Analysis of Dual-Task Elderly Gait Using Wearable Plantar-Pressure Insoles and Accelerometer

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***Abstract*—Dual-task gait allows assessment of impaired executive function and mobility control in older individuals, which are risk factors of falls. This study investigated gait changes in older individuals due to the addition of a cognitive load, using wearable pressure-sensing insole and tri-axial accelerometer measures. These wearable sensors can be applied at the point-of-care. Eleven elderly (65 years or older) individuals walked 7.62 m with and without a verbal fluency cognitive load task while wearing FScan 3000E pressure-sensing insoles in both shoes and a Gulf Coast X16-1C tri-axial accelerometer at the pelvis. Plantar-pressure derived parameters included center of force (CoF) path and temporal measures. Acceleration derived measures were descriptive statistics, Fast Fourier Transform quartile, ratio of even-to-odd harmonics, and maximum Lyapunov exponent. Stride time, stance time, and swing time all significantly increased during dual-task compared to single-task walking. Minimum, mean, and median CoF stance velocity; cadence; and vertical, anterior-posterior, and medial-lateral harmonic ratio all significantly decreased during dual-task walking. Wearable plantar pressure-sensing insole and lower back accelerometer derived-measures can identify gait differences between single-task and dual-task walking in older individuals and could be used in point-of-care environments to assess for deficits in executive function and mobility impairments.**

I. Introduction

Traditionally, dynamic stability was thought to require minimal cognitive resources and was primarily controlled by automatic or reflex motor responses [1]. However, recent evidence [2] suggests that maintaining stability requires sensorimotor and cognitive processes, particularly executive function and attention [3,4], with a positive relationship between cognitive impairment and gait abnormalities [5,6]. Furthermore, a cautious, conservative gait pattern, often adopted by older individuals, may require more cognitive control and result in gait deterioration under attention-demanding, dual-task (DT) conditions [7].

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DT gait involves walking while simultaneously performing an attention-demanding task and is assessed in older individuals to identify impaired executive function, particularly the inability to appropriately allocate attention [8] and increased attentional demands associated with impaired control of walking. Impaired executive function and impaired mobility control can increase fall risk [4]. For older individuals, DT walking has been associated with the following gait changes compared to single-task (ST) walking: reduced walking speed [1,7,9-19]; decreased stride frequency [7]; increased percentage of missteps [20]; increased step duration [13]; increased stride time [7]; increased stance time [19]; increased [19] and decreased swing time [15,17]; increased variability in swing time [15,17], stride-to-stride gait velocity [1], stride time [7,18], and stride length [18]; increased phase variability index [7]; decreased root mean square and peak anterior-posterior (AP) and medial-lateral (ML) trunk accelerations [7]; increased local stability exponent for AP and ML trunk accelerations [7]; and increased sample entropy for AP trunk accelerations [7]. Older individuals tend to prioritize motor tasks over cognitive tasks in a DT scenario [16,19,21], as an unconscious, protective strategy to reduce fall risk [21].

Wearable sensors could be applied at the point-of-care to evaluate gait deterioration under attention-demanding, DT conditions. Inertial wearable-sensors [7,13,14] and force-sensitive wearable-insoles [15,17] have been successfully used to detect change in elderly gait between ST and DT walking. Inertial wearable-sensors have been applied to the lower leg [13,14], head [13], and trunk [7]. However, the lower back location has not yet been assessed even though it has advantages over other locations since it approximates the center of mass location and can be easily used by attaching the sensor to a belt [22]. Most wearable-sensor-derived measures for DT walking have been temporal measures. Only Lamoth et al. 2011 [7] identified non-temporal changes in gait under DT conditions in older individuals. Non-temporal measures may further elucidate gait pattern changes under DT walking conditions.

This study investigated gait changes in older individuals due to the addition of a cognitive load using wearable pressure-sensing insole and tri-axial accelerometer measures.

II. Method

A. Participants

Eleven elderly independent community dwellers or residents of retirement homes voluntarily participated in this study. Participants had an average age of 76.2 ± 6.5 years, height of 167.2 ± 9.4 cm, and weight of 71.3 ± 13.7 kg. The University of Waterloo Research Ethics Committee approved the study and all participants gave informed written consent. Participants were excluded if they had a cognitive disorder or were unable to walk for six minutes without an assistive device. Exclusion due to cognitive disorder was based on participant self-report.

B. *Protocol*

Pressure-sensing insoles (F-Scan 3000E, Tekscan) were equilibrated using a multi-point calibration (137.9, 275.8, and 413.7 kPa) according to manufacturer instructions. After measuring participant height and weight, pressure-sensing insoles were trimmed and fit into each person's shoes. The insoles were calibrated using a step calibration technique according to manufacturer instructions. A step calibration could not be performed with two participants, as the participants could not stand on one foot for the required period of time. For these two participants, the insoles were calibrated using a walking calibration technique according to manufacturer instructions. An accelerometer (Gulf Coast X16-1C) was attached to the posterior pelvis with an adjustable belt. Plantar pressure data were collected for all activities at 120 Hz, and accelerometer data were collected at 50 Hz. Participants completed a 7.62 m walk with and without a cognitive load. The cognitive load was a verbal fluency task requiring the participants to say words starting with A, F, or S. The letter and order of walking activities were randomized.

C. *Data Processing*

Plantar-pressure insole and lower-back accelerometer data were exported to Matlab v2010a to calculate outcome variables. Plantar pressure derived parameters were:

- **Center of Force (CoF) path**: Since the CoF path should advance monotonically in the anterior direction, posterior CoF path movements were identified as irregular. The number, length, and duration of posterior deviations (PD) per stride were determined. Similarly, smooth medial and lateral movements were expected during typical gait. Deviations from the expected ML path were identified as instances when the first derivative of the CoF ML signal exceeded a dual threshold of ± 0.5 mm/frame [23]. The number, length, and duration of ML path deviations per stride were determined. The minimum, maximum, mean, and median CoF path velocities were also calculated and normalized by stance time.
- **Temporal**: Cadence, stride time, stance time, swing time, percent stance time, percent double support time, and stride time symmetry between the left and right limbs were calculated. Stride time symmetry index was calculated as in [24].

For the accelerometer data, the positive vertical axis was in the upwards direction, positive AP axis was in the anterior direction, and positive ML was towards the participant's right side. Accelerometer-derived parameters were:

- **Descriptive statistics:** Minimum, maximum, mean and standard deviation of acceleration for the vertical, AP, and ML axes.
- **Fast Fourier Transform (FFT) Quartile:** Percentage of motion frequencies in the first quartile of an FFT frequency plot for vertical, AP, and ML acceleration.
- **Ratio of even to odd harmonics:** Proportion of the acceleration signal that is in phase with the participant's stride frequency. The harmonic ratio was calculated for the vertical, AP, and ML axes using the technique presented in [25].
- **Maximum Lyapunov exponent:** This local dynamic stability measure is the average rate of expansion or contraction of the original trajectory in response to perturbations [26,27]. The maximum Lyapunov exponent for vertical, AP, and ML acceleration was calculated as in [28] with the number of dimensions determined using the global false nearest neighbours method [29] and a fixed time delay based on the first minimum of the average mutual information [30].

Acceleration data were filtered using a 5^{th} order, low pass Butterworth filter with a cut-off frequency of 12.5 Hz for descriptive statistics and maximum Lyapunov exponent parameters. Unfiltered acceleration data were used to calculate FFT quartile and the ratio of even to odd harmonics to ensure that all frequency information remained intact.

D. *Data Analysis*

Paired statistical tests were performed to compare walking variables with and without a cognitive load. For each variable, normality was assessed using the Shapiro-Wilk Test with a critical p value of 0.05 and the Kolmogorov-Smirnov Test with a critical p value of 0.2. If at least one normality test indicated a non-normal data set, a Wilcoxon Signed-Rank Test was used to compare walking conditions. If both normality tests indicated a normal data set, a paired t-test was used.

III. RESULTS

Of the 39 variables assessed, 10 variables showed a significant difference ($p < 0.05$) with the addition of a cognitive load (Table 1).

Minimum, mean, and median CoF stance velocity all significantly decreased during DT walking. With the addition of a cognitive load, the minimum CoF stance velocity decreased by 18.77%, mean CoF stance velocity decreased by 7.83%, and the median CoF stance velocity decreased by 5.89%.

Cadence significantly decreased during the DT. Stride time, stance time, and swing time all significantly increased during DT. With the addition of a cognitive load, cadence decreased by 4.93%, stride time increased by 4.85%, stance time increased by 6.78%, and swing time increased by 2.27%.

TABLE I. PLANTAR PRESSURE AND ACCELERATION PARAMETERS FOR GAIT WITH AND WITHOUT A COGNITIVE LOAD.

	Without Cognitive Load	With Cognitive Load
CoF Path		
PD per Stride (#)	3.1 ± 4.3	3.4 ± 4.1
PD Length (mm)	3.4 ± 4.8	1.9 ± 2.5
PD Duration (s)	0.01 ± 0.00	0.01 ± 0.00
ML Deviations per Stride (#)	11.8 ± 2.3	12.8 ± 2.9
Medial Length (mm)	1.9 ± 0.9	1.7 ± 0.7
Lateral Length (mm)	2.1 ± 1.3	1.9 ± 1.1
ML Deviation Duration (s)	0.04 ± 0.01	0.04 ± 0.01
Minimum Velocity [(m/s)/s]*	0.037 ± 0.016	0.030 ± 0.013
Maximum Velocity [(m/s)/s]	1.369 ± 0.688	1.530 ± 1.241
Mean Velocity [(m/s)/s]*	0.345 ± 0.065	0.318 ± 0.052
Median Velocity [(m/s)/s]*	0.280 ± 0.056	0.263 ± 0.055
Temporal		
Cadence (steps/min)*	117.6 ± 10.8	111.8 ± 11.7
Stride Time (s)*	1.03 ± 0.10	1.08 ± 0.12
Stance Time (s)*	0.59 ± 0.10	0.63 ± 0.13
Swing Time (s)*	0.44 ± 0.08	0.45 ± 0.07
Percent Stance (%)	57.73 ± 7.44	58.11 ± 7.11
Percent Double Support (%)	7.85 ± 7.43	8.23 ± 7.22
Stride Time Symmetry	2.49 ± 1.36	2.88 ± 2.53
Acceleration Descriptive Statistics (g)		
Vertical Minimum	-0.50 ± 0.20	-0.48 ± 0.18
Vertical Maximum	0.43 ± 0.17	0.43 ± 0.16
Vertical Mean	0.03 ± 0.02	0.04 ± 0.02
Vertical Standard Deviation	0.18 ± 0.06	0.17 ± 0.04
AP Minimum	-0.13 ± 0.20	-0.10 ± 0.19
AP Maximum	0.74 ± 0.21	0.71 ± 0.17
AP Mean	0.18 ± 0.14	0.20 ± 0.13
AP Standard Deviation	0.19 ± 0.05	0.18 ± 0.05
ML Minimum	-0.40 ± 0.20	-0.40 ± 0.19
ML Maximum	0.48 ± 0.16	0.45 ± 0.16
ML Mean	0.03 ± 0.09	0.02 ± 0.10
ML Standard Deviation	0.18 ± 0.06	0.17 ± 0.04
FFT Quartile (%)		
Vertical	17.6 ± 11.5	16.0 ± 10.4
AP	29.5 ± 12.8	27.3 ± 9.3
ML	18.4 ± 4.8	20.4 ± 4.9
Ratio of Even to Odd Harmonics		
Vertical*	2.99 ± 1.14	2.32 ± 0.86
AP*	2.63 ± 0.70	2.07 ± 0.69
ML*	0.67 ± 0.17	0.48 ± 0.14
Maximum Lyapunov Exponent		
Vertical	0.55 ± 0.22	0.49 ± 0.16
AP	0.54 ± 0.20	0.48 ± 0.09
ML	0.36 ± 0.12	0.35 ± 0.11

a. * indicates a significant difference ($p < 0.05$)

Vertical, AP, and ML harmonic ratio all significantly decreased during DT. Vertical harmonic ratio decreased by 22.41%, AP harmonic ratio decreased by 28.36%, and ML harmonic ratio decreased by 21.29%.

IV. DISCUSSION

This study investigated whether accelerometer and plantar pressure-sensing wearable sensors could detect DT gait changes using CoF, acceleration descriptive statistics, frequency, harmonic ratio, and Lyapunov exponent measures in addition to temporal measures. Wearable sensors were used to allow application at the point-of-care. Variables that identified differences between ST and DT walking could be used clinically to identify older individuals with executive function and attention deficits and impaired mobility control.

As expected, differences in temporal variables were found between ST and DT walking. Stride time, stance time, and swing time all increased for the DT condition and cadence decreased. The stride time and stance time findings correspond to [7] and [19], respectively, during DT walking. The increased swing time for DT walking was also found in [19] but not in [15,17].

CoF stance velocity also changed with the addition of a cognitive task. Minimum, mean, and median CoF velocity all decreased for DT walking. Since mean and median CoF velocity should relate to walking speed, these decreases were consistent with literature where walking velocity decreased under DT conditions [1,7,9,10-19]. CoF velocity could be considered as a surrogate for walking speed in gait analysis by wearable-sensors, since the measurement of stride length would not be required to calculate the outcome measure.

The ratio of even to odd harmonics decreased with DT walking and exhibited a larger percent decrease than the percent decrease and increase in the temporal and CoF stance velocity measures. This is the first study to report a significant difference in the ratio of even to odd harmonics between ST and DT walking in older individuals without cognitive impairments. The harmonic ratio reports the proportion of the acceleration signal that is in-phase with the participant's stride frequency. Since lower back acceleration signals are biphasic with respect to the gait cycle, a lower harmonic ratio would indicate an increase in out-of-phase, irregular walking components and a decrease for in-phase, repetitive walking components. Therefore, lower harmonic ratios indicate an instable, irregular gait pattern and higher harmonic ratios indicate a stable, consistent gait pattern. The decrease in harmonic ratio with DT walking showed that older individual's gait becomes less stable and more variable with a cognitive load.

The temporal, CoF stance velocity, and harmonic-ratio measures identified differences between ST and DT gait in older individuals and can be measured with wearable sensors. Furthermore, the harmonic ratio measures examine pelvis movement signals that may provide information not attainable with temporal measurements.

The portable nature of the acceleration and plantar pressure sensors make the study outcomes transferable to a point-of-care setting. These sensors and test methods could be used during home visits, at medical facilities, and in retirement and nursing home environments to test for deficits in executive function and attention [8] and deficits that affect gait stability. These assessments might also be used as a fall risk indicator for older adults, given the reported link between fall risk and deficits in executive function [4] and the link between fall risk and reduced walking speed during DT walking [31].

Since this study is limited by the small sample size, these results should be confirmed in a larger sample of older adults. Furthermore, participants were not formally screened for cognitive disorders, and the cognitive disorder exclusion criteria were based on participant self-report. Therefore, some participants may have undiagnosed and unreported cognitive disorders. This study should be replicated in young adults to determine if similar gait changes occur or whether the results are specific to older adults.

V. Conclusion

Plantar-pressure-sensing insoles and lower-back accelerometer-derived measures were able to identify differences in gait between ST and DT walking in older adults. These differences included temporal, CoF-stance velocity, and the ratio of even to odd harmonic measures. The ratio of even to odd harmonic measures exhibited the largest percent change with the addition of a cognitive load. Using a DT scenario, these wearable sensors could be used in point-of-care environments to assess for deficits in executive function and attention and impaired mobility control that affect gait, and potentially to ultimately assess fall risk.

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