous literature [12, 23-27]. These values were observed to be different in the case of the Optogait where we had an average stance time of 0.705 (±0.045) seconds for an average oscillation time of 0.393 (± 0.026) seconds and an average time cycle of 1.098 (± 0.055) seconds (Table 2). A Spearman correlation test between these parameters demonstrated a medium correlation with the time of the stance and the swing and the time of gait cycle with $p<0,0001$. By contrast, the resulting percentage of stance and swing, being 60.24 % and 39.75% for the smart shirt and 64.18% and 35.81% for swing were not correlated using the Spearman correlation test (Table 2). The percentage of foot flat, terminal stance and pre-swing were not correlated between the two devices. In term of step length calculation, the two formulas, Eq.(1) and Eq.(2) were applied for determining the step length using the smart shirt (Table 4).

Table 2. Mean, minimum, maximum and correlation of spatio-temporal parameters (Tps-CG=gait cycle duration, Tps-ST= stance phase duration, Tps-SW= swing phase duration, ST=stance, SW=swing, DS=double support, LR=loading response, FFL=foot flat, TS=terminal stance, PSW=pre-swing) calculated using the smart shirt and the Optogait.

	Smart t-shirt		***Optogait***			
Spatio-temporal parameters	**Mean (SD)**	**Minimum Maximum**	**Mean (SD)**	**Minimum Maximum**	**Spearman's rs**	**p-value**
Tps GC (s)	1.085 (0.047)	0.967 1.209	1.098 (0.055)	0.972 1.286	0.6725	<.0001
Tps ST (s)	0.653 (0.033)	0.546 0.748	0.705 (0.045)	0.614 0.848	0.4176	<.0001
Tps SW (s)	0.431 (0.027)	0.351 0.514	0.393 (0.026)	0.338 0.473	0.5410	<.0001
ST (%)	60.247 (1.770)	55.118 65.648	64.189 (1.998)	59.6 69.9	0.1377	0.0854
SW (%)	39.752 (1.770)	34.351 44.881	35.81 (1.998)	30.1 40.4	0.1375	0.0859
DS (%)	20.991 (2.950)	9.655 28.057	27.321 (3.107)	20.3 36.8	0.2010	0.0116
LR (%)	10.631 (1.618)	7.246 15.441	12.654 (6.335)	0.2 25.4	0.0758	0.3453
FFL (%)	17.606 (2.368)	10.791 24.489	13.846 (1.605)	10.1 25.4	0.1191	0.0904
TS (%)	21.428 (2.527)	14.084 27.941	38.489 (8.487)	21.5 59.3	-0.2285	0.0010
PSW (%)	10.658 (1 .648)	7.092 15.714	13.491 (1.648)	9.8 18	0.0937	0.2430

Table 3. Mean, SD (standard deviation), Minimum, Maximum, Median (SLO=step length calculated with the Optogait, SO=speed calculated with the Optogait, SL1=step length calculated using Eq.(1), SL2=step length calculated with smart shirt using Eq.(4), S1=speed calculated using the SL1in Eq.(5), S2=speed calculated using the SL2 in Eq.(5) (Figure 6).

Variable	**Mean**	**SD**	**Minimum**	**Median**	**Maximum**
SLO	0.786	0.038	0.69	0.780	0.89
SL1	0.750	0.027	0.710	0.747	0.797
SL2	0.743	0.033	0.654	0.742	0.865
SO	1.456	0.047	1.260	1.460	1.55
S1	1.385	0.060	1.249	1.386	1.571
S2	1.371	0.071	1.180	1.360	1.606

Optogait step length detection (SLO) was automatically determined using the Optogait software, (Table 3). A small correlation ($r=0.229$, $p<0.005$) was found between the SLO and SL1. By contrast the speed calculated with Optogait was not correlated with the speed S2 but with the SL2 ($r=-0.201$, $p<0.005$) and SL1 ($r=-0.230$, $p<0.005$). While the step length SL1 was correlated with SL2 ($r=0.456$, $p<0.0001$) (Table 4). As a result, their speed was also correlated ($r=0.544$, $p<0.0001$) as shown in Table 4.

While, the step length calculated with Eq.(1) does not take in consideration the step length variation as the inverted pendulum model Eq.(4). According to the previous studies, 1.4 m/s is considered the natural walking speed and this corresponds to a value of the stance phase between 60-62% and 38-40% of the swing, [12, 23-27]. This result is in accordance with our evaluation using the smart shirt and calculating the speed with Eq.(5) and this is the case when we are calculating the variation of the chest height using Eq.(4).

Table 4. Step length and speed correlation between the smart shirt and the Optogait (SLO=step length calculated with the Optogait, SO=speed calculated with the Optogait, SL1=step length calculated using Eq.(1), SL2=step length calculated with smart shirt using Eq.(4), S1=speed calculated using the SL1in Eq.(5), S2=speed calculated using the SL2in Eq.(5).

Variables	Spearman's rs	95% CI		p-value
SLO, SL1	0.229	0.090	to 0.355	0.0010
SO, SL2	-0.201	-0.329	to -0.065	0.0042
SO, SL1	-0.230	-0.356	to -0.095	0.0009
S2, SLO	-0.289	-0.411	to -0.158	<0.0001
S1, SLO	-0.288	-0.354	to -0.0931	0.0011
SL1, SL2	0.456	0.340	to 0.558	<0.0001
S1, S2	0.544	0.439	to 0.634	<0.0001

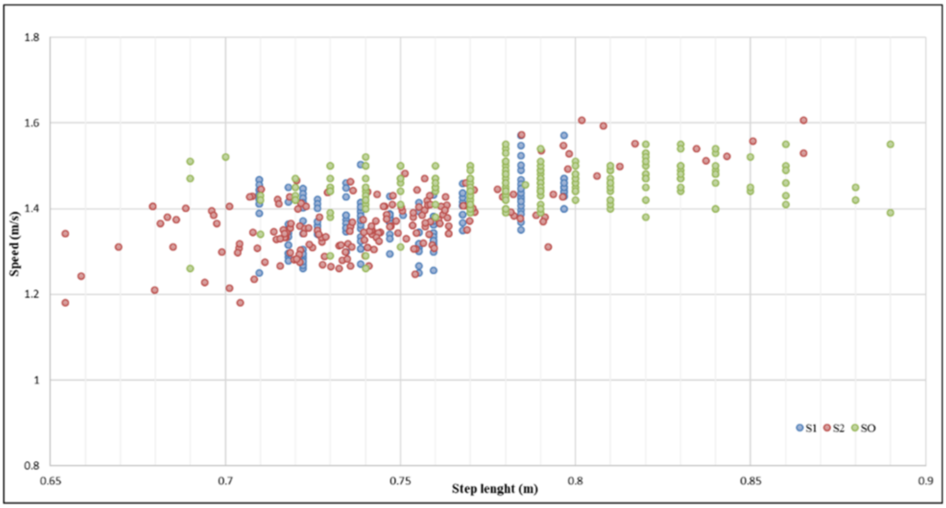

Figure 6. Step length and walking speed (SL1=step length calculated using Eq.(1), SL2=step length calculated with smart shirt using Eq.(4), S1(in blue)=speed calculated using the SL1in Eq.(5), S2(in red)=speed calculated using the SL2in Eq.(5) and SO (in green)=speed calculated using the Optogait).

4. Conclusion

In conclusions, the smart shirt based on a chest-worn accelerometer revealed to be a non-intrusive way of calculating the spatio-temporal parameters in an ecological approach according with the previous literature.

In fact, our results, are in line with previous literature presenting an average of 60.247 % of stance phase, 39.752% of swing phase, a foot flat of 17.60%, a terminal stance of 21.42%, a pre-swing of 10.65%, a step length of 0.74 m for an average speed of 1.371 m/s using the smart shirt.

Several methods were used for calculating either the step length and the speed. Indeed, this study presents a study limitation regarding the comparison of these measurements using a commercial system that not correspond the gold standard scientific method such as camera based (e.g. Vicon system). And, in this study Spearman correlation test demonstrates that the chest inverted pendulum model adopted in this study can be used for calculating step length variation and speed.

As a result, future perspective will be addressed in evaluating this method using the gold standard scientific method to assess gait analysis.

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