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Abstract

The availability of wearable sensors allows shifting gait analysis from the traditional laboratory settings, to daily life conditions. However, limited knowledge is available about whether alterations associated to different testing environment (e.g. indoor or outdoor) and walking protocols (e.g. free or controlled), result from actual differences in the motor behaviour of the tested subjects or from the sensitivity to these changes of the indexes adopted for the assessment. In this context, it was hypothesized that testing environment and walking protocols would not modify motor control stability in the gait of young healthy adults, who have a mature and structured gait pattern, but rather the variability of their motor pattern.

To test this hypothesis, data from trunk and shank inertial sensors were collected from 19 young healthy participants during four walking tasks in different environments (indoor and outdoor) and in both controlled (i.e. following a predefined straight path) and free conditions. Results confirmed what hypothesized: variability indexes (Standard deviation, Coefficient of variation and Poincaré plots) were significantly influenced by both environment and walking condition. Stability indexes (Harmonic ratio, Short term Lyapunov exponents, Recurrence quantification analysis and Sample entropy), on the contrary, did not highlight any change in the motor control.

In conclusion, this study highlighted an influence of environment and testing condition on the assessment of specific characteristics of gait (i.e. variability and stability). In particular, for young healthy adults, both environment and testing condition affect gait variability indexes, whereas neither affect gait stability indexes.

Key words: daily life gait; variability indexes; stability indexes; indoor and outdoor walking; inertial sensors; accelerometers.

Introduction

TABLE NOMENCLATURE HERE

Laboratory assessment has been the standard setting for quantitative gait analysis for several decades. However, in recent years, the availability of wearable inertial measurement units has allowed to quantitatively and easily assess gait also out of the lab [1,2].

The assessment of gait out of the laboratory, whereby it is not constrained to a predefined path, aims at reproducing a testing condition more similar to that of daily living. This type of assessment is particularly interesting for the investigation of gait performance and of the underlying motor control with a specific focus on the quantification of dynamic stability and fall risk. It can potentially overcome the limitations (e.g. limited acquired number of stride) of data acquired in laboratory conditions [2]. Moreover, the monitoring of gait, as obtained from various types of quantitative descriptive indexes, provides information that can significantly impact the design of more effective training and rehabilitative interventions [3].

Several studies [2,4,5] analysed the gait pattern of faller and non-faller elderly and pathological subjects in daily-living conditions using indexes assumed to quantify the motor performance and the underlying motor control. However, limited knowledge is available regarding if and how the testing environment (e.g. indoor or outdoor) and the imposition of a specific walking path (e.g. free or controlled) might affect gait pattern and performance, and whether the indexes, commonly adopted to quantify these aspects, are sensitive to these changes.

Therefore, it is crucial to understand whether the alterations, associated to different testing conditions, result from actual differences in the motor behaviour of the analysed subjects or rather from the sensitivity of the indexes adopted for the assessment.

It is almost impossible to infer this knowledge analysing elderly and/or pathologic subjects, however for young healthy subjects, it can be assumed that the motor control of a mature and structured gait pattern [6], will not be significantly affected by the testing conditions. Therefore, environmental and testing conditions are not expected to modify the motor control stability in the gait of a young healthy adult, who has the ability to face far more challenging conditions, but changes in the variability of the motor pattern could be expected as an adaptation to the environment in order to maintain stability.

The definition and applicability of the concepts of variability and stability is well defined in mechanics, while the two are often used addressing similar meanings in gait analysis referring to motor control. On one hand, in a complex dynamic system as human gait, variability could arise from the deterministic dynamics of the system (e.g. when a chaotic attractor is present as in human gait [7]). It follows that the measured variability is a reflection of the multiple degrees of freedom of the system and does not necessarily imply destabilization of the system itself [7]. On the other hand, stability could arise from both the intrinsic properties of the system (i.e. motor control) and the specific movement pattern (i.e. gait) [7,8].

It could be argued that while gait variability is an indirect assessment of the motor control through gait performance (e.g. stride time), stability is instead a direct evaluation of the performance of the underlying motor control [7–9].

Besides traditional approaches based on the quantification of mechanical features of gait [10], a number of indexes have been proposed to quantify aspects more related to motor control [11,12]. These indexes can be generally grouped as variability (i.e. standard deviation, coefficient of variation, Poincarè plots) and stability indexes (i.e. Lyapunov exponents, harmonic ratio, sample entropy and recurrence quantification analysis) [11], based on their mathematical implementation and which characteristics of the analysed signal they are expected to quantify.

According to the above mentioned concepts of variability and stability, variability indexes, usually applied on stride time data, are meant to assess changes in the peripheral realization of the gait pattern [7,8,13,14], whereas stability indexes, usually applied on trunk acceleration data, are meant to assess the stability of the trajectory of the centre of mass. Indeed, recent studies [13,15,16], analysing both healthy (from 4 years-old children to 25 years-old young adults) and pathological subjects (stroke), analysed the role of the variability in joint kinematics in determining a successful control of the stability of the centre of mass trajectory, approximated by the lower trunk [7,17,18]. Stride time and trunk acceleration data are two manifestations of the same control system in healthy and pathologic subjects [19,20].

With this differentiation in mind, and since healthy young subjects have a well achieved and stabilized gait pattern [6], our hypothesis is that, when testing young healthy subjects walking along both controlled and free paths, the indexes related to motor stability are not expected to be significantly affected. Conversely, modifications should be observed in variability indexes, due to the possibility to adjust the gait pattern to the environment in order to maintain stability.

In particular, an increase in variability indexes both from indoor to outdoor and from controlled to free conditions is expected, while no significant changes in gait stability indexes should be observed.

The present study aims at testing this hypothesis evaluating the influence of environment (indoor and outdoor) and testing conditions (controlled and free) on gait assessment when using variability and stability indexes in a young healthy population.

Materials and Methods

In a cross-over study, nineteen healthy young volunteers (5 females, 14 males, 28±3 years, 1.75±0.09 m, 72.0±9.2 kg) were recruited after having provided informed consent. Only subjects with no self-reported history of locomotor disturbances or injuries that could affect their normal walking behaviour, or cause fatigue during the experimental protocol were included in the study. The University of Sheffield's Research Ethics Committee granted ethical approval for the study.

Subjects wore two inertial measurement units (Opal, APDM, USA): one located on the lower trunk on the fifth lumbar vertebra, and one attached frontally on the right shank, 2 cm above the lateral malleolus, for stride detection [10]. Measures of accelerations of the trunk and angular velocity of the right shank were recorded at 128 Hz.

Subjects completed four walking tasks in two different environments (indoor and outdoor) and in both controlled (i.e. following a predefined straight path) and free conditions (see details in Table 1) [21], indicated as ICW (Indoor Controlled Walking), OCW (Outdoor Controlled Walking), IFW (Indoor Free Walking) and OFW (Outdoor Free Walking), respectively. All participants performed the walking task in the different testing conditions, in one day, following the same order: OCW, OFW, IFW, ICW.

TABLE 1 HERE (walking conditions)

- ICW was performed in a quiet corridor of the university building, and participants were asked to walk on a straight line for 20 m. The distance was measured and marked on the floor using adhesive tape.
- For IFW condition, participants were instructed to walk inside the university corridors starting from the main entrance, with no restriction of route, opening and closing doors as necessary. The data was always collected during normal working hours, in mostly busy corridors.
- OCW was performed in a quiet open space within the university premises, on a flat tarmac surface.
- For OFW, participants were instructed to walk freely in the city centre, with no restrictions regarding route or walking speed, but avoiding stairs.

During IFW and OFW the participants did not have verbal interaction with other people, but they may have had to adjust their gait due to the presence of others in the surroundings. Interactions with other people were possible, particularly during IFW. Finally, during IFW and OFW turns could also be recorded in addition to straight walking. However, turns and resting periods were segmented and excluded from the analysis. Turn events with durations between 1-3 stride time and angles around the vertical axis over 40° were identified and removed using the method specified by El-Gohary et al. [22]. Resting periods were defined as those when the time between subsequent heel strikes [10] was higher than 1.5 s.

For each participant and each condition 80 strides were analysed, since this was the maximum number of strides available in all conditions.

Gait variability was assessed on stride times using the variability indexes:

- Standard Deviation (SD)
- Coefficient of Variation (CV) [23]
- Short term variability of stride estimated *via* Poincaré plots (PSD1) [24].

Gait stability was assessed applying to the vertical (v), medio-lateral (ml), and antero-posterior (ap) trunk acceleration components the stability indexes:

- Harmonic Ratio (HR), calculated decomposing the whole signal components into its harmonics (HR_v, HR_ap, HR_ml) [25];
- Short term Lyapunov exponents (sLE) [26], calculated using the method defined by M.T. Rosenstein et al. [26]. The state space reconstruction was

composed by the delay embedded state spaces of each acceleration component (sLE_v, sLE_ml and sLE_ap); data were not normalized.

- Recurrence quantification analysis (RQA) implying the calculation of recurrence rate (RR), determinism (DET) and averaged diagonal line length (AvgL) [27]
- Sample entropy (SEN_v, SEN_ml and SEN_ap), calculated for values of τ ranging from 1 to 6 according to methodology defined by previous analysis [28].

These indexes were selected, among those previously used to detect changes in the gait pattern [4,12,29,30], based on the available number of consecutive strides per trial, which would ensure a reliability of at least 20% [11,31].

For calculation of sLE and RQA, the state space was constructed with an embedding dimension dE = 5 and a time delay of 10 samples, as these parameters were defined appropriate for the analysis of gait data [32,33]. Raw unfiltered data were analysed to assure that information was not lost or altered.

Matlab R2015b (MathWorks BV, USA) was used for data and statistical analysis.

A Shapiro-Wilk test was performed on all the above-mentioned indexes, showing that they were not normally distributed. Median, 25th and 75th percentile values were hence calculated. Kruskal-Wallis test with minimum level of significance of 5% was performed to compare the indexes values obtained in the different walking conditions. Dunn-Sidak correction was considered for post-hoc analysis.

Results

Figure 1 shows a representative time series of trunk acceleration in the antero-posterior direction and the angular velocity of the shank around the medio-lateral axis for each condition.

FIGURE 1 HERE

All variability indexes varied significantly between the analysed walking conditions, conversely from the stability indexes (with the only exception of HR in both v and ap) as shown in Figure 2. In particular, the Kruskal-Wallis test showed statistically significant differences for PSD1 between OCW and OFW and between ICW and OFW, with values 35% higher in OFW than in OCW and ICW.

SD and CV in ICW were significantly different from both OCW and OFW conditions, being approximately 20% lower.

Despite the fact that HR_v and HR_ap significantly diminished when moving from ICW to OFW, the observed numerical differences were lower than the known reliability thresholds of this indexes [11]. Similarly, significant but not reliable variations were observed for HR_ap between OFW and OCW and between OFW and IFW.

FIGURE 2 HERE (BOX PLOT)

Discussion

The walking pattern of young healthy adults was analysed in different environments (indoor and outdoor) and testing conditions (controlled and free) to assess if and how variability and stability, quantified using commonly used variability and stability indexes [11], would be affected. The hypothesis in the specific population was that stability would not change significantly, while variability would increase moving from indoor to outdoor and from controlled to free condition.

Overall, the results confirmed the study hypothesis: on one hand variability indexes, associated to the specific gait pattern, can be altered by testing conditions; on the other hand, stability indexes, related to the underlying motor control, are influenced neither by the environmental nor by the type of walking.

The differences observed in SD e CV values between Indoor Controlled Walking (ICW) and Outdoor Free Walking (OFW) indicate that stride time variability changes significantly when moving from the laboratory to outdoor walking conditions. This was further confirmed by the PSD1 values: both observed differences (ICW vs OFW and OCW vs OFW) and the trend (increased values from indoor controlled condition to the outdoor free one) highlighted how short-term variability of stride times [24] should be interpreted with caution when analysing data from different environments and testing conditions.

The variability indexes were influenced also by the environment in the controlled walking (ICW vs OCW): it has to be acknowledged that besides the change in the environment, differences in the length of the path in the two walking conditions can also affect gait variability, as suggested for older subjects [34].

No significant difference was found in stability indexes, in accordance with the study hypothesis. SEN showed similar values for all testing conditions, moreover the observed trends, in all directions, are in accordance to those reported in the literature [4,35]: higher SEN values for increasing τ. This further supports the study hypothesis, highlighting how the stability of trunk acceleration during gait is not influenced by testing conditions and environment in young healthy adults.

The increase in gait variability, associated to different testing conditions of gait in healthy young adults, suggests that this behaviour should not always be considered as a warning symptom, as usually interpreted for elderly subjects [36]. Changes in variability are not necessarily related to a reduction of gait stability, hence not necessarily to be interpreted as an increase in fall risk.

Given the many comparisons performed simultaneously, type I errors (multiple comparison problem) are deemed possible. However, in the present study, several comparisons were performed to investigate different aspects of gait control and, when assessing similar aspects (e.g. variability), the same trends were obtained from different parameters, thus reinforcing the results. In addition, a bias could have been introduced by the choice of performing the four walking tasks in the same order. However, both the homogeneity of the results (similar analysed aspects showed same behaviour) and, when present, highly significant differences (*p_value* << 5%) suggest the potential bias to be marginal, if not negligible.

In conclusion, this study highlighted the influence of environment and testing condition in the assessment of specific characteristics of gait (i.e. variability and stability). In particular, when assessing the gait of young healthy adults, both environment and testing condition affect variability indexes, whereas neither of the two affects stability indexes.

In general, these results cannot be generalised to other populations, assuming that testing in or out of the lab will not affect gait stability assessment, for instance, in elderly and/or pathologic subjects. Nevertheless, the eventual assessment of significant differences in stability indexes, quantified for indoor and outdoor walking conditions in elderly and/or pathologic populations, would suggest an increased frailty of these subjects in terms of motor stability and fall risk, when compared to the reference performance of young healthy adults.

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