Analysis of the Effect of Cognitive Load on Gait with off-the-shelf Accelerometers

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***Abstract*—Recent research has shown that cognitive load has an effect on gait, especially noticeable in people with neurodegenerative disorders. Sophisticated and expensive systems are commonly used to measure the variability of gait parameters under different cognitive loads. In this paper, we propose the use of smart phones and off-the-shelf wireless accelerometers to study the influence of cognitive load on gait. Making use of this new approach, we measure the effect of common "working memory" or "motor" tasks on gait. We also analyze the effect on gait variability derived from imposing a speed while walking in a treadmill. Our results show that current state-of-the-art smart phones and off-the-shelf accelerometers can be successfully used to analyze the effect of cognitive load on gait.**

Keywords- cognitive load, dual task, gait.

I. INTRODUCTION

There is a growing interest in clarifying the relationship between cognition and gait. In the past, walking was considered a motor activity independent of any cognitive processes and performed automatically by healthy adults. However, recent research shows that cognitive load has an effect on gait [1-4], especially noticeable in people with neurodegenerative disorders such as Alzheimer's disease [5], vascular dementia, mixed dementia [6] or Parkinson's disease [7]. Psycho affective conditions such as anxiety and depression are also linked to specific gait disorders [8]. More specifically, a decrease in the frontal cerebral blood flow has been associated with modifications in gait [9]. As shown in [10, 11] and references therein, cerebral vascular abnormalities are associated with modifications of the gait pattern, namely an increased variability of spatio-temporal gait parameters. These observations are consistent with studies claiming that gait requires cognitive processes such as attention, memory and planning [12, 13], demanding frontal and parietal activity in the brain [14, 15]. In fact, changes in the frontal regions including the bilateral medial areas of the frontal cortex have been identified as a risk factor for dementia [16-18], and reductions in the motor strength associated with aging increase the attentional demands needed for walking.

The most popular method to analyze the effect of cognitive load on gait is the dual task test [3, 4, 10, 12, 19, 20, 21-29], in which the subject under study performs a cognitive task while simultaneously walking. Most researchers choose to avoid prioritizing any of the tasks. Since the dual task conditions impose a higher attentional demand, the performance in one or both tasks can be impaired if the attentional reserve capacity available is challenged [22, 30, 31]. This is known as "dual task interference". The effect of the dual task test on gait can be quantified through the variability in the spatio-temporal parameters of gait, which will depend on the complexity of the task and the general condition of the subject [32-36]. For example, the effect of the cognitive task on gait can depend on factors such as age, gender, executive function, memory and verbal IQ [2, 32, 33, 37-42].

Another application of the dual task test is to show the link between attentional demands and postural control [32, 43-49]. Recent studies claim that postural stability requires both cognitive and sensorimotor processes [50], and researchers are analyzing the impact of different details (e.g. speech complexity [51]) on postural control. In the same sense, the dual task test can be utilized to study the capacity of older adults to avoid obstacles [52]. In fact, gait stability can be a better predictor of falling than static measures of balance [40]. Recent studies have shown a relationship between dual task interference and fall risk [53, 54]. For instance, a simple measurement of the counting performance while walking in comparison with while seated has proved to be a good indicator of fall risk in the elderly [53]. In particular, there is a growing interest in studying the link between the variability of spatial-temporal parameters in gait under dual task conditions and the risk of falling in seniors [20, 37, 38, 55, 56].

In this paper, we review the state of the art in the study of cognitive load on gait, showing the different systems, dual task tests and spatio-temporal parameters employed by researchers in this field. Subsequently, we propose the use of smart phones and off-the-shelf accelerometers to measure the effect of common "working memory" and "motor" tasks on gait. To the best of our knowledge, this is the first work in this field employing this new technology.

The rest of this paper is organized as follows. In Section 2, we survey the most common dual tasks employed by researchers, and in Section 3, we review the systems utilized to analyze the influence of cognitive load on gait and postural control. Section 4 focuses on the spatio-temporal parameters leveraged for the analysis of cognitive load on gait. In Section 5, we describe our proposed methodology using smart phones with off-the-shelf accelerometers, and summarize tests results. Conclusions are drawn in Section 6.

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II. DUAL TASK TESTS

Most of the existing research in this field involves the analysis of the effect of a second task on gait or postural control. Some researchers claim that dual task interference is only possible if the neural networks involved in the two processes overlap [2]. For instance, reference [33] suggests that only visual/spatial dual tasks would interfere with postural control, since postural control demands visual/spatial processing. However, there is no consensus on the optimum dual tasks with which to evaluate gait or postural control.

Some of the dual tasks employed by researchers are borrowed from neuropsychological tests, while others are created specifically for each experiment. And even if there is a lack of a standardized evaluation technique to compare the cognitive loads demanded by each task, most researchers follow practical guidelines to carry out the tests: the task should be difficult enough to load the attentional system, but it should not cause undue stress or anxiety. Also, the test should take into consideration the subject's skills (e.g. mathematical, verbal fluency), since the cognitive loads brought by a same task can vary depending on the subject's skills [2]. Table I gathers the most common tasks employed by researchers. These tasks can be assigned different percentages according to their importance levels and the application context.

III. SYSTEMS EMPLOYED TO ANALYZE THE INFLUENCE OF COGNITIVE LOAD ON GAIT AND POSTURAL CONTROL

A basic approach to analyze human kinematics is chronophotography [57]. More sophisticated motion tracking systems utilize mechanical, acoustic (including ultrasounds), radio-frequency, optical, magnetic, and inertial sensors. Descriptions and examples of these systems can be found in [58]. The suitability of each system depends on the particular conditions and goals of each test. The combination of different methods in a multi-modal approach allows an enhancement in accuracy and robustness in terms of security. In other words, complementing methods can help overcome their weaknesses.

One of the most common and sophisticated commercial systems employed in existing research is the GAITRite walkway [59, 60], with embedded force sensors to detect footfalls and a length of nearly 5 meters, allowing the estimation of gait parameters such as speed, length and width of the step, and symmetry of the gait pattern. This system enjoys high reliability and high concurrent validity when compared with video-based motion analysis systems for spatiotemporal gait parameters such as gait speed, cadence, and stride length.

For the analysis of postural control, the most common solution consists of sensors or force plates installed on the floor [61-63]. Commercial examples of such systems employed in existing research are described in [20] and [51]. Other researchers utilize custom made plates attached to the subject to overcome the movement restriction due to the small size of force plates. Examples of these approaches include the employment of force transducers beneath the shoe, pressure insoles and miniature triaxial piezoelectric transducers inside the shoe [58].

TABLE I. COMMON TASKS EMPLOYED TO STUDY THE EFFECT OF COGNITIVE LOAD ON GAIT THROUGH "DUAL TASK TESTS".

Working memory tasks
Attention and articulation: counting backwards out loud
Attention without demands for articulation: silent counting backwards
Articulation alone: number repetition
Arithmetic task (backward counting, serial 3 or 7 subtractions)
Other arithmetic calculations
Counting backwards from 50 by steps of 2 out loud
Random digit generation
Backward digit recall
Digit span recall
Generating a monologue
Audibly reciting as many male names as possible
Backward spelling
Naming of months from December to January
Reciting the days of the week backwards
Counting backwards silently by 7's
Performing a rote repetition task
Verbal fluency tasks
Enumerating animals out loud
Modified Stroop test
Naming items that start with a certain letter or have a certain common characteristic (e.g., farm animals)
Conducting a conversation
Remembering similar sentences
Motor tasks
Fine motor task (opening and closing a coat button continuously during gait)
Finger tapping at 5 Hz or faster
Combination of memory-retention and fine motor tasks (digit recall and buttoning task)
Carrying a tray
Carrying a tray with four plastic glasses on it
Carrying a tray with filled glasses of water
Sequential finger movement
Transfer of coins between pockets
Other simple manual motor tasks
Auditory tasks
Listening to a spoken word recording of a book excerpt, or simple white noise
Auditory Stroop test
Visual tasks
Brooks spatial memory task
Carrying out tests under different visual conditions, no vision, static visual image, and a moving visual image
Color judgment
Other visual-spatial cognitive tasks
Classical tests of executive function
Wisconsin Card Sorting
Stroop test
Verbal fluency tests
The Executive Interview (EXIT25) test
CLOX (an executive clock drawing task)

More specific techniques employed to discover possible reasons for falling include Holter electrocardiography (ECG), 24-hour blood pressure monitoring, electromyography (EMG), electroencephalography (EEG), and Doppler and duplex sonography of the extra- and intracranial vessels [20]. Other methodologies utilized to diagnose clinical conditions that can influence gait are based

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on the analysis of electroencephalogram (EEG) signals and magnetic resonance imaging (MRI) [1]. Methods such as single photon emission tomography, functional near infrared spectroscopy or functional Magnetic resonance imaging (fMRI) and positron emission tomography, have also been employed to identify brain areas related to attentional resources during walking [21].

Table II gathers a summary of systems employed by researchers for the measurement of kinematic parameters in gait.

TABLE II. COMMON SYSTEMS EMPLOYED TO ANALYZE THE SPATIO-TEMPORAL PARAMETERS OF GAIT.

Systems
Absorbent paper to record wet footprint placements
Talcum powder dusted on the plantar surface of the foot to record footprint placements
Ink pads on the sole of the shoes and walk along a large piece of paper
Shoe-integrated wireless sensor systems (e.g. Stride Analyzer; B&L Engineering, Tustin, Calif., USA)
Accelerometers (e.g. DynaPort MiniMod; McRoberts Moving Technology, The Hague, The Netherlands)
Angular velocity transducer systems (e.g. Sway- Star; Balance International Innovations GmbH, Iseltwald, Switzerland)
Electronic walkways with integrated pressure sensors (e.g. GAITRite; CIR Systems, Havertown, Pa., USA)
Video-based motion analysis systems (e.g. Vicon Motion Systems, Los Angeles, Calif., USA)
On-body sensors based systems (e.g. STEP 32 gait analysis system by DEM, Italy)
Inner soles with 4 pressure-sensitive footswitches
Muscle activity measured with electromyography (EMG)

IV. SPATIO-TEMPORAL PARAMETERS EMPLOYED TO ANALYZE THE EFFECT OF COGNITIVE LOAD ON GAIT

Gait velocity can be used as an indicator of the quality of life in the elderly [64]. In this sense, increased variability of spatio-temporal gait parameters has been linked to cognitive abnormalities [1, 11]. And although numerous gait parameters can be measured in sophisticated gait labs, many studies focus basically on mean gait speed and stride-to-stride variability in gait speed [37]. In fact, gait velocity and stride-to-stride variability in gait velocity have been identified as the best predictors of falls for the elderly [38, 65]. Stride-to-stride variability (*V*) in gait speed is commonly quantified as the percentage of the standard deviation (*SD*) to the mean [37]:

$$V(\%) = \frac{SD}{mean} * 100 \qquad (1)$$

Other researchers also focus on stride time and swing time variabilities [66, 67]. Table III gathers representative gait parameters used by researchers to analyze the effect of cognitive load on gait.

TABLE III. COMMON SPATIO-TEMPORAL GAIT PARAMETERS ANALYZED BY RESEARCHERS TO STUDY THE INFLUENCE OF COGNITIVE LOAD ON GAIT.

Gait Parameters
Gait speed
Stride-to-stride variability in gait speed
Stride time
Double support time
Stride length
Cadence
Percentage of the gait cycle in double-limb stance
Range of motion and peak velocity of the center of mass
Duration of single and double support
Step time
Swing time
Stance time

Table IV gathers a summary of the typical modifications measured for the spatio-temporal parameters of gait under dual task conditions.

TABLE IV. SUMMARY OF MODIFICATIONS IN SPATIO-TEMPORAL GAIT PARAMETERS UNDER DUAL TASK CONDITIONS.

Gait Parameters
Decreased gait velocity (as a compensation mechanism which people take when stability is challenged). It is interesting to note that this parameter is associated with errors in the cognitive dual-task (e.g. poorer arithmetic ability [12] or verbal reaction time [52])
Decreased stride length
Increased double support time
Increased gait cycle time variability
Increased variability in stride length
Increased variability in gait speed (greater variability in men than in women)
Decreased cadence
Increased lateral gait instability (only with arithmetic dual task, but not with verbal fluency task)
Increased postural sway, which is impacted by articulation and visual conditions, but not by attentional load (e.g. silent counting)

V. PROPOSED METHODOLOGY AND TESTS TO ANALIZE THE EFFECT OF COGNITIVE LOAD ON GAIT

We propose to study the effect of cognitive load on gait leveraging off-the-shelf wireless accelerometers and smart phones implementing a light-weight and low-cost system that enables the analysis of gait parameters' variability with an accuracy comparable to the most sophisticated and expensive systems available in the market. In particular, we analyze through the wavelet transform the signals obtained from off-the-shelf wireless accelerometers placed on the waist and the ankle of the person under study. These wireless accelerometers transmit their signals to a processing unit (e.g. smart phone or laptop) using Bluetooth. The signal processing methodology we use is summarized next.

Reviewing the wavelet transform decomposition of a signal *x(t)* into approximation $a_j(k)$ and detail $d_j(k)$ coefficients:

$$a_j(k) = \int x(t)\varphi_{j,k}(t)dt \qquad (2)$$

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$$d_j(k) = \int x(t)\psi_{j,k}{}^{*}(t)dt \tag{3}$$

where $\varphi_{j,k}(t)$ represents the scaling function and $\psi_{j,k}(t)$ the wavelet function (* represents conjugate), it can be seen that these coefficients are integrating the signal *x(t)*, weighted by the $\varphi_{j,k}(t)$ and $\psi_{j,k}(t)$ functions. Focusing on the acceleration from the waist (which approximately corresponds to the center of mass of the human body), the application of the wavelet transform delivers the integration of weighted accelerations, thus obtaining weighted velocities (of the center of mass). Further analyzing the relationship between the wavelet transform coefficients and the kinetic energy of different walking patterns, we can actually infer the speed of the movement with the following expression:

$$Speed = \frac{1}{2}\sqrt{WE_{d_1} + \frac{WE_{d_2}}{2} + \frac{WE_{d_3}}{3} + \frac{WE_{d_4}}{4} + \frac{WE_{d_5}}{5}} \tag{4}$$

in which we include a new metric that we call "Weighted Energy":

$$WE_{d_i} = \begin{cases} \dfrac{\sum d_i^{\,2}}{n_0\sqrt{2}(J-i)} & i = 1..J-1 \\[2ex] \dfrac{\sum d_i^{\,2}}{n_0\sqrt{2}} & i = J \end{cases} \tag{5}$$

where *J* represents the number of levels of decomposition we are using in the wavelet transform, *i* accounts for the specific level we are considering, d_i symbolizes the detail coefficients at level *i*, and n_0 represents the number of coefficients considered. In (4), we have considered the first 5 levels of decomposition in order to cover the frequency content of the acceleration ranging from 0.46 Hz to 15 Hz (our sampling frequency is 30 Hz), thus including the most important frequencies of gait, which are typically between 0.5 Hz and 4 Hz. We have tested this approach with a total of 14 individuals (males and females with ages ranging from 21 to 77), obtaining excellent accuracies in the velocities, with average errors around 5%. In fact, the accuracy of our approach is comparable to that obtained with more complex and expensive systems, and our results are achieved with significantly lower hardware requirements. Once we obtain the velocity of the movement, the step length can be calculated dividing the velocity by the step frequency, which we can obtain from an accelerometer on the ankle (through the detection of peaks).

Making use of this new approach, we carried out tests to study the influence of cognitive load on gait. In particular, we measured the variability of velocities and stride lengths under classical dual task tests such as walking while holding a tray with a glass full of water, or walking while performing arithmetic calculations out loud (serial 7 and 13 subtractions). Comparing these results with free walking conditions (summary in Table V), we can notice decreases in the mean velocities and stride lengths of the individuals while performing the dual tasks. Regarding the percentage variabilities of velocity and stride length, these terms increase in all the dual task tests. All these results match perfectly with those obtained by other researchers employing more sophisticated systems. In conclusion, the effect of common "working memory" or "motor" tasks employed in tests for the analysis of cognitive load on gait can be measured with current state-of-the-art smart phones and off-the-shelf accelerometers, without the need of sophisticated and expensive equipment.

TABLE V. MEASURED EFFECTS OF DIFFERENT DUAL TASKS ON GAIT

	Mean Velocity (mph)	**Velocity Variability(%)**	**Mean Stride Length (meters)**	**Stride Length Variability(%)**
Free Walk	3.05	23.2	1.25	32.04
Carrying tray	1.82	24.93	0.65	61.9
Walk while calculating	2.6	25.17	0.85	35.29

Making use of our new approach we also analyzed the effect of imposing a velocity (the person should walk on a treadmill at a selected speed). For these tests, 20 individuals (ages ranging from 11 to 59) walked in a treadmill at the suggested speeds of 1 mph, 2 mph, 3 mph, 5 mph and 2 mph with inclination. The results regarding the variabilities in velocities (obtained as the percentage of the standard deviation to the mean) are summarizes in Figure 1.

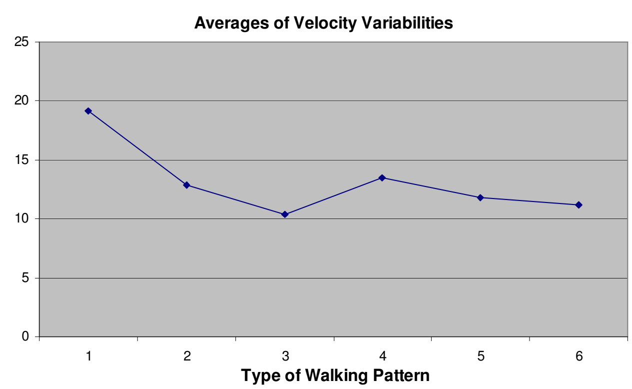

Figure 1. Averages of velocity variabilities for 20 individuals and 6 types of walking patterns: 1) 1mph, 2) 2mph, 3) 3mph, 4) 2mph inclined, 5) 5mph, 6) free walking.

As observed in Figure 1, there is no significant effect on the variability of velocity when the individual is told to keep a fixed speed, in comparison with walking at free speed. Only at very low speeds (walking type 1 in Figure 1) or when the walking surface is kept inclined (walking type 4 in Figure 1), the velocity variabilities are higher than those obtained without the cognitive load of having to keep a constant speed.

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VI. CONCLUSION

In this paper, we have reviewed the most common systems, dual tasks and spatio-temporal parameters employed by researchers to analyze the influence of cognitive load on gait and postural control. We have also proposed a new methodology to study the effect of cognitive load on gait leveraging smart phones and off-the-shelf accelerometers. Making use of our new methodology, we have examined the influence on gait posed by common “working memory” or “motor” tasks, obtaining results that match perfectly with those obtained by other researchers employing more sophisticated systems. We have also studied the influence on gait derived from the imposition of a constant speed while walking on a treadmill. In conclusion, the effect of cognitive load on gait can be measured with current state-of-the-art smart phones and off-the-shelf accelerometers, without the need of sophisticated and expensive equipment.

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