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Evaluation of daily walking activity and gait profiles: a novel application of a time series analysis framework

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ABSTRACT

Wearable technology allows an in-depth analysis of gait behaviour in free-living environments. This investigation aimed to use Alzheimer’s disease as an example to apply the time series analysis technique of statistical parametric mapping (SPM) to create daily gait profiles and test if they differed from cognitively intact controls. A framework of macro (habitual walking behaviours) and micro characteristics (spatiotemporal gait variables) characteristics were calculated on an hourly basis. SPM showed that select micro gait characteristics differed from controls at specific hours of the day. Therefore, the application of SPM may provide a more in-depth reflection of activity and gait time-dependent fluctuations than commonly used whole day values. Considering macro and micro gait hour-by-hour may have applications towards disease management, personalized care, monitoring medication and targeted interventions for people with a range of neurodegenerative diseases.

I. INTRODUCTION

Evaluation of gait has traditionally been tested under controlled laboratory-based conditions [1]. Only recently, due to the advances in wearable technology (WT), has gait been examined in free-living (habitual/uncontrolled) environments [2], [3]. WT is capable of objectively and continuously quantifying clinically relevant outcomes unobtrusively for extended periods of time in the home and community [4]. Typically, these measures are summarised over the recording duration (e.g. 3 or 7 days) despite evidence that discrete gait and postural control measures can vary when measured at set times of the day [5]. Continuously assessing gait may provide a more subtle reflection of activity and gait time-dependent fluctuations in addition to averaged values, or even, highlight time specific changes masked when averaged. Few examples exist where gait has been assessed on an hourly basis creating patterns of gait quantity/physical activity [3], [6] and, for novel acceleration specific measures indicative the multimodal

relationship between gait cycle and vertical gait acceleration [7].

Understanding how gait fluctuates throughout the day may provide novel insights of behavior in neurodegenerative diseases, such as AD. For example, if monitored continuously, sundown syndrome, where people with AD experience symptoms such as agitation, confusion, anxiety, pacing, wandering and hyperactivity in the late afternoon, evening or at night [8], may be highlighted by gait metrics. The time and duration of such a phenomena could therefore be better defined and consequently targeted. Equally because people with AD are at a greater risk of falling [9], gait variables indicative of falling risk may highlight when people with AD are at greatest risk. To our knowledge, a method to assess both measures indicative of behavioral walking activity and clinically relevant spatiotemporal measures of gait on an hourly basis has yet to be assessed continuously throughout the day for people with AD.

An additional advantage of continuous monitoring of gait is that daily gait characteristics can be expressed as a time series, thus, opening the potential application of many time series analysis techniques. The use and comparison of time series techniques towards this goal is a methodological gap that if addressed could better unlock the potential of continuous monitoring of gait. For example, such techniques could describe how gait fluctuations occur differently from controls and at what time of day, and also take into account what happened prior and what happens after the hour of observation [10]. As such, the effect of factors such as fatigue or medication effect and their impact on subsequent activities may be taken into account.

This study aims to apply Statistical Parametric Mapping (SPM) to daily gait time series to investigate the fluctuation of gait performance in people with AD relative to controls. The use of AD participants as an example cohort for this method and the examination of free-living gait data collected by WT could provide evidence that time series analysis techniques can highlight additional details indicative of unique signatures of both spatiotemporal and behavioral gait impairment fluctuations. Therefore, we propose that the application of creating a daily gait time series and then applying SPM, may contribute towards the integration and improvement of unobtrusive disease management, patient care and targeted interventions.

II. METHODS

A. Participants, protocol and data collection

36 people with AD (age: 77 ± 6 years, BMI: 26 ± 4 , standardised mini mental state exam (0-30): 23 ± 4) and 26 (age: 74 ± 9 years, BMI: 27 ± 4 , standardised mini mental state exam (0-30): 29 ± 1) age matched control subjects were recruited. This study was conducted according to the declaration of Helsinki and had ethical approval from the Newcastle and North Tyneside research ethics committee (REC Reference:

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16/NE/005). Participants were asked to wear a tri-axial accelerometer (Axivity AX3, York, UK) continuously on the lower back for one week. The water-proof device was programmed to capture data for seven days at 100Hz (16-bit resolution, range $\pm 8g$). Participants were asked to continue their daily activities as usual and not to change their routine. Upon completion of recording, participants removed the device and posted it back to the researcher as detailed in previous work [11], [12].

B. Data Processing and Generation of Daily Gait Time Series

Once the device was received, data were downloaded, segmented (per calendar day) and analysed using bespoke MATLAB® programs. For each day, a logical heuristics paradigm was embedded into walking bout identification and quantification algorithm which has shown to be accurate in detecting ambulatory bouts (ABs) and step count in free-living conditions [13]. Individual ABs were extracted via MATLAB®, where a ‘bout’ was defined as the continuous length of time spent walking with at least three consecutive steps. Ambulatory bouts were detected by applying selective thresholds on the triaxial acceleration data as detailed elsewhere [13].

Daily gait time-series of walking activity outcome measures were evaluated according to a broad framework of Macro and Micro characteristics [2], [11]. Macro (behavioral) outcomes included the volume (total walking time, percentage (%) of walking time, number of bouts and steps), mean AB length, and variability (S_2) (estimated using a maximum likelihood technique) of ABs. A set of 14 clinically relevant Micro spatiotemporal gait characteristic were also determined for each walking bout. Characteristics were selected based upon a validated model of gait [2], [14]. Individual daily gait time series of Macro and Micro outcomes were generated based on the AB detected hourly from 00:00 to 24:00 and averaged across the 7 days. Due to insufficient walking periods > 3 steps in the late evening and early morning, the micro characteristics were analysed between 8am to 9pm in order to analyse a complete time series for each participant.

B. SPM: Analysis of daily Gait Characteristics Time Series Profiles

Statistical parametric mapping (SPM) [15] was used to statistically compare daily gait characteristics time series profiles. SPM has been previously used for comparison of time series in the biomechanical field [10], [16]. Specifically, a SPM two-tailed independent t -test was used to compare walking activity and gait characteristics time series between control and AD groups ($\alpha=0.05$). The scalar output statistic, $SPM\{t\}$, was calculated separately at each individual time node and is referred to as a Statistical Parametric Map. Conceptually, a SPM t -test is similar to the calculation and interpretation of a scalar t -test; if the $SPM\{t\}$ trajectory crosses the critical threshold at any time node, the null hypothesis is rejected. Typically, due to waveform smoothness and the inter-dependence of neighbouring points, multiple adjacent points of the $SPM\{t\}$ curve often exceed the critical threshold known as a ‘supra-threshold clusters’. SPM then uses Random Field Theory expectations regarding supra-threshold cluster size to calculate cluster specific p -values

which indicate the probability with which supra-threshold clusters could have been produced by a random field process with the same temporal smoothness [17]. All SPM analyses were implemented using the open-source `spm1d` code (v.M0.1, www.spm1d.org) in MATLAB® (R2015) [10].

III. RESULTS

Table 1 indicates the time of the day when Macro and Micro gait variables time series significantly differ between AD group and HC. Time series of Macro characteristics were not significantly different between the two groups. For the Micro characteristics, step length and Step velocity time series differed from HC at three separate times of the day. Step, stance and swing time variability time series were significantly different between groups for one hour during the evening hours (between 18:00 and 20:00).

Table 1. Indication of the variable where significant differences between groups was found and the time of day it occurred.

Variable	Time of threshold cluster and corresponding p value
Mean Step Length	10–11 ($p = 0.005$), 13–14 ($p = 0.015$), 18–19 ($p = 0.026$)
Mean Step Velocity	10–11 ($p = 0.158$), 14–15 ($p = 0.041$), 18–19 ($p = 0.002$)
Step Time SD	18–19 ($p = 0.029$)
Stance Time SD	19–20 ($p = 0.008$)
Swing Time SD	18–19 ($p = 0.043$)

Figure 1 highlights one example of Macro (total walk time) and one example Micro gait characteristic time series (mean step velocity) over a 24 and 12 hour time period respectively. Figure 1d highlights when mean step velocity was significantly different between groups. Three [supra-threshold] clusters exceeded the critical threshold of 2.81 at the hours of 10–11, 14–15 and 18–19. The probability of threshold clusters of these sizes would be observed in a random sampling of the same smoothness was $p = 0.005$, $p = 0.015$ and $p = 0.026$, respectively.

IV. DISCUSSION

Results showed that when creating a time series representative of hourly gait characteristics it was feasible to apply SPM. This framework was able to highlight distinct differences between the AD and control group at specific times of day. Although showing trends where the macro characteristics differed between groups, only select micro characteristics reached significance. For this population, these results therefore support the collective macro and micro approach to provide a holistic picture of free-living gait.

Previously, when assessing gait and posture at three time points of the day (11:00am, 14:00pm, 18:00pm), Paillard et al., [5] found that both gait and postural control was worse in the evening for people living with AD in care homes. They concluded the evening period was when the participants were at highest risk of falls and were linked to potential sundowning behaviours. Our community living results appear to reflect these findings as it was predominantly in the evening periods when the micro gait characteristics significantly differed from the controls. It is beyond the scope of this exploratory paper

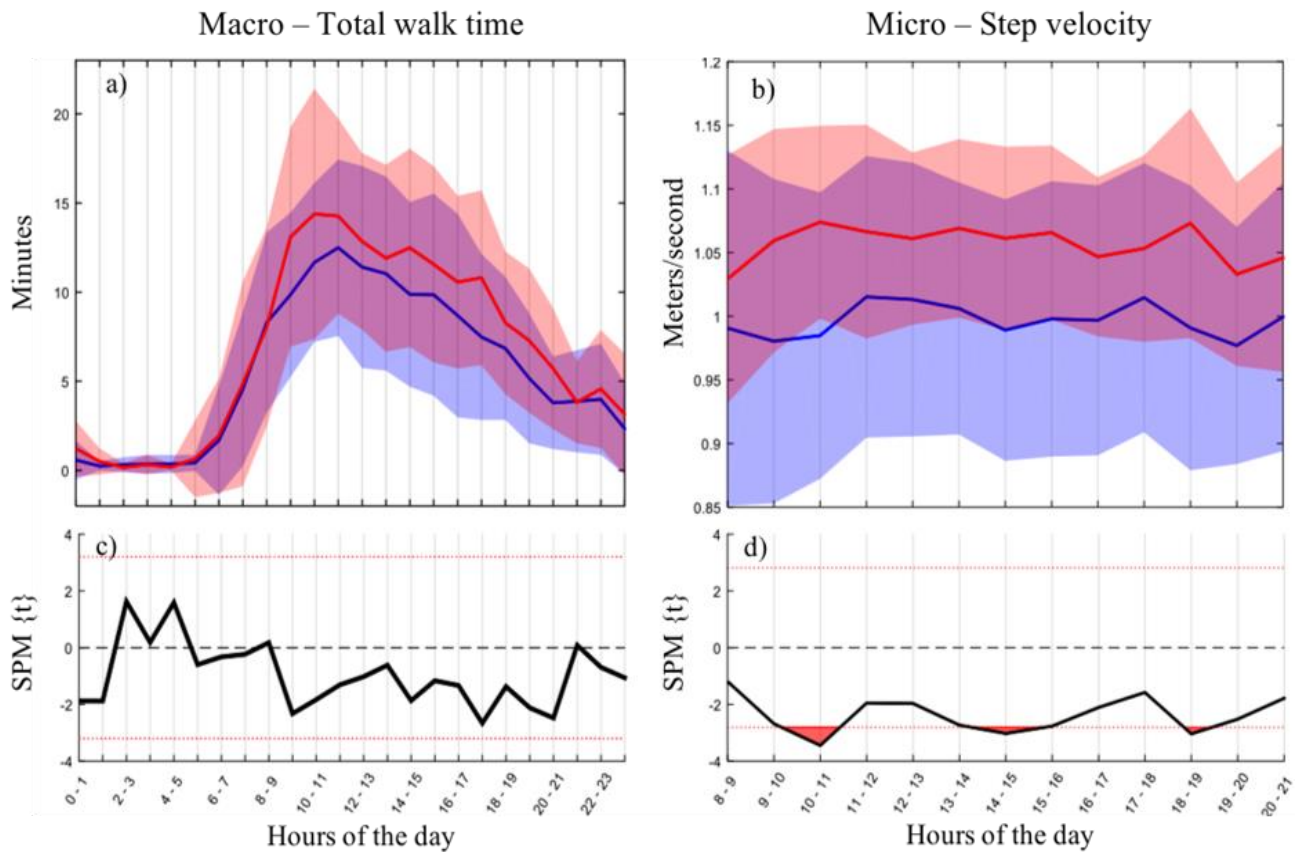


Figure 1. One macro and micro gait example of a 24-hour and 12-hour time series respectively. For graph a and b, the red line represents the healthy controls and the blue line represents the Alzheimer's group. Graphs c and d indicate the independent sample t-test $SPM\{t\}$. Critical threshold (3.20 and 2.81 for c and d respectively, depicted by the dotted red line) was exceeded in d three times. The threshold was exceeded at hours 10-11, 14-15 and 18-19 with [supra-threshold] cluster probabilities of $p = 0.005$, $p = 0.015$ and $p = 0.026$, respectively, indicating a reduced step velocity.

to infer the altered gait characteristics relate to fall risk or potential sun down syndrome. However, significant impairments in the evening suggest use of SPM for identifying fluctuations throughout the day, which may have useful applications in AD, such as establishing “at-risk” fall periods, and targeted interventions.

When assessing measures indicative of physical activity throughout the day, previous results have shown that people tend to be most active in the mornings and then decrease their activity throughout the day [3]. For people with AD it has been found that they replicate this pattern, but their activity peaks later in the morning and at a reduced amount relative to controls [3]. These results demonstrate similar behaviors, which may indicate they are attempting to manage the same amount of activity but over a sustained period [4]. Alternatively, the delayed and reduced activity may also indicate the reliance on a primary care giver who may impact the structure of activity of the person being cared for [18]. Future work should explore for the interaction between diurnal activity profiles of the caregiver with those of the person being cared for. Although for these participants the behavioral measures did not reach significance between the groups, the framework of time series based profiles created on an hourly basis and the application of SPM provides opportunity to explore such relationships where average values of the whole day may not.

In this paper, we provided an example of SPM to a small population of people living with AD and controls to assess daily gait time series profiles. The application of SPM in this context has many possible advantages for other neurodegenerative conditions. For example, for people with Parkinson's disease, both macro and micro characteristics of gait may be influenced by medication intake and motor fluctuations i.e. periods with either a good levodopa therapy response (“ON” state) or periods when the medication effects wear off and motor symptoms re-emerge (“OFF” state) [6]. The framework of creating daylong gait timeseries for people with PD and the application of SPM appears ideally suited to monitor medication effectiveness and adjust dosage accordingly. Future research is warranted to apply SPM to the daily gait time series for people with PD while also monitoring medication intake.

One limitation to the currently applied method was that not all participants had the sufficient number of walking bouts required to calculate micro gait metrics during the night; therefore, nighttime fluctuations could not be analysed. Sleep is likely to impact fluctuations both in cognition and mobility in AD, [3], and therefore, greater understanding of the relationship between sleep quality and gait behaviours would enhance interpretation of results. Future research should consider the application time series analysis to sleep-specific metrics in conjunction with gait analysis.

The proposed framework where accelerometer based measures are divided into a daily time series and the application of a time series analysis technique is not limited to the macro and micro measures used in this example. Future research investigating a variety of additional gait measures and time series techniques is encouraged. This will allow for the comparison of how different time series created from different metrics relate to each other. For example, figure 2 provides opportunity to see how total walk time and gait velocity interact during the day and how this can differ between two populations. Such an approach when applied to different daily time series' may provide an improved holistic understanding of free-living gait.

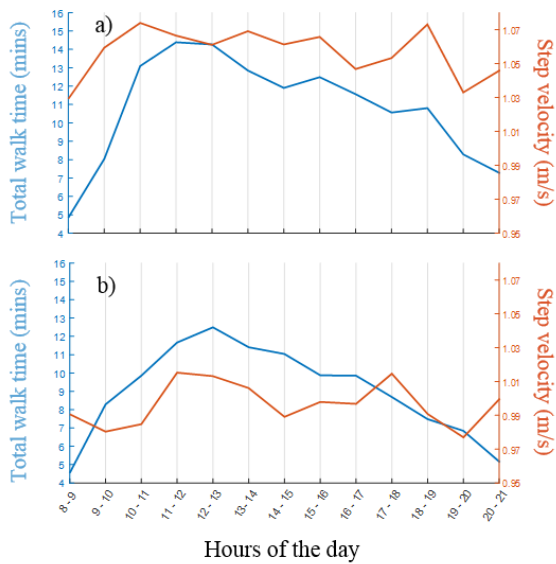


Figure 2. An indication of how two separate daily time series can be explored relative to each other. Graph a) indicates the relationship of total walk time (blue) and step velocity (orange) for the control subjects and graph b) explains the same relationship for the Alzheimer's group.

V. CONCLUSION

To our knowledge, this was the first application of SPM to analyse gait profiles presented as a time series throughout the day. Using the example of AD, results showed that gait characteristics differed at set hours of the day. The application of SPM may therefore help indicate when impairments occur and may contribute towards personalized care, disease management and targeted intervention strategies for people with AD. SPM used in this way provides additional detail advantageous in capturing how gait characteristics fluctuate during the course of the day. Therefore, it may have a range of healthcare applications towards care, disease management, monitoring effects of medication and applying targeted interventions.

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