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Gait as a Biomarker? Accelerometers Reveal that Reduced Movement Quality while Walking is Associated with Parkinson's Disease, Ageing and Fall Risk

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***Abstract*—Humans are living longer but morbidity has also increased; threatening to create a serious global burden. Our approach is to monitor gait for early warning signs of morbidity. Here we present highlights from a series of experiments into gait as a potential biomarker for Parkinson's disease (PD), ageing and fall risk. Using body-worn accelerometers, we developed several novel camera-less methods to analyze head and pelvis movements while walking. Signal processing algorithms were developed to extract gait parameters that represented the principal components of vigor, head jerk, lateral harmonic stability, and oscillation range. The new gait parameters were compared to accidental falls, mental state and co-morbidities.**

We observed: 1) People with PD had significantly larger and uncontrolled anterioposterior (AP) oscillations of the head; 2) Older people walked with more lateral head jerk; and, 3) the combination of vigorous and harmonically stable gait was demonstrated by non-fallers. The results suggest that human gait may reflect well-being, the new gait parameters may be complementary to current methods, and have potential for use as biomarkers for different conditions. However, further research is required to validate our observations in larger populations, to identify longitudinal changes in gait and to establish utility in clinical practice.

I. Introduction

Decreased mobility levels are prevalent in older people, and the predicted aging of the world's population will increase the global burden of these conditions on morbidity and mortality [1]. Changes in gait may prelude major events [2], for example, strokes, cognitive decline, falls, or death, which may be preventable. Accelerometers have previously been connected to the head [3], pelvis [4], trunk [5, 6], and even ski boots [7] to provide an inexpensive way to monitor human movement [8]. In clinical settings, accelerometers have been used to identify between-group differences in the gait of old and young [9, 10], fallers and non-fallers [11], and people with and without Parkinson's disease (PD) [3, 12]. Statistical associations, however, do not necessarily translate into biomarkers, if prevalence is low, as for PD, and false-positive rates are high.

Previous research with accelerometers has generally focused on the direct interpretation of acceleration [8]. Here, novel signal processing algorithms were developed to extract new measures of gait jerk, harmonic stability, and oscillation range, using accelerometers attached to the head and pelvis. We investigated if these measures improved group separation, and therefore, determine the potential of gait as a biomarker for PD, aging, and increased fall risk.

II. Methods

Approval by the Human Studies Ethics Committee at the University of New South Wales was given and informed consent was obtained prior to participation. Participants were eligible if they were able to walk 20 meters unassisted, had normal hearing and vision and scored ≥24 on the Mini Mental State Examination [13]. With respect to people with PD, only mild idiopathic clinical stage I-II of illness according to Hoehn and Yahr [14] were assessed. Falls in the previous 12 months were recorded. Fallers (one or more reported falls) were compared to non-fallers.

Age differences in gait were investigated using data from 30 young people, mean age 29 (SD 4) years and 100 older people, mean age 80 (SD 4) years. Potential biomarkers for PD were investigated using data from 10 people with idiopathic PD, mean age 67 (SD 4) years, and 10 healthy age-matched, mean age 66 (SD 7) years. Potential biomarkers for falls were investigated using data from independent-living older people: 35 fallers, mean age 79 (SD 4) years, and 61 non-fallers, mean age 80 (SD 4) years.

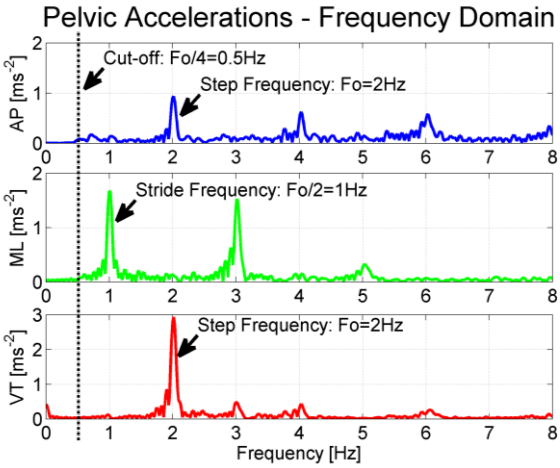

Fig. 1. Pelvic accelerations transformed into the frequency domain by discrete Fourier transform. A high-pass filter cut-off frequency of 0.25 times the step frequency (Fo) preserves most within-stride information.

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Tri-axial accelerometers were attached to the head and pelvis (Opal™ by APDM, sampling frequency 128 Hz). The data from the middle 15 meters of a 19 meter walkway were marked with an external trigger [15]. Results from two repeat walks were combined prior to statistical analysis.

A. Signal Processing

The acceleration signals were processed to extract parameters that represented the principal components of vigor, head jerk, harmonic stability, and oscillation range. Calculations were performed in MATLAB. Step frequency (Fo) was determined by the dominant VT peak in the frequency domain after a discrete Fourier transform (Fig. 1).

A continuously rotational correction was applied to align the vertical axes of the sensors with the global vertical (VT). Accelerations were transformed into the body centered coordinate system [16], whereby anterioposterior (AP) accelerations act in the direction of ambulation, and mediolateral (ML) accelerations act right to left in the horizontal plane. A fourth order low-pass Butterworth filter with cut-off scaled to a quarter of the step frequency (dashed line, Fig. 1) was used to obtain the changing low frequency error matrix (**R**). The corrected accelerations ($\mathbf{A}_{\mathbf{Corr}}$) were then obtained by rotating the raw accelerations (**A**), see equation (1).

$$\mathbf{A}_{\mathbf{Corr}} = \mathbf{RA} \quad (1)$$

The new continuous correction may provide greater reduction in gravitational 'cross-talk' relative to previous static methods [4].

Head and pelvic oscillations (Fig. 2) were calculated by integrating the corrected body centered accelerations with respect to time, and filtered to remove any accumulated integration drift. A fourth order high-pass Butterworth filter with cut-off scaled to a quarter of the step frequency (dashed line, Fig. 1) was used to obtain both velocity and displacement oscillations during gait, which may be visualized as similar to the paths swept out during treadmill walking. The new scaled cut-off approach was developed to preserve most within-stride information while filtering out most accumulated integration error. Optical motion capture was used to determine any accuracy improvements.

Linear head jerk was calculated by differentiating the corrected linear acceleration with respect to time. Root Mean Square (RMS) head jerk was calculated over the AP, ML, and VT axes. The log ratio (2) of lateral to vertical ML/VT jerk was calculated in decibels (dB) creating a normally distributed and dimensionless gait parameter [18].

$$Ratio = 10\log_{10}\left(\frac{RMS\ ML\ Jerk}{RMS\ VT\ Jerk}\right) \quad (2)$$

Lateral harmonic stability of the pelvis was calculated using spectral decomposition to identify the magnitude and dispersion of "stabilizing" ML acceleration peaks. Different to previous analyses using harmonic ratios [15], overlapping eight-step data windows were used instead of two-step data windows, therefore, better adjusting for the monophasic basis of ML movements while walking, providing increased spectral resolution, incorporating measurement of between stride variability, and reducing any noise associated with taking Fourier transforms over finite data windows.

B. Statistical Analysis

Classification accuracy (with sensitivity equal to specificity) was assessed using two-fold cross validation boot strapped 5000 times. Group differences between young and old people, between people with PD and healthy controls, and between fallers and non-fallers were assessed using ANOVA. Subspace clusters were partitioned by medians. Principal component analysis (PCA) using the Varimax rotation method was used to investigate which gait parameters were most representative of different gait constructs. Extraction of components was terminated by an Eigenvalue value below unity. Pearson's correlations were used to assess the independence between different aspects of gait.

III. Results

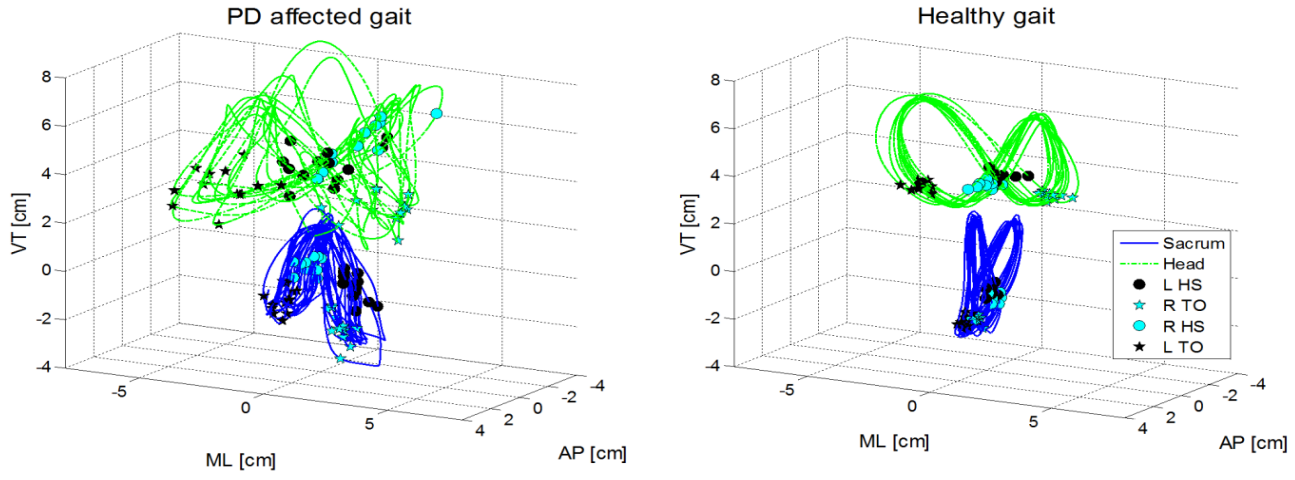

Fig. 2. Head and pelvic (sacrum) oscillations while walking for PD affected and healthy gait. Left (L) and right (R) heel strikes (HS) and toe-offs (TO) are represented by circles and stars.

When pelvic movements using accelerometers were compared to the optical motion capture analysis of walking: The continuous rotational correction and new scaled filter cut-off approach reduced errors by approximately 10-fold relative to a fixed approach that used a static correction and 0.1Hz high-pass filter cut-off (Table 1).

Within our data, PCA (Table 2) revealed gait parameters reflecting vigor, for example walking speed and step length, were largely independent of gait parameters that described head or pelvic stability.

TABLE 1. ERROR AS A PERCENTAGE OF MEASUREMENT RANGE. THE NEW SCALED APPROACH RESULTED IN AN APPROXIMATELY 10-FOLD REDUCTION IN ERROR.

	Pelvis		
	AP	**ML**	**VT**
95% Range of Movement			
Optical System [cm]	4.62	6.55	4.17
Root Mean Square Error (RMSE)			
Scaled Method [cm]	0.76	1.06	0.22
Error [%]	16%	16%	5%
Fixed Method [cm]	8.03	5.51	2.01
Error [%]	174%	84%	48%

On average, older people presented increased RMS lateral head jerk and took shorter steps than younger people. ML/VT jerk correctly classified 89% of participants (Fig. 3) and was superior in this regard to all other gait parameters including step length, which was the best established gait parameter we tested. A step length of 67 cm correctly classified 71% of participants. ML/VT jerk and step length were only weakly correlated (r^2=0.03) suggesting they largely reflect different aspects of gait.

People with PD presented significantly (p=0.02) faster AP head movements (33.2 cms^{-1}), as measured by the velocity of AP head oscillations, than the healthy age matched group (24.5 cms^{-1}), which was uncorrelated (r^2=0.008) with the

TABLE 2. PRINCIPAL COMPONENT ANALYSIS OF GAIT. NORMALIZED WEIGHTINGS ARE SHOWN AND SORTED FOR EACH COMPONENT. HIGHLIGHTED HAVE A WEIGHTING GREATER THAN 0.5. THREE SEPERATE COMPONENTS WERE OBSERVED.

Principal Components of gait	**1) Gait Vigor**	**2) Pelvic Stability**	**3) Head Stability**
Head Jerk VT	.88	-.03	-.21
Head Jerk ML	.77	.09	.47
Cadence	.75	.24	-.12
Speed	.74	.39	-.28
Head Jerk AP	.57	-.24	.53
Step Length	.56	.39	-.29
Harmonic Ratio AP	-.08	.87	-.00
Step Time Variability	-.20	-.82	-.09
Harmonic Ratio VT	.19	.70	-.12
ML/VT Jerk	-.08	.17	.86
AP/VT Jerk	-.20	-.25	.79

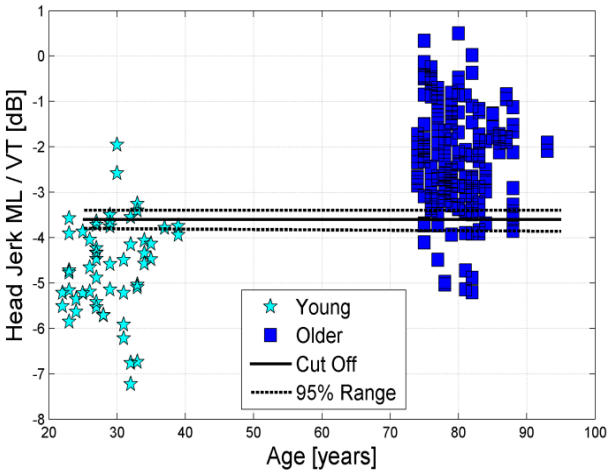

Fig. 3. Classification of age, ML/VT head jerk was 89% accurate.

significant (p=0.02) slower walking speed (1.2 ms-1 for PD, vs. 1.4 ms-1 for the healthy age matched).

With respect to falls, when different walking speeds were taken into account, a significant subspace clustering effect was observed for lateral harmonic stability (Fig. 4). The fast and stable group (top right quadrant) were 5.3 times less likely to have fallen than all other participants: relative risk 0.19, 95% confidence interval 0.06-0.57.

IV. Discussion

Measurement noise was reduced 10-fold using the new methods. The new scaled filter cut-offs were generally around 0.5 Hz and were significantly higher than previous approaches that have used fixed cut-offs around 0.1 Hz [17]. For measurements of head and pelvic stability in gait, we suggest scaling the filter cut-offs with step frequency is optimal because it preserves most information about the movements of interest, within strides, while rejecting most measurement noise. This error reduction was important for the subsequent investigation into gait as a biomarker.

In our experiments, we observed; different aspects of gait reflected health status and different functional outcomes such

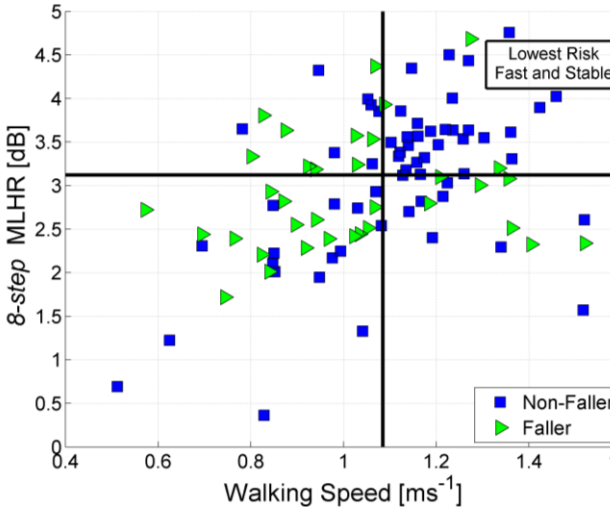

Fig. 4. Improved separation, the fast and stable walkers (top right quadrant) had a 5.3 times lower risk of falls.

as fall risk. Similar to previous research [3, 8, 10-12], we observed that younger people, non-fallers, and those without PD walk faster, and take longer steps, with reduced variability of step time. However, when we assessed these established gait parameters using univariant statistical analysis, we found substantial overlap between the distributions from different groups, which limited their utility as specific biomarkers at an individual level.

The PCA revealed that head and pelvic stability could be measured and were largely independently of walking speed. Therefore, we investigated if these new measures could provide additional information about gait impairments in different populations. Both as independent variables and through non-linear combination with walking speed, an existing measure of gait vigor.

We found, superior group separation, reflecting age differences in gait, was achieved using the log ratio of ML/VT head jerk. Older people presented an increased ratio, indicating greater lateral jerk which was largely independent of reduced walking vigor. The jerkier lateral movements therefore suggest that the older people were less able to rely on their mechanical (inverted pendulum) stability as they oscillated in-time with their stepping.

People with PD walked with increased AP head oscillations, which were uncorrelated to their decrease in walking speed. This suggests motor impairment symptoms relating to gait instability maybe distinct from hypokinetic gait symptoms. Potentially this provides separate targets for therapy.

Separation between fallers and non-fallers was significantly improved when above average walking speed was combined with above average lateral harmonic stability. An observation that suggests fast walking alone may not always be protective of falls. Therefore, future falls research should investigate if interventions aimed at reducing fall risk and improving mobility should also focus on enhancing lateral stability.

V. Summary

Human gait may reflect well-being. We found the new gait parameters were associated with different principal components or aspects of "gait stability" and were sensitive to different conditions. Measures of "gait stability" appear complementary to existing measures of gait vigor, and combining them with walking speed enabled more homogeneous subgroups to be identified, which increases the potential for gait to be used as a biomarker. However, further research is required to validate our observations in larger populations, to identify longitudinal changes in gait using remote devices, and to establish utility in clinical practice.

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