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The interacting effect of cognitive and motor task demands on performance of gait, balance and cognition in young adults

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ABSTRACT

Mobility limitations and cognitive impairments, each common with aging, reduce levels of physical and mental activity, are prognostic of future adverse health events, and are associated with an increased fall risk. The purpose of this study was to examine whether divided attention during walking at a constant speed would decrease locomotor rhythm, stability, and cognitive performance. Young healthy participants ($n = 20$) performed a visuo-spatial cognitive task in sitting and while treadmill walking at 2 speeds (0.7 and 1.0 m/s).Treadmill speed had a significant effect on temporal gait variables and ML-COP excursion. Cognitive load did not have a significant effect on average temporal gait variables or COP excursion, but variation of gait variables increased during dual-task walking. ML and AP trunk motion was found to decrease during dual-task walking. There was a significant decrease in cognitive performance (success rate, response time and movement time) while walking, but no effect due to treadmill speed. In conclusion walking speed is an important variable to be controlled in studies that are designed to examine effects of concurrent cognitive tasks on locomotor rhythm, pacing and stability. Divided attention during walking at a constant speed did result in decreased performance of a visuo-spatial cognitive task and an increased variability in locomotor rhythm.

1. Introduction

Successful aging has become one of the most important aspects of health care in the 21st century. As people live longer risks of cumulative illness, chronic disability increase [1,2]. Mobility limitations and cognitive impairments, both common with aging, reduce levels of physical and mental activity, are prognostic of future adverse health events, and are associated with an increased fall risk [2]. Importantly, the link between cognitive impairment, mobility limitations and the tendency to falls is recognized in the literature [3].

Maintaining stability during walking through the environment is a complex, multi-dimensional process requiring higher level motor control, and cognitive flexibility to address balance threats, while attending to environmental demands and concurrent cognitive tasks [2]. A key factor in locomotor control is executive cognitive functioning and deficits are associated with increased risk of falling [3,4]. Various dual task (DT) studies have affirmed that difficulty in assigning attention to each task simultaneously may contribute significantly to increased fall risks. Poor DT performance in either the motor or cognitive task could be caused by altered prioritization between the two tasks [5]. The most common and consistent finding of DT studies has been the reduction of gait speed [3], likely as a strategy for concurrent task processing or to avoid stability threat. Reduced speed is commonly observed in elderly, and when negotiating obstacles, irregular or unpredictable terrain [6].

Dual-task studies have utilized cognitive tasks, like animal enumeration or number subtraction that are typically only assessed qualitatively, do not involve the visuomotor system and are limited in recruitment of individual brain areas. Visual–spatial processing of object locations/motions and their spatial relations with respect to body and space are key aspects of balance and locomotor skills, and evidence supports visual–spatial processing as an important aspect of cognition to explore in mobility decline [7,8].

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Virtual environments, viewed during treadmill walking, have been used as an ecological approach to rehabilitation [9]. Computerized cognitive tasks and games have received interest from researchers and clinicians, both as a model for learning a broad range of cognitive tasks and as a means to examine training and transfer of skills to daily life activities [10–12]. A treadmill rehabilitation platform (TRP) was designed around a treadmill as it is an excellent choice for conducting gait training with dual-tasks. It can incorporate walking skills while interacting with computer-generated cognitive activities viewed on a standard LCD display [9]. DT treadmill walking has important advantages versus over ground walking as gait variables are significantly influenced by walking speed [13,14] and reduced gait speed is a highly consistent strategy used during dual-task over-ground walking [3]. It is a convenient method to determine steady-state walking speed. It also allows gathering hundreds of consecutive steps in a few minutes. Data from 5–10 strides (i.e. in gait laboratories or during repeated walks over short, instrumented walkways) may reliably measure gait speed, but is not sufficient for measures of gait variability or periodicity, particularly during dual task walking and for older adults with mobility limitations [15,16].

The purpose of this study was to further explore the interplay between cognitive and walking demands on task performance. Since previous studies have shown that gait speed is an important factor affecting gait parameters, the treadmill speed is held constant to prevent a strategy of slowing walking speed. The first objective was to evaluate the effect of walking speed on temporal gait parameters and measures of walking stability, amplitude and variation of center of foot pressure (COP) displacements and trunk motion. The objective was to examine whether divided attention during walking at a constant speed would decrease locomotor rhythm, stability, and cognitive performance. This study addresses three hypotheses:

(1) Walking speed has a significant effect on temporal gait variables, and measures representing walking stability.
(2) Stability, locomotor, and cognitive performance will significantly decline from single task to DT conditions during constant speed.
(3) Cognitive performance will decline with increasing treadmill speed.

2. Methods

Twenty healthy young adults aged 20–30 years (mean age 26.3 ± 3.2 years) participated. Participants were excluded if they had past neurological impairment, musculoskeletal disorder or were taking medications that may have influenced their walking.

3. Instrumentation and data recording

Fig. 1 illustrates the experimental set-up. Participants were positioned on the treadmill 100 cm from the 30-inch monitor connected to a computer running the cognitive game. Vertical foot contact pressures were recorded from each foot using in-shoe pressure insoles. (Vista Medical Ltd, WPG. MB). The pressure insoles each consist of an array of 128 piezo-resistive sensors, calibrated to 300 mm Hg (12-bit). Pressure signals from left and right insoles were recorded at 35 Hz. The 3D Track STAR (Ascension Tech, Burlington, VT, US) was used to record the position of the trunk (80 Hz). The track STAR sensor was secured to the skin at the second thoracic spinal process. A commercial motion mouse (Gyration Air Mouse, USA) was secured to a head band and used as the computer input device to control on-screen cursor motion with head rotation (left–right). This Air Mouse has inertial sensors used to derive angular position signals. With this simple method, seamless and responsive hands-free interaction with the computer application is made possible. In a similar manner, a number of studies have used reaching or pointing tasks to evaluate perception, attention, and higher-level cognitive decision-making [17,18]. Visually guided head movements are among the most natural, therefore these tasks are easily performed with minimal

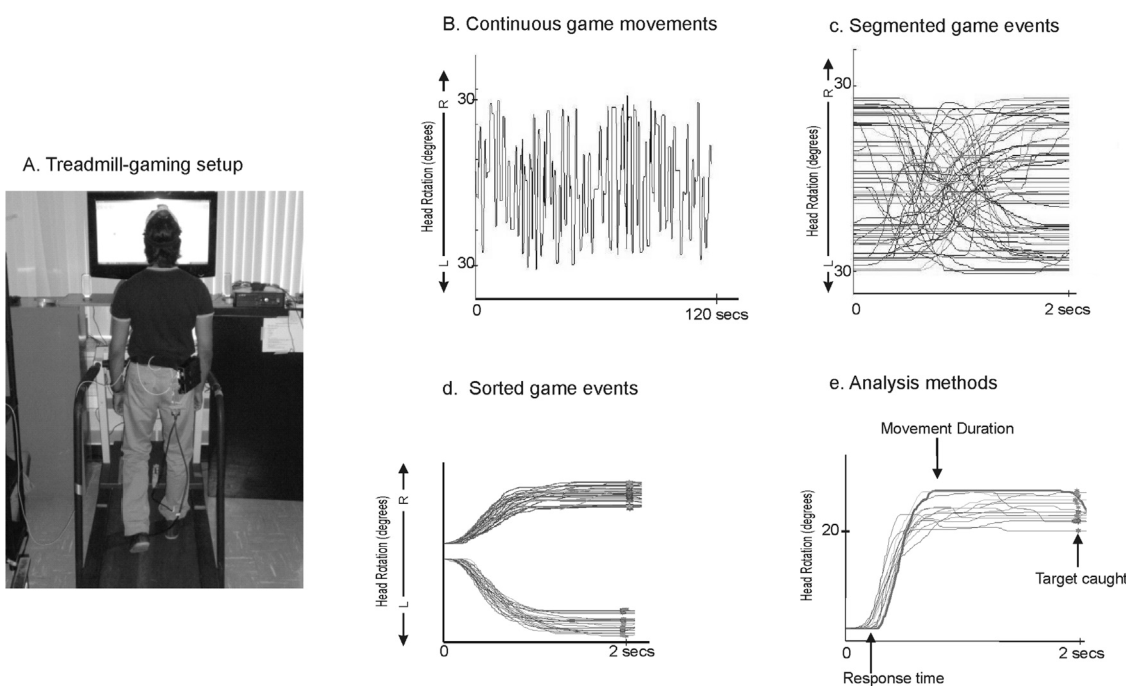

Fig. 1. Experimental set-up. Participant is shown walking on treadmill while viewing a computer monitor and using head rotation (motion mouse) to interact with cognitive game. Panel B presents trajectory of game paddle movements for one logged game file, 120 s duration. Each game event is 2 s in length; thus, recording includes a total of 60 game events (random presentation of different amplitudes and directions). Panel C presents overlay of individual game events segmented based on index times of target appearance and disappearance Time zero is onset of target appearance, end of event is time when target disappears. Panel D: segmented game events shown in D are sorted grouped in functional bins, which in this case represent medium amplitude player movements in leftward direction (upward trajectories), and rightward direction (downward trajectories). Panel E illustrates analysis methods to quantify response time and movement time.

instruction. Computer controlled goal-directed movements can provide an easily accessible way to track a wide range of cognitive events while walking.

4. Cognitive game task

Studies have used computer-based games to probe and evaluate cognitive function [11]. The Useful Field of View (UFOV) is a computer-based test that requires the ability to select relevant information and ignore irrelevant information (cognitive inhibition) [19]. Studies have found that older adults with slower cognitive speed of processing, as measured by the UFOV test, experienced the greatest mobility loss [20]. A modified version of the UFOV has been designed to evaluate visual–spatial processing together with eye-head coordination. The goal of the test game is to move a paddle (game sprite) to catch falling bright circle objects (targets) moving vertically top to bottom, and to avoid triangle shaped objects (distracters). The objects appear at fixed intervals (2 s) and at random locations on the monitor. The game is instrumented with an assessment module. This generates a logged game file recording (80 Hz) the following signals associated with player performance with respect to game events: (a) time index and coordinates of each object and (b) position coordinates of the game paddle (slaved to head rotation). Fig. 1C, presents trajectory of head rotation of one game file (obtained in standing), and Fig. 1D shows all segmented game events within one trial. These contextual game events are sorted by direction and amplitude to obtain multiple event groupings with similar movement features (Fig. 1E). For a full description see Lockery et al. [21].

5. Protocol

Participants played the computer game using a standard optical mouse for 2 min in sitting to familiarize themselves with the cognitive task. The viewing height of the display during sitting and walking was maintained by placing an adjustable stool on the treadmill. A rest period of 2–3 min was given between test conditions. Participants walked on a level treadmill for 10 min at 0.7 m/s for treadmill acclimation. During testing, participants walked for 2 min at two treadmill speeds; 0.7 m/s (lower speed) and 1.0 m/s (higher speed), singly, while performing the cognitive game task. The order of treadmill speed, single and DT conditions were randomized within a session to minimize potential order effect. The cognitive tasks were also performed while standing on the stationary treadmill (single task condition).

6. Data analysis

Custom built scripts in MATLAB version 7.1 (The Math Works, Natick, MA) processed the pressure data of each insole array into footfall patterns. Time indices were computed for pressure onset and offset, stance and swing phases for each right and left step, and double support times. The average and coefficient of variation (COV) of stance time (ST), swing time (SW), and double support time (DS) were computed for each walk trial (45 steps per leg). These gait variables have been identified based on associations with falls, cognitive impairment [1] and balance impairments [22].

Center of pressure excursions in the anterior-posterior (AP) and medial–lateral (ML) directions were calculated by summing the contact forces recorded from each insole sensor. Based on the time indices for stance onset and offset, the COP time's series data were segmented into individual right and left stance phases for each step. The segmented stance COP trajectories were time normalized and the average COP trajectory and standard deviation across the trial was computed for each foot. Fig. 2 presents overlay of typical time normalized COP trajectories for steps of one walk trial at each speed. Traces are offset to a common baseline value of zero for display purpose. Thickened lines represent ensemble average and dotted lines standard deviation. Also presented are scatter plots (means and SD) of stance and swing time for each of the 45 steps obtained. The following variables were computed from the average COP trajectory; (a) peak-to-peak COP displacement, (b) root mean square (RMS), and (c) total path length (TLP) [23,24]. In addition variance in step to step COP trajectories over each walk trial was computed, defined as the average of the COP standard deviation. Peak-to-peak amplitude and RMS of AP and ML trunk position data were computed. Control of the motion of the trunk is a main contributor to overall stability during walking [25,26].

Different features of the test game events provide a basis for objective quantification of cognitive functions. As illustrated in Fig. 1E the following variables were determined: (1) game success rate (percentage of target caught), (2) average motor response time (time from appearance of the target to start of the paddle movement), (3) average movement execution time (time between movement initiation and final paddle position).

7. Statistical analysis

A two-way repeated measures ANOVA was used to determine the effects of treadmill speed and cognitive load (single vs. DT conditions) on temporal gait variables, COP and trunk excursion

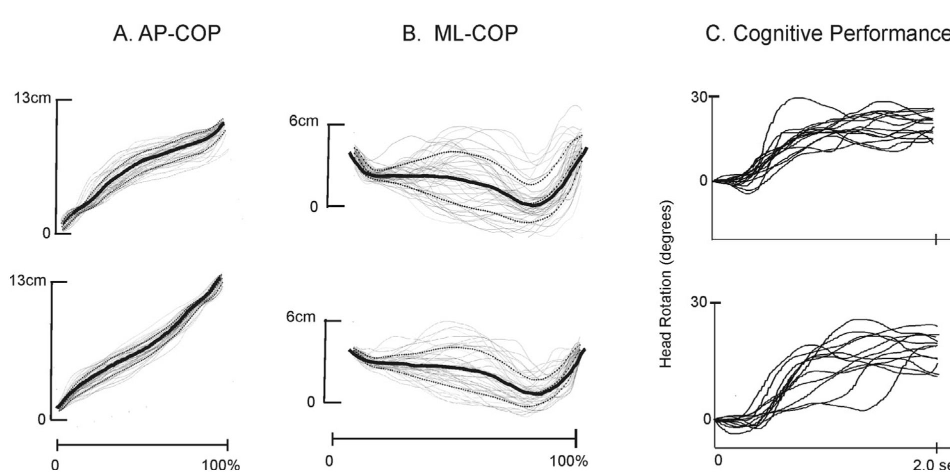

Fig. 2. Overlay plots of segmented time normalized AP-COP and ML-COP trajectories of each stance phase in one walk trial. Trajectories are offset to a common baseline value of zero for display purpose. Thickened lines represent ensemble average and dotted lines standard deviation. Panel C presents typical plots of segmented game events of medium leftward movements from one game trial obtained during walking. Top row are for 0.7 m/s treadmill speed and bottom for 1.0 m/s.

measures, and cognitive performance measures. The significance level was set at alpha level of 0.5.

8. Results

Group means and standard error of means (SEM) for average and COV of ST, SW, and DS are presented in Fig. 3. There was no significant difference in gait variables (average or COV) between left and right steps and therefore only results of analysis of right steps is presented in Table A1 (Appendix A). Average and COV of ST, SW and DS significantly decreased as a function of walking speed ($p < 0.01$). There was no significant effect of cognitive load for walk only versus DT walking on average ST, SW, or DS. In contrast COV of ST, SW, and DS significantly increased from single to DT conditions ($p < 0.01$).

Group means (SEM) of COP peak-to-peak amplitude, RMS and TPL are presented in Fig. 4. As presented in Table A2 (Appendix A) all variables of COP excursion in ML direction significantly increased with increasing treadmill speed (peak to peak: $p < 0.02$; RMS: $p < 0.01$; TPL: $p < 0.01$). However there was no significant effect of treadmill speed on AP-COP excursion variables. As seen in Fig. 5 there was a significant effect of walking speed on the variation of COP trajectories across steps within a trial. The average standard deviation of ML-COP trajectories increased with increasing treadmill speed ($p < 0.01$) but the opposite was observed for AP-COP ($p < 0.01$). Cognitive load at either treadmill speed had no significant effect on either COP excursion variables, or average COP standard deviation.

Group means (SEM) of peak-to-peak amplitude and RMS of trunk horizontal translation is shown in Fig. 5. As presented in Table A2 (Appendix A) there was no significant effect of walking speed on magnitude of linear trunk excursion in either AP or ML direction. In contrast, peak-to-peak amplitude and RMS of trunk horizontal translation in ML and AP directions were found to significantly decrease while performing the cognitive tasks compared to walking alone ($p < 0.01$).

Fig. 2D presents typical plots of segmented game movements obtained at both speeds compared to standing (Fig. 1E). There was a significant decrease in success rate (88–65%; $p < 0.001$; $F(2, 18)$, 25), and a significant increase in; (a) response time (410–680 ms; $p < 0.001$; $F(2, 18)$, 35), and (b) execution time (510–580 ms; $p < 0.01$; $F(2, 18)$, 16), while walking compared to standing. There was no significant difference in these variables between the two treadmill speeds.

9. Discussion

Treadmill speed had a significant effect on temporal gait variables (average and COV) in keeping with previous studies. The present results are consistent with Jordan et al. [13] and Kang and Dingwell [27] who observed a decrease in gait variability with increased walking speed. Measures of variability provide a perspective on the consistency of locomotor rhythm, and are often reported to represent walking stability. This view is supported by the present findings wherein the magnitude and variation in ML-COP displacements were influenced by treadmill speed. Other studies have reported that walking speed affects dynamic stability measures (e.g. Lyapunov exponents based on trunk velocity/acceleration) [16,28]. To note AP-COP excursion was not affected by treadmill speed, and in fact variation of AP-COP trajectories across the 45 consecutive steps decreased with increasing walking speed (as well as decreased stance/swing duration). This may reflect the consistency of heel contact and a more constant AP path length to toe off.

We hypothesized that an increase in walking speed would result in an increase in trunk motion. However, the present results did not show any significant effect of speed on linear ML or AP trunk motion. In contrast to this finding, Kavanagh [25] found a significant increase in ML trunk motion with increasing over ground walking speed. The difference in these findings might be explained by the difference in walking speeds or may reflect a consequence of treadmill walking. In the present study speeds were 0.7–1.0 m/s, whereas, in the Kavanagh study it was much greater (0.9–1.7 m/s). The treadmill's safety rails, front panel and monitor provided stationary visual cues that could help orientate and stabilize the body location and trunk position during walking.

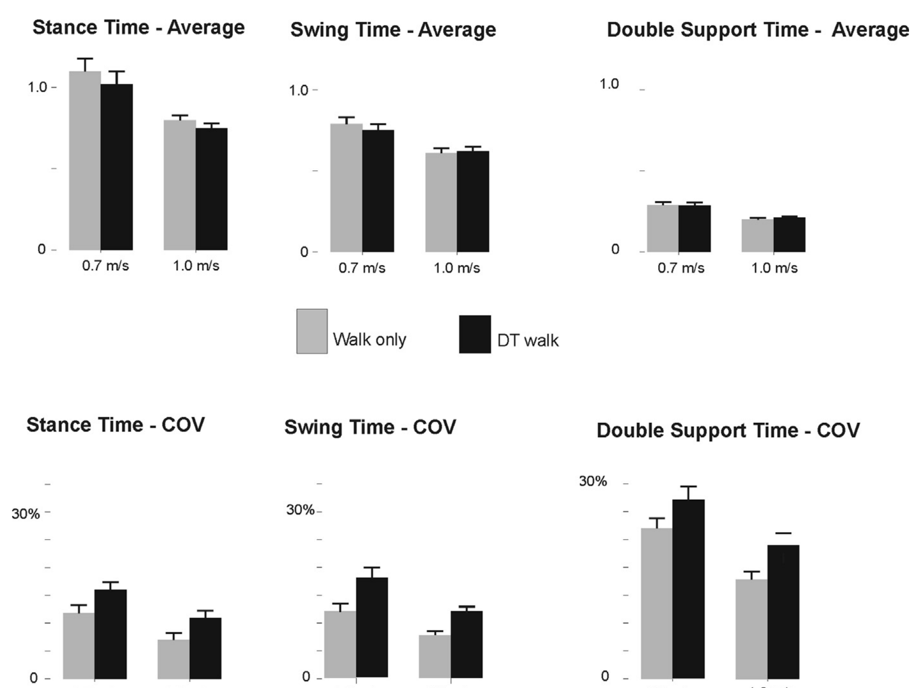

Fig. 3. Presents group means and standard error of means (SEM) of trial average and COV of ST, SW, and DS at the two speeds, walk-only and DT walks conditions.

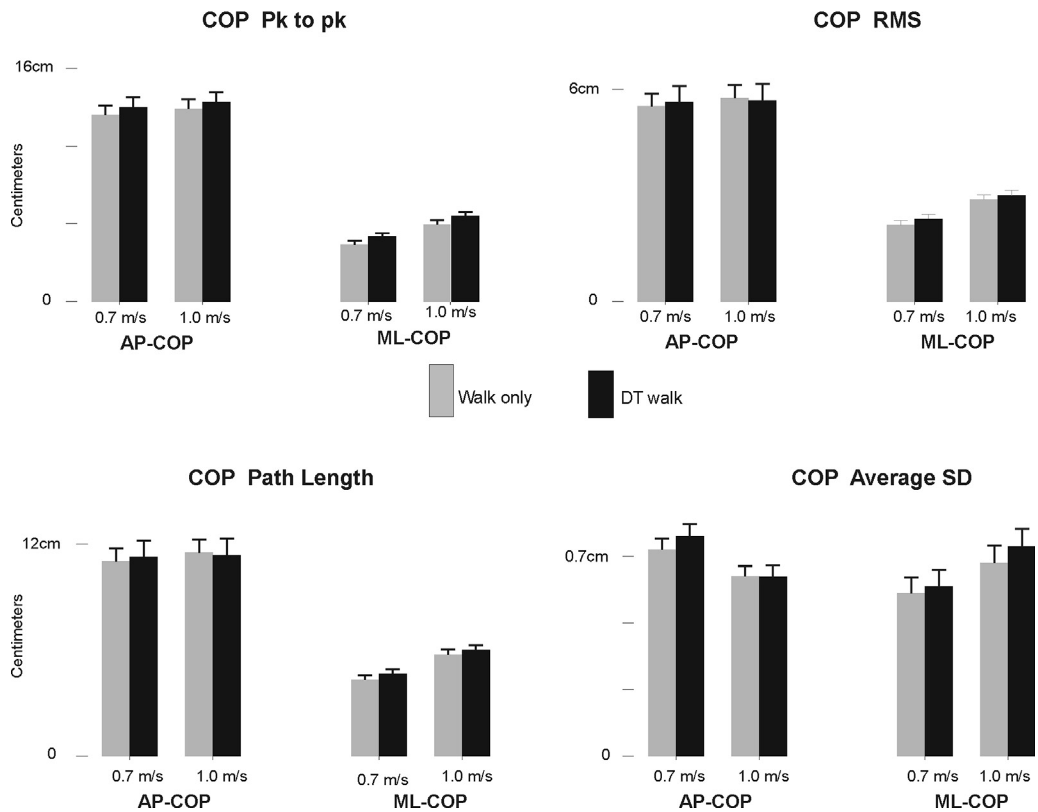

Fig. 4. Present group means and (SEM) of peak-to-peak amplitude, RMS and path length of COP displacement at the two speeds, walk only and DT walks conditions. Bottom right histogram presents group means (SEM) of the average SD of COP trajectories within a trial.

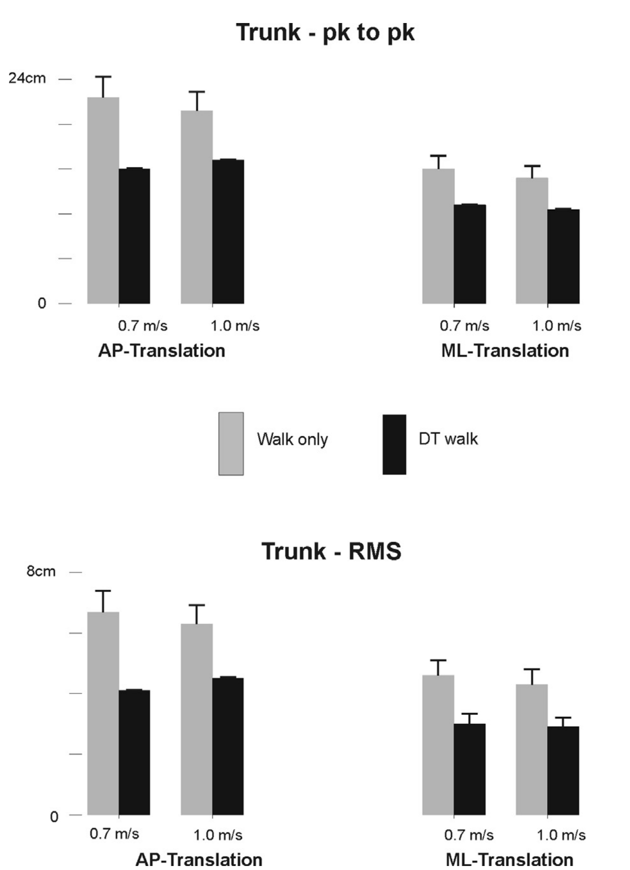

Fig. 5. Presents group means (SEM) of peak-to-peak amplitude and RMS of trunk linear displacement at the two speeds, walk only and DT walks conditions.

The present findings demonstrate that ML and AP trunk motion was reduced while tracking and interacting with moving images on a monitor. Dingwell et al. [29] examined the effect of performing a visual Stroop task on trunk motion during treadmill walking. Variability of trunk velocity in all three directions decreased during the DT condition. Similar findings have been reported by Doi et al. [26] that ML trunk acceleration was significantly decreased during DT over ground walking using a color Stroop task with images projected onto the wall. A decrease in trunk motion would minimize head motion and thus help to stabilize gaze while tracking and interacting with moving targets or when reading words. In this regard Lambert et al. [30] has shown that visual acuity does not decrease during treadmill walking in young healthy participants, although visual acuity decreased significantly in patients with a peripheral vestibular loss.

In the present study the head rotational pointing movements used to interact with the visual targets were ramp movements, duration approximately 600 ms, and amplitudes less than 30. Studies which have examined tracking visual targets (up to 25°) during treadmill walking using eye movements only compared to eye-head and trunk rotation show little lateral deviation of the COP from the heading direction when they performed the tracking task with eye or head rotation, whereas, trunk rotations led to a doubling of ML-COP deviation [24]. Also of note with respect to the present cognitive outcome measures, response time was found to increase during walking. The head is stationary during this time period i.e. from initial appearance of objects to start of head movement.

Thus far, most DT walking studies have been limited to a single cognitive performance indicator (example correct response number) while performing the cognitive tasks during a walk of a few meters on a walkway. In most of these studies, both walking speed and cognitive performance decreased (for review see Al Yahya et al. [3]). In the present study during DT walking it took longer to initiate movements to specified targets (presence of distracters), movement times to reach the final target position were longer, and the number of targets caught decreased. Cognitive load also did not have a significant effect on average temporal gait variables or magnitude of COP excursion. At first glance this appears different from the previous research findings, but given a constant treadmill speed it would be expected that average values of temporal gait variables would be consistent among conditions performed at the same speed. A significant increase in variability of stance time, swing time, and double limb support time during DT walking was seen, consistent with results of recent studies [3]. Analysis of gait variability (e.g. standard deviations) only quantifies the average magnitude of differences across all strides, regardless of temporal order. Other analyses reflective of dynamic stability include Lyapunov exponents and Floquet multipliers. These measures have been shown to be sensitive to change in treadmill walking speed and DT conditions [16,27]. These methods however require large numbers of consecutive steps (i.e. hundreds) therefore are often conducted during treadmill walking. In the present study 45 steps, using 2 min of walking data, were collected.

The application of computer tasks can provide a broad range of executive cognitive functions. Employing computer tasks, and parsing subjects' actions and choices can provide recordings of multiple contextual events. This permits quantification of process measures in addition to objective measures of cognitive performance [17]. Thus one can make principled comparisons of the influence that cognitive demands have on stability, gait and fall risk. This will provide a better understanding of the functional consequences of decline in physical and mental skills with age and in early stages of disease, and help in making choices for prevention, treatments, and lifestyle decisions.

In conclusion, walking speed is an important variable to be controlled in studies that are designed to examine effects of concurrent cognitive tasks on variables representing locomotor rhythm, pacing and stability. Divided attention during walking at a constant speed did result in decreased performance of a visuo-spatial tracking task, an increased variability in locomotor rhythm. It also appears that gaze control is an important priority during DT tasks that depend on processing of visual information.

Funding

None.

Conflict of interest

There is no conflict of interest.

Appendix A

Table A1
Results of analysis of variance: effect of speed and DT on gait parameters. *F*-statistics (d*f*).

	Averages		Coefficient of variance (COV)	
	Speed	DT	Speed	DT
Stance time	$p < 0.01$ $F(2, 18)$ 48.5	NS	$p < 0.01$ $F(2, 18)$ 30.6	$p < 0.01$ $F(2, 18)$ 27.3
Swing time	$p < 0.01$ $F(2, 18)$ 19.5	NS	$p < 0.01$ F(2, 18) 6.25	$p < 0.01$ $F(2, 18)$ 18.5
Double support time	$p < 0.01$ $F(2, 18)$ 39.8	NS	$p < 0.01$ $F(2, 18)$ 29.3	$p < 0.01$ $F(2, 18)$ 8.5

Table A2
Results of analysis of variance, effects of speed and DT on COP parameters and trunk translations. *F*-statistics (d*f*).

	Center of pressure (COP)				Trunk translations			
	Speed		DT		Speed		DT	
	AP	ML	AP	ML	AP	ML	AP	ML
Pk-Pk	NS	$p < 0.01$ $F(2, 18)$ 5.3	NS	NS	NS	NS	$p < 0.01$ $F(2, 18)$ 11.2	$p < 0.01$ $F(2, 18)$ 4.3
RMS	NS	$p < 0.01$ $F(2, 18)$ 7.2	NS	NS	NS	NS	$p < 0.01$ $F(2, 18)$ 21.3	$p < 0.01$ $F(2, 18)$ 12.6
TPL	NS	$p < 0.01$ $F(2, 18)$ 15.2	NS	NS				

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