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Instrumenting gait with an accelerometer: A system and algorithm examination

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ABSTRACT

Gait is an important clinical assessment tool since changes in gait may reflect changes in general health. Measurement of gait is a complex process which has been restricted to the laboratory until relatively recently. The application of an inexpensive body worn sensor with appropriate gait algorithms (BWM) is an attractive alternative and offers the potential to assess gait in any setting. In this study we investigated the use of a low-cost BWM, compared to laboratory reference using a robust testing protocol in both younger and older adults. We observed that the BWM is a valid tool for estimating total step count and mean spatio-temporal gait characteristics however agreement for variability and asymmetry results was poor. We conducted a detailed investigation to explain the poor agreement between systems and determined it was due to inherent differences between the systems rather than inability of the sensor to measure the gait characteristics. The results highlight caution in the choice of reference system for validation studies. The BWM used in this study has the potential to gather longitudinal (real-world) spatio-temporal gait data that could be readily used in large lifestyle-based intervention studies, but further refinement of the algorithm(s) is required.

1. Introduction

Gait is a useful measure of overall health [1], and is a predictor for cognitive decline [2], falls status [3], quality of life [4] and longevity [5]. Thus, measuring characteristics of gait is becoming increasingly important as a robust method to determine many facets of health [6]. Typically, expensive (and large) laboratory systems, such as an instrumented walkway (e.g. GaitRite), are used to assess gait. While such a system is essential for developing and fine tuning protocols, its cost and size make it unviable to quantify gait characteristics in many settings [7]. This has driven the demand for cheaper and portable methods that can be more readily deployed, such as in large lifestyle-based intervention studies [6] allowing cost-effective and easy assessment of gait in a wide variety of environments [8].

As a result, the use of accelerometer-based body worn monitors (BWM, defined here as a sensor(s) with algorithms) and their application in instrumented testing has steadily risen in recent years [6,9–12]. Instrumented testing is not limited to any patient group, is not biased by age or gender differences and can provide highly accurate and objective data [7,13]. However, the popularity of BWM worn has been fuelled by commercial companies with black box methods of analysis and the introduction of a variety of accelerometer-based characteristics with little focus on which are the most valid [7,13–15]. Moreover, the closed system of analysis has created a limited understanding of the true strengths and weaknesses of algorithms.

Numerous testing limitations are also encountered within the literature. Typically, studies involving a BWM and instrumented walkway focus their attention on small ($N = 7$–23) single group sample sizes [16–18] making it difficult to considered the findings as representative of the groups. Robust testing of any BWM should include assessment of different populations (e.g. young/old [19–21]) and where homogeneity for gait characteristics may be low (healthy ageing), large sample sizes should be used to increase the ability to detect between group differences [22]. Alternatively, studies that have used larger sample sizes ($N \geq 80$) have other limitations: a limited number of gait characteristics (3–5) with nondescript of age or pathology [15] or during a limited testing protocol [23]. These can be overcome by quantifying the appropriate mean, variability and asymmetry

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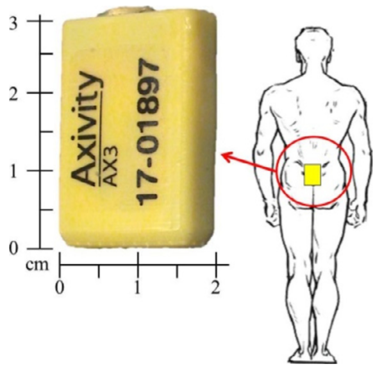

Fig. 1. The accelerometer-based sensor and site of attachment on the lower back (L5).

characteristics [1] during a suitable (continuous) testing protocol and separate estimates for left/right steps [24].

Our aim was to carry out a validation of a low-cost BWM to quantify a comprehensive group of gait characteristics in a large cohort of young and older adults to enhance generalisability, and to explore the sensitivity of the characteristics when comparing young and older adults. We adopted a suitable and robust methodology to examine a low cost BWM on the lower back during instrumented testing of gait in a large cohort of young and older adults to (i) define step count and quantify a comprehensive set of spatio-temporal gait characteristics described by the mean value, variability and asymmetry of each characteristic, (ii) compare the values to a laboratory reference and assess each system in gait quantification and (iii) compare discriminative gait characteristics of younger versus older adults by each system. We present our findings and discuss a new rationale for any poor agreement. The results from this study will help inform our ongoing work within the LiveWell Programme,[1] defining a panel of measures which capture key features of healthy ageing during lifestyle-based intervention: the healthy ageing phenotype (HAP) [6].

2. Methods

2.1. Participant recruitment

Participants were recruited from staff and students at Newcastle University and VOICENorth,[2] an older adult volunteer group who participate in research. Participants were included only if they were healthy i.e. had no physical or neurological disabilities that might impede their movement or balance. Eighty healthy adults aged 20–40 years (40 young healthy participants, YHP) and 50–70 years (40 older healthy participants, OHP) were recruited. All participants gave informed written consent and ethical consent for the project was granted by the National Research Ethics Service (County Durham and Tees Valley) and the Newcastle-upon-Tyne Hospitals NHS Foundation Trust (11/NE/0383).

2.2. Body worn monitor

Each participant wore a low cost (<£90) tri-axial accelerometer-based movement sensor[3] (Fig. 1, dimensions: 23.0 mm × 32.5 mm × 7.6 mm, weight: 9 g) located on the fifth lumbar vertebrae (L5). The sensor was held in place by double sided tape and Hypafix.[4] The sensor was programmed at a sampling frequency of 100 Hz (16-bit resolution) and at a range of ±8 g. Recorded signals were stored locally on the sensor's internal memory (512MB) as a raw binary file that was downloaded upon the completion of each participant trial.

2.3. Laboratory references

We used the GaitRite instrumented walkway and a video camera as the laboratory references for the gait characteristics in this study. The GaitRite dimensions were 7.0 m long and 0.6 m wide and had a spatial accuracy of 1.27 cm and sampling frequency of 240 Hz. Previous studies have verified that the GaitRite is a valid and reliable method for measuring mean gait characteristics in healthy younger and older adults [25]. During each walk, the video camera (Sony DCR-SR77) recorded at 25 frames per second and was used to determine total step count over the complete trial.

2.4. Experimental protocol and system set-up

Participants were instructed to perform a walking task under the condition of a normal, self-selected (preferred) walking pace. The walk was performed for 2 min and followed a 25 m route as illustrated in Fig. 2. This protocol was adopted based upon previous findings that the use of a continuous walking protocol of no fewer than 30 steps (≥50 steps optimal) is recommended when examining the reliability of gait variability [24]. In addition, the use of continuous walks limit any perturbations in the spatiotemporal rhythm of gait and the inflation of gait variability characteristics that are evident with repeated single trials [26].

The BWM was placed on L5 and could continuously gather data for the full test duration. However, GaitRite was placed in the circuit (Fig. 2) only allowing gait to be repeatedly sampled each time participants traversed the walkway [26,27]

2.5. Spatio-temporal characteristics: accelerometer algorithms

After testing was concluded, data were downloaded to a computer and analysed using a MATLAB® program (R2012a). Temporal and spatial estimations of initial contact (IC), final contact (FC) and step length were derived from algorithms developed by McCamley et al. [28] and Zijlstra and Hof [29], respectively. These algorithms were designed for optimal use with a sensor on the lower back. A brief description of both is provided here.

2.5.1. Temporal characteristics

A continuous wavelet transform (CWT, convolution of the accelerometer data and an analysing function, i.e. mother wavelet) estimated IC/FC gait time events from the vertical acceleration (a_v). Firstly a_v was integrated and then differentiated using a Gaussian CWT, where IC's were identified as the times of the minima. The differentiated signal underwent a further CWT differentiation from which FC's were identified as the times of the maxima, Fig. 3(a). Initial inspection of the signal traces found spurious IC events (non-IC events which may constitute a scuff or artefact due to clothing). As a result, the algorithm was updated to include a previous methodology for step detection: restricting IC peaks within a predetermined timed interval (0.25–2.25 s) [30]. Whilst previous use of the algorithm estimated step time and stride time only, in this study we utilised the detection of IC/FC events for the novel estimation of stance time and swing time based upon the analysis of a gait cycle, Fig. 3(b).

Subsequently, the total number of steps estimated by the BWM was derived from the corrected algorithm. This was compared with the video recording for step count estimation. Additionally, the number of steps estimated by the corrected algorithm were used to segment the accelerometer data for direct comparison with GaitRite i.e. number of steps whilst on the GaitRite mat and in the remainder of the circuit. Previously, right and left ICs were identified by a

[1] LiveWell is a research programme intended to develop interventions to enhance health and well-being in later life. LiveWell focusses on the retirement period (55–70 years) as a window of opportunity for successful intervention, http://www.livewell.ac.uk.
[2] www.ncl.ac.uk/changingage/engagement/VOICENorth.
[3] Axivity AX3, York, UK. This is a movement sensor and not specifically designed for gait instrumentation.
[4] BSN Medical Limited, Hull, UK.