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The influence of altered foot placement and cognitive load on balance control during walking in healthy young adults

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ABSTRACT

Background: Clinical populations often walk with altered foot placement, which can adversely affect balance control. However, it is unknown how balance control during walking is influenced when combining a cognitive load with altered foot placement.

Research Question: Is balance control during walking adversely affected by the combination of a more complex motor task, such as walking with altered foot placements, with a cognitive load?

Methods: Fifteen young healthy adults walked on a treadmill with and without a spelling cognitive load during normal walking, with step width targets (self-selected width, narrow, wide and extra wide), or with step length targets (self-selected length, short and long).

Results: Cognitive performance, measured by correct spelling response rate, decreased from self-selected (2.407 ± 0.6 letters/s) to the extra wide width (2.011 ± 0.5 letters/s). The addition of the cognitive load caused a decrease in frontal plane balance control across all step lengths (15% change) and at the wider step widths (16% change), but only caused a slight decrease in the sagittal plane for the short step length (6.8% change).

Significance: These results suggest that when combining a cognitive load with walking at non-self-selected widths, a threshold exists at wider steps where attentional resources become insufficient and balance control and cognitive performance decrease. Because decreased balance control increases the risk of falling, these results have implications for clinical populations who often walk with wider steps. Furthermore, the lack of changes to sagittal plane balance during altered step length dual-tasks further supports that frontal plane balance requires more active control.

1. Introduction

Dual-task (DT) studies often combine walking with an additional cognitive load to determine the cognitive load's influence on gait performance [1]. Performing a challenging cognitive task during steady-state walking has been shown to negatively affect frontal plane balance control [2,3] and increase fall risk [4]. Balance control during walking is often assessed using whole-body angular momentum (*H*) [5], which is partially mediated through foot placement by changing the moment arm between the foot center of pressure and the body center of mass (CoM). Thus, altering foot placement by changing step width or step length directly influences balance control. Motor tasks with increasing complexity can further distract and tax the cognitive resources available during walking [6,7]. However, frontal plane balance has been shown to require more active control compared to the sagittal plane [8]. Thus, there may be differential effects of altered foot placement on balance control in each plane, which are further exacerbated with the addition of a cognitive load.

There is evidence for a relationship between balance control and step widths during DT walking. Previous studies analyzing walking with altered step widths and lengths during DT walking mostly focused on natural changes in step width [e.g., [9,10]] and step length [e.g., [11]], and the few that altered foot placement examined narrow walking (e.g., [12,13]). One study investigating DT narrow path walking found a reduction in speed, stride length and cognitive performance in older adults [12]. However, how the combination of a cognitive load with altered foot placement affects balance control remains unclear. Thus, the purpose of this study was to determine the effect of combining a cognitive load with altered step widths or lengths on balance control and cognitive performance in young healthy adults during walking.

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Table 1
Average demographic data of participants (mean ± 1 standard deviation).

Age (years)	25 ± 4
Gender (male/female)	7 male/8 female
Height (cm)	168 ± 11
Weight (kg)	69 ± 12
Self-selected walking speed (m/s)	1.3 ± 0.2

Previous studies demonstrated that young healthy individuals prioritize cognitive performance over balance control when faced with a challenging cognitive task and no risk of falling by maintaining cognitive performance while allowing balance control to decrease [2]. However, individuals prioritize balance control if the motor task involves a balance perturbation [14,15]. The effects of increasing motor task difficulty between steady-state and altered walking tasks has not been well studied, with most adding a concurrent carrying task [e.g., [16,17]] or obstacle avoidance [e.g., [11,18]]. Thus, it remains unclear how tasks are prioritized when a cognitive load is paired with a challenging motor task, such as walking with altered foot placement. With frontal plane balance requiring more active control [8], altering step widths may pose a challenging enough motor task that attentional resources become strained and cognitive performance decreases. In contrast, in the more passively controlled sagittal plane, a change in step length may not produce similar results.

Thus, we hypothesize that balance control will be more adversely affected with the combination of altered step widths and a cognitive load rather than with just the cognitive load or the altered step widths independently. Furthermore, we hypothesize that cognitive performance will also decrease from normal walking to the altered step width conditions because individuals will prioritize performing the more challenging motor task over their cognitive performance. In contrast, in the sagittal plane we hypothesize that altering step length will not affect balance control nor cognitive performance between single- and dual-task walking.

2. Methods

2.1. Human subject protocol

Fifteen young healthy adults (Table 1) were recruited from the local community. All subjects provided written informed consent to participate in this protocol approved by The University of Texas at Austin Institutional Review Board. All participants were free from any musculoskeletal and neuromuscular injuries. To determine their SS walking speed, three trials of 10-meter overground walking at their "comfortable, typical walking speed" were collected and averaged. Data collection trials consisted of 30 s of steady-state treadmill walking at their SS walking speed. Three-dimensional full-body kinematic data were collected at 120 Hz using 56 reflective markers with a 10-camera motion capture system (Vicon, Oxford, UK). Three-dimensional ground reaction force (GRF) data were collected at 960 Hz from a split-belt instrumented treadmill (Motek, Amsterdam, NL).

The DT cognitive load was spelling words backwards, and participants first performed a cognitive control (spelling-while-standing) and then walked on the treadmill with (DT) and without (single-task (ST)) the cognitive load under the following conditions: normal treadmill walking with no foot placement targets and treadmill walking with altered step width or step length targets. For the altered step widths, individuals walked with each foot in the middle of a line projected onto the treadmill at their SS step width, 25% narrower (narrow), 50% wider (wide) and 100% wider (extra wide) (Fig. 1a). Altered step lengths were performed with the individual's foot in the middle of a line projected perpendicular to the treadmill (moving at the same speed as the belt) at their SS step length and 20% shorter (short) and 20% longer (long) (Fig. 1b). Walking conditions and the order of the words were randomized.

2.2. Cognitive loads

During the spelling conditions, participants were instructed to spell each word backwards as quickly and accurately as possible, which were recorded through a microphone. One-hundred common 5-letter words were selected from the English dictionary (Appendix A) and presented in a randomized order for each subject. A recording of each word was played for each subject so that the words were pronounced identically. Participants completed as many words as possible with the subsequent word coming immediately after they spelled the previous word. No specific task-prioritization instructions were given.

2.3. Prescribed step widths and lengths

Step width was defined as the mediolateral (ML) distance between the left and right heel markers at consecutive heel-strikes. Step length was the anteroposterior (AP) distance between the left and right heel markers at consecutive heel-strikes plus the distance the treadmill moved during that time. The position of the heel markers as well as the position of the posterior superior iliac spine markers were input into D-Flow's software (Motek, Amsterdam, NL) and used to determine heel-strikes [19]. During an initial no targets walking trial, custom D-flow software calculated each individual's SS step widths and lengths by averaging these values over 20 consecutive steps.

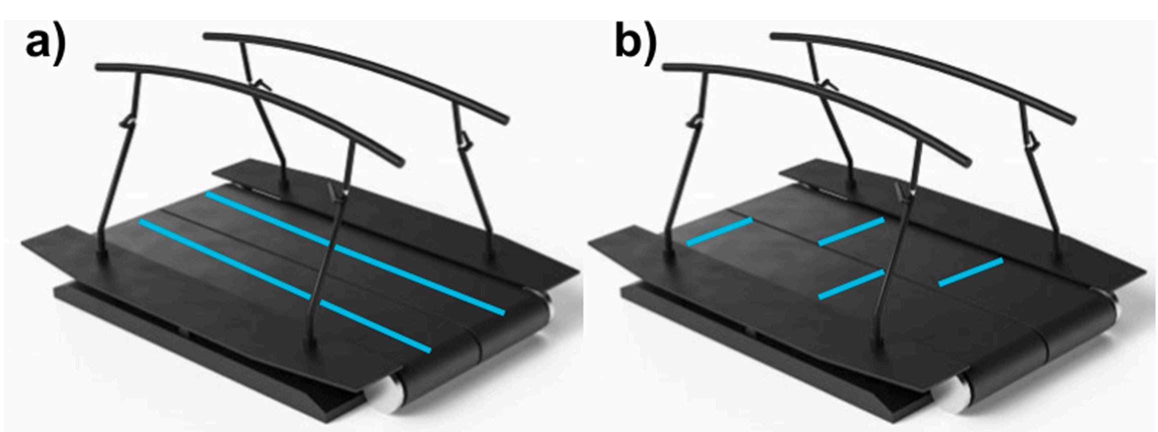

Fig. 1. Illustration of the step width (a) and step length (b) targets.

Table 2
Desired and actual percent changes from the self-selected (SS) width or length conditions and the group and follow up Tukey HSD test *p*-values for the single-task (ST) and dual-task (DT) conditions. Bold indicates significance of $p < 0.05$.

	Desired % change from the SS condition (%)		Actual % change from the SS condition (%)		*p*-value from linear mixed effect model	*p*-value for follow up tests comparing to SS condition	
	ST	DT	ST	DT	Group Effect	ST	DT
				Length			
No Targets	0	0	-1.57 ± 2.78	-1.25 ± 4.13	**< 0.001**	0.113	0.386
Short	-20	-20	-20.43 ± 1.65	-20.03 ± 1.28		**< 0.001**	**< 0.001**
Long	20	20	20.97 ± 1.82	21.1 ± 2.11		**< 0.001**	**< 0.001**
				Width			
No Targets	0	0	3.27 ± 10.48	10.3 ± 11.73	**< 0.001**	0.679	**< 0.001**
Narrow	-25	-25	-12.95 ± 6.33	-14.66 ± 4.13		**< 0.001**	**< 0.001**
Wide	50	50	35.65 ± 16.08	31.47 ± 15.58		**< 0.001**	**< 0.001**
Extra Wide	100	100	75.27 ± 19.94	70.89 ± 25.64		**< 0.001**	**< 0.001**

2.4. Data analysis

Marker and force plate data were low-pass filtered at 6 Hz and 15 Hz, respectively, using a fourth-order Butterworth filter. A 13-segment inverse dynamics model was created for each subject using Visual3D (C-Motion, Germantown, MD). Dynamic balance was quantified using *H*, which was calculated by summing the angular momentum of each body segment about the whole-body CoM as:

$$\vec{H} = \sum_{i=1}^{n}[(\vec{r}_i^{COM} - \vec{r}_{body}^{COM}) \times m_i(\vec{v}_i^{COM} - \vec{v}_{body}^{COM}) + I_i\vec{\omega_i}] \qquad (1)$$

where $\vec{r}_i^{COM}$, $\vec{v}_i^{COM}$ are the position and velocity vectors of the i^{th} segment's CoM, respectively. $\vec{r}_{body}^{COM}$ and $\vec{v}_{body}^{COM}$ are the position and velocity vectors of the whole-body CoM, m_i, I_i and $\vec{\omega_i}$ are the mass, moment of inertia and angular velocity vector of the i^{th} segment, respectively, and n is the number of body segments. H was normalized by subject mass, height and walking speed. The range of H (H_R) was defined as the difference between the peaks of frontal or sagittal plane H and calculated over each gait cycle, where lower H_R indicates more tightly controlled balance [20].

Recorded audio data was examined to determine correct response rate (correct letters per second) as the measure of cognitive performance.

2.5. Statistics

A linear mixed effects model was used to assess differences in the outcome measures (frontal and sagittal plane H_R, step length, step width and correct response rate) between the walking conditions. Separate models were created for the altered step width and step length conditions. The walking conditions (ST or DT and step width or length condition) were the fixed effects, and the study subjects were the random effects. If the linear mixed effects model revealed significant effects, Tukey HSD post-hoc tests were performed to identify pairwise differences between the conditions. The significance level was set at $p < 0.05$. All statistical analyses were performed using the statistical toolbox in MATLAB (Mathworks, Natick, MA).

3. Results

3.1. Spatiotemporal results

The step lengths were approximately equal to the targeted step lengths while the step widths were slightly narrower than the targeted step widths (Table 2). For the altered step length conditions, the variability was notably higher in both length and width for the long step length compared to the SS step length condition (length: $p = 0.017$ for ST, $p < 0.001$ for DT, width: $p < 0.001$ for both ST and DT conditions). No other changes in variability were noteworthy and can be found in Appendix B.

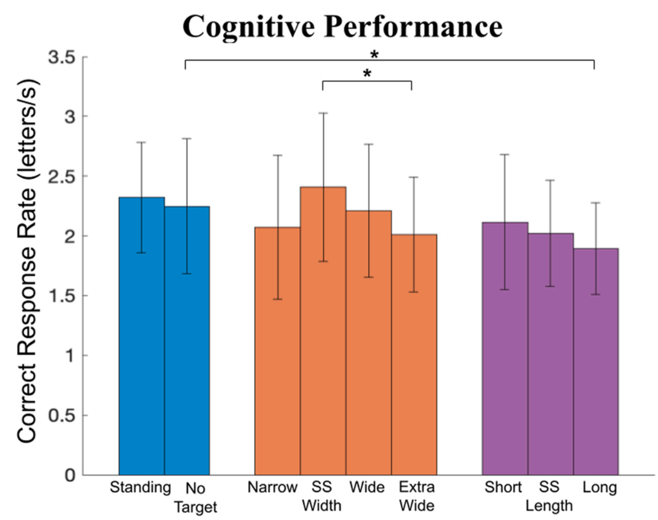

Fig. 2. Correct response rate for the standing control single-task (spelling while standing), normal treadmill walking (no target) and the prescribed step width and length conditions. * indicates significance of $p < 0.05$.

3.2. Cognitive performance

On average the subjects spelled 7.38 ± 0.4 words per trial. In the step width conditions, there was a trend of a decrease in cognitive performance, measured by the correct response rate (Fig. 2). However, the difference only reached significance at the extra wide condition ($p < 0.01$). Cognitive performance did not change across step length conditions except for a decrease between the control no target and long step length conditions ($p = 0.014$, Fig. 2).

3.3. Balance control

As expected, frontal plane H_R increased as step width increased from the SS width to the wide widths (Fig. 3a, $p < 0.01$), and sagittal plane H_R increased as step length increased (Fig. 3d, $p < 0.001$), but there were no changes between the ST no target and the SS conditions ($p > 0.05$). The percent difference in the frontal plane H_R between the ST and DT conditions trended upwards as step width increased (Fig. 3a), but only reached significance at the wide and extra wide steps ($p < 0.01$ for both). The control no targets, SS length and long length conditions all showed similar changes in frontal plane H_R between the ST and DT conditions ($p < 0.001$ for all three, Fig. 3c), while the short length had a small but significant difference between the ST and DT conditions ($p = 0.016$, Fig. 3c).

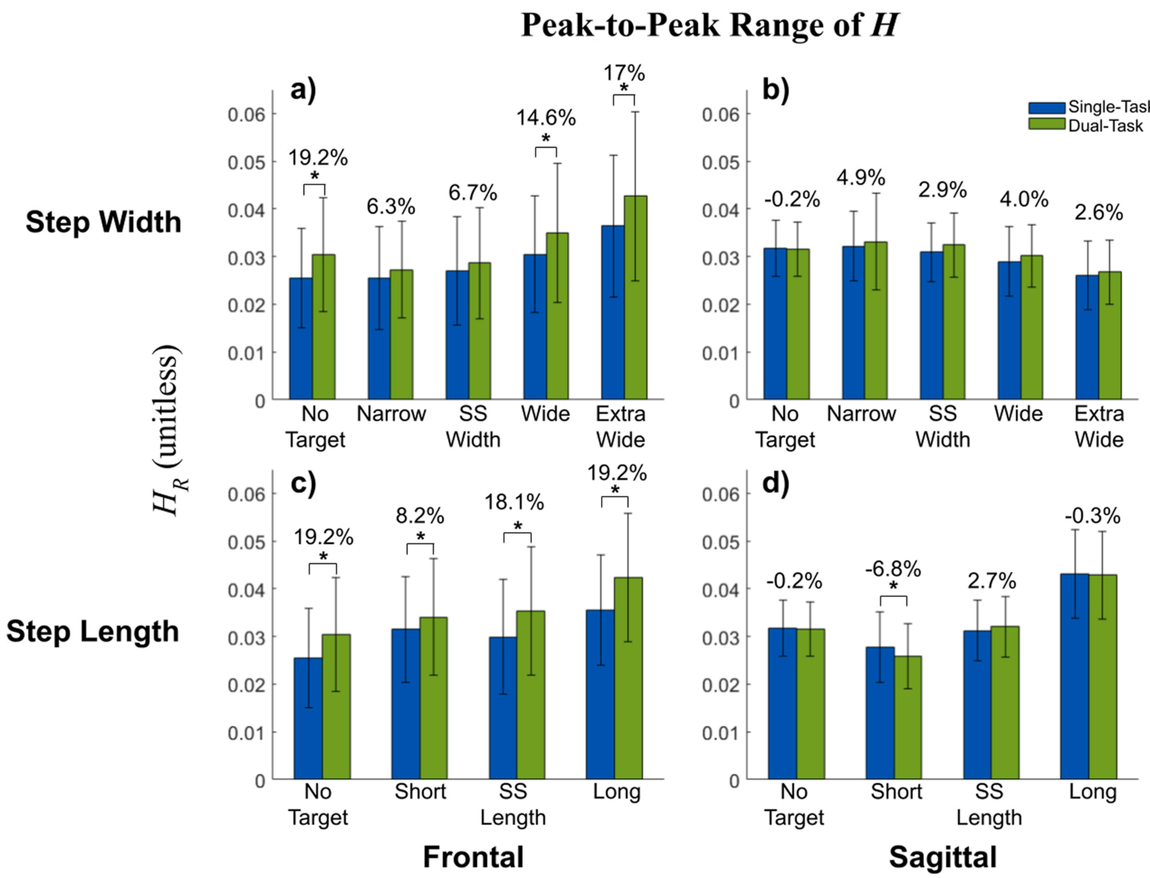

Fig. 3. Normalized peak-to-peak difference in frontal (a and c) and sagittal plane (b and d) whole-body angular momentum (H, normalized by height, mass and speed of each individual) for the different step width and length walking conditions: the no targets control, self-selected (SS) width, narrow, wide and extra wide widths, short, SS length and long lengths. * indicates significance of $p < 0.05$.

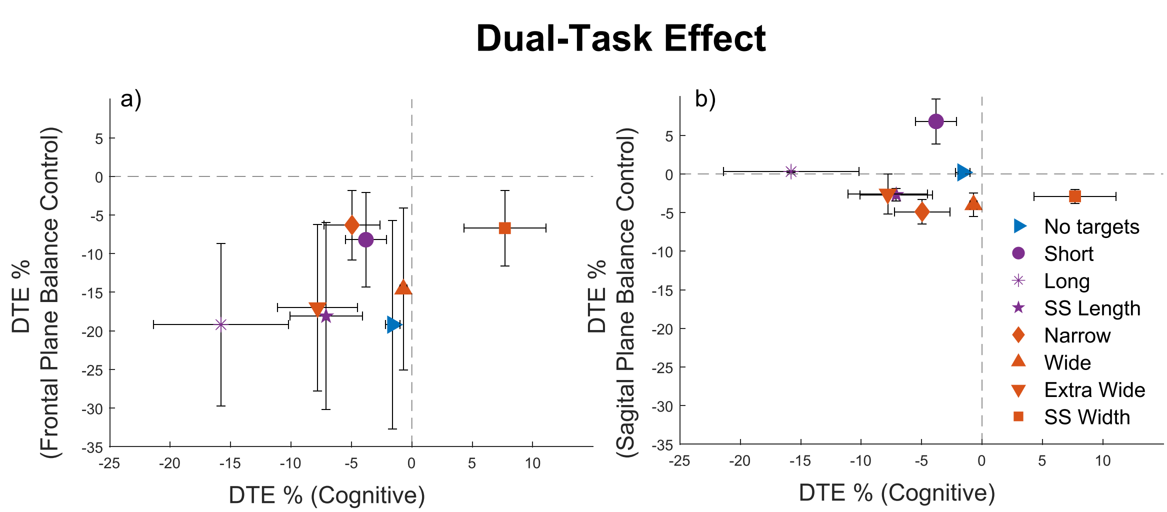

Fig. 4. The dual-task effect (DTE) for the different conditions: (a) frontal plane and (b) sagittal plane range of whole-body angular momentum, which is the balance control metric where a negative number represents a decrease in balance control (i.e., an increase in the range of angular momentum) between the single and dual-task for each condition. The cognitive axis represents the change in correct response rate where negative numbers represent a decrease in cognitive load. The no targets cognitive response is compared to the standing trial and all other cognitive changes are compared to the no targets condition.

Sagittal plane H_R decreased slightly as the step widths increased, but there were no differences between the ST and DT conditions (Fig. 3b). Sagittal plane H_R increased as step length increased; however, the only difference between the ST and DT conditions was a slight decrease at the short length ($p = 0.006$, Fig. 3d).

4. Discussion

This study assessed how young healthy individuals' cognitive performance and balance control were affected by the combination of a cognitive load and an altered motor task (i.e., walking with step width or length targets). We hypothesized that balance control would be adversely affected by the combination of altered step widths and a cognitive load rather than just the cognitive load or the altered step widths independently, which was partially supported at the wide and extra wide conditions. Furthermore, our hypothesis that cognitive performance would decrease from no target walking to the altered step widths was partially supported, with a decrease between the SS width and extra wide conditions. Finally, we hypothesized that changes in step length would not affect sagittal plane balance control or cognitive load between the ST and DT conditions, which was partially supported at all but the short step length.

The control no targets condition resulted in significantly worse balance control with the addition of the cognitive load (Fig. 3), which was consistent with previous results suggesting that individuals focus on their cognitive performance more than their motor performance if the cognitive load is sufficiently challenging [2] (see also Fig. 4 showing the dual-task effect across all conditions). The spatiotemporal results show that participants were able to match step length targets (Table 2). However, the SS step width was slightly smaller than the no targets condition and the actual non-SS step widths were lower than what was targeted (Table 2). Even with these differences, individuals still walked across a range of step widths as desired. The differences could be due to the heel markers simply not lining up with the projected lines or the individuals were attempting to make the motor task easier by not walking on the projected lines.

4.1. Altered step width

The addition of the cognitive load caused frontal plane H_R to trend upwards between the ST and DT across all conditions, which was significant at the wide and extra wide steps ($p < 0.01$ for both). The percent difference in frontal plane H_R between the ST and DT increased as step width increased (Fig. 3a). We did not see an increase between ST and DT in frontal plane H_R at the narrow step width, likely because a smaller step width decreases frontal plane H_R. Furthermore, one study suggested that narrow and wide step widths have different control mechanisms and are essentially different motor tasks [21]. The lack of significant change in frontal plane H_R at the SS width with the addition of the cognitive task was likely due to the easier and more natural walking task. There was a difference in DT frontal plane H_R between the no targets control and the SS width condition, likely due to the targets causing participants to focus more on the motor task and constraining the step width, unlike the slight increase in step width in the DT no targets condition (Table 2). Previous studies have shown that instructed focus can change task-prioritization [22]. However, even with more attention on foot placement, the wide and extra wide DT conditions were challenging enough and required enough attentional resources to see a decrease in both balance control and cognitive performance (Fig. 4a). The additional attentional resources could also be due in part to the precise visual aspect of our motor task requiring a synergy between visual and motor control [23].

There was a trend towards a decrease in the correct response rate from SS width to narrow and wide conditions. However, the difference only reached significance at the extra wide condition (Fig. 2), further suggesting that the wider steps are a sufficiently challenging motor task to decrease both balance and cognitive performance.

4.2. Altered step length

The control no targets, SS length and long conditions were all similarly affected by the addition of a cognitive load with minimal change in balance control between conditions, suggesting that frontal plane balance control during DT does not change with longer steps. The lower percent difference in the frontal plane and the decrease in sagittal plane H_R in the short length condition is analogous to shorter steps that emulate a cautious shuffling gait [24]. This idea is further supported by

Table A1
Words used in the spelling task and their frequency from the Corpus of Contemporary American English [1].

Word	Frequency
Acorn	2418
Ankle	10394
Arrow	8936
Blaze	4258
Block	62504
Brown	108073
Chase	24282
Clump	1692
Crazy	86071
Decaf	835
Depth	22906
Dream	78373
Drunk	27840
Eagle	11413
Eight	103615
Exact	29219
Fight	128863
Forum	20720
Frame	36665
Frizz	324
Frost	7940
Fruit	33321
Ghost	20128
Giant	41788
Globe	18578
Guest	36286
Guide	48374
Hairy	3642
Hotel	68761
Humor	23204
Irony	11618
Japan	51945
Joker	3165
Judge	97503
Juicy	4160
Knack	2503
Knife	29251
Liver	12619
Local	206590
Loser	10045
Lucky	51769
Metal	40543
Money	437215
Moral	59090
Mourn	2698
Nasty	15628
Ninja	4177
Ocean	41384
Opera	16608
Organ	9759
Picky	1961
Plain/Plane	54082
Plaza	9950
Porch	17236
Pound	16138
Print	39985
Prize	24808
Proud	51937
Quack	1164
Ready	160214
Rigid	7414
Rinse	3944
Rival	13961
Roast	7550
Rogue	5690
Rumor	7212
South	175813
Spray	13834
Storm	51585
Stove	9219
Straw	10537
Style	72489

(*continued on next page*)

Table A1 (*continued*)

Word	Frequency
Sugar	46747
Sunny	11566
Swear	20349
Swipe	2489
Swirl	2505
Trial	72720
Troop	5963
Trunk	12999
Trust	98401
Twice	61606
Twirl	757
Ulcer	1122
Usual	43794
Valid	18714
Value	125606
Viral	7377
Vogue	3082
Whack	3049
Woman	316918
World	715338
Worse	88024
Wrist	11714
Write/Right	1443820
Yeast	4024
Youth	49814
Yummy	2131
Zebra	1644

[1]M. Davies, Corpus of Contemporary American English, (2019).

the increased cognitive performance during the short length condition (Fig. 2). These results could provide additional insight as to why certain clinical populations walk with a shorter step length as it was less affected by a DT. Unlike the decrease in DT frontal plane balance with wider step widths, altering step lengths, a similarly challenging motor task, did not affect DT balance control. Even though individuals focused on the sagittal plane motor task, the only observed changes were in frontal plane H_R and a slight decrease in cognitive performance in the long length relative to the no targets control condition (Figs. 2 and 3c). These results further support that frontal plane balance requires more active control than the sagittal plane [8].

4.3. Limitations

One potential limitation of this study was the motor task involved individuals looking down at their feet to match the targets projected onto the treadmill. Having the head pointed down could change their posture; however, this change was consistent across the different step conditions and would not change our results comparing the within-subject SS to the altered conditions. Another potential limitation was a learning effect on the cognitive task. However, a post-hoc linear regression was run to test for learning effects in all subjects with no effects found (average R-squared = 0.0249).

5. Conclusion

This study showed that the combination of a cognitive task with wider step widths caused frontal plane balance control to decrease during walking. Given that decreased balance control while walking may increase the risk of falling, our results could have implications for clinical populations (e.g., the elderly or individuals post-stroke) who often walk with wider step widths [25]. When walking at non-SS conditions, these results suggest there is a wider step threshold where attentional resources become insufficient and balance control and cognitive performance decrease. Furthermore, the lack of changes to sagittal plane balance during altered step length DTs further supports that the frontal plane balance requires more active control. These results also provide insight into the automaticity of walking and task-prioritization in healthy individuals at various step widths and lengths [6], which provides a basis for future studies to determine differences in neurologically impaired populations.

Table B1
Variability in step width and length (± 1 standard deviation) for all the different conditions.

Condition	Step Width Variability (m)		Step Length Variability (m)	
	ST	DT	ST	DT
No Targets	0.017 ± 0.005	0.017 ± 0.007	0.031 ± 0.008	0.028 ± 0.012
Narrow	0.013 ± 0.004	0.013 ± 0.003	0.027 ± 0.009	0.028 ± 0.012
SS Width	0.012 ± 0.003	0.013 ± 0.003	0.030 ± 0.010	0.031 ± 0.014
Wide	0.016 ± 0.004	0.014 ± 0.003	0.031 ± 0.011	0.032 ± 0.011
Extra Wide	0.018 ± 0.005	0.016 ± 0.005	0.034 ± 0.011	0.035 ± 0.011
Short	0.017 ± 0.007	0.016 ± 0.004	0.041 ± 0.012	0.045 ± 0.017
SS Length	0.018 ± 0.005	0.016 ± 0.004	0.047 ± 0.017	0.036 ± 0.012
Long	0.023 ± 0.007	0.020 ± 0.005	0.056 ± 0.018	0.061 ± 0.021

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Conflict of Interest

The authors declare that they have no competing interests.

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Appendix A

See Table A1.

Appendix B

See Table B1.

References

[1] G. Ebersbach, M.R. Dimitrijevic, W. Poewe, Influence of concurrent tasks on gait: a dual-task approach, Percept. Mot. Skills 81 (1995) 107–113, https://doi.org/10.2466/pms.1995.81.1.107.

[2] G.H. Small, L.G. Brough, R.R. Neptune, The influence of cognitive load on balance control during steady-state walking, J. Biomech. 122 (2021), https://doi.org/10.1016/j.jbiomech.2021.110466.

[3] J.H. Hollman, F.M. Kovash, J.J. Kubik, R.A. Linbo, Age-related differences in spatiotemporal markers of gait stability during dual task walking, Gait Posture 26 (2007) 113–119, https://doi.org/10.1016/j.gaitpost.2006.08.005.

[4] P.L. Sheridan, J.M. Hausdorff, The role of higher-level cognitive function in gait: executive dysfunction contributes to fall risk in Alzheimer's disease, Dement. Geriatr. Cogn. Disord. 24 (2007) 125–137, https://doi.org/10.1159/000105126.

[5] R.R. Neptune, A. Vistamehr, Dynamic balance during human movement: measurement and control mechanisms, J. Biomech. Eng. 141 (2019), https://doi.org/10.1115/1.4042170.

[6] D.J. Clark, Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies, Front. Hum. Neurosci. 9 (2015) 1–13, https://doi.org/10.3389/fnhum.2015.00246.

[7] J.A. Perry, M. Srinivasan, Walking with wider steps changes foot placement control, increases kinematic variability and does not improve linear stability, R. Soc. Open Sci. 4 (2022), 160627, https://doi.org/10.1098/rsos.160627.

[8] C.E. Bauby, A.D. Kuo, Active control of lateral balance in human walking, J. Biomech. 33 (2000) 1433–1440, https://doi.org/10.1016/s0021-9290(00)00101-9.

[9] F. Fallahtafti, J.B. Boron, D.M. Venema, H.J. Kim, J.M. Yentes, Task specificity impacts dual-task interference in older adults, Aging Clin. Exp. Res. (2020), https://doi.org/10.1007/s40520-020-01575-3.

[10] E. Nordin, R. Moe-Nilssen, A. Ramnemark, L. Lundin-Olsson, Changes in step-width during dual-task walking predicts falls, Gait Posture 32 (2010) 92–97, https://doi.org/10.1016/j.gaitpost.2010.03.012.

[11] K. Kaewkaen, T. Chueathaeo, S. Angart, S. Chomkan, S. Uttama, W. Chaiut, P. Namkorn, C. Sutalangka, P. Kaewkaen, The interactive effect of cognitive and physical dual task interventions on obstacle negotiation while walking in healthy young, and older, adults, Neurol. India 69 (2021) 883–888, https://doi.org/10.4103/0028-3886.325349.

[12] C. Hennah, G. Ellis, M. Doumas, Dual task walking in healthy aging: effects of narrow and wide walking paths, PloS One 16 (2021), e0261647, https://doi.org/10.1371/journal.pone.0261647.

[13] A. Uematsu, K. Tsuchiya, S. Suzuki, T. Hortobágyi, Cognitive dual-tasking augments age-differences in dynamic balance quantified by beam walking distance: a pilot study, Exp. Gerontol. 114 (2018) 27–31, https://doi.org/10.1016/j.exger.2018.10.016.

[14] A. Deblock-Bellamy, A. Lamontagne, B.J. McFadyen, M.-C. Ouellet, A. K. Blanchette, Virtual reality-based assessment of cognitive-locomotor interference in healthy young adults, J. Neuroeng. Rehabil. 18 (2021) 53, https://doi.org/10.1186/s12984-021-00834-2.

[15] G.H. Small, R.R. Neptune, Task-prioritization and balance recovery strategies used by young healthy adults during dual-task walking, Gait Posture 95 (2022) 115–120, https://doi.org/10.1016/j.gaitpost.2022.04.010.

[16] L. Rochester, V. Hetherington, D. Jones, A. Nieuwboer, A.-M. Willems, G. Kwakkel, E. Van Wegen, Attending to the task: interference effects of functional tasks on walking in Parkinson's disease and the roles of cognition, depression, fatigue, and balance, Arch. Phys. Med. Rehabil. 85 (2004) 1578–1585, https://doi.org/10.1016/j.apmr.2004.01.025.

[17] S.W. Hunter, A. Divine, C. Frengopoulos, M. Montero Odasso, A framework for secondary cognitive and motor tasks in dual-task gait testing in people with mild cognitive impairment, BMC Geriatr. 18 (2018) 202, https://doi.org/10.1186/s12877-018-0894-0.

[18] O. Bock, Dual-task costs while walking increase in old age for some, but not for other tasks: an experimental study of healthy young and elderly persons, J. Neuroeng. Rehabil. 5 (2008) 27, https://doi.org/10.1186/1743-0003-5-27.

[19] J.A.J. Zeni, J.G. Richards, J.S. Higginson, Two simple methods for determining gait events during treadmill and overground walking using kinematic data, Gait Posture 27 (2008) 710–714, https://doi.org/10.1016/j.gaitpost.2007.07.007.

[20] H. Herr, M. Popovic, Angular momentum in human walking, J. Exp. Biol. 211 (2008) 467–481, https://doi.org/10.1242/jeb.008573.

[21] H.-J.S. Shih, J. Gordon, K. Kulig, Trunk control during gait: walking with wide and narrow step widths present distinct challenges, J. Biomech. 114 (2021), 110135, https://doi.org/10.1016/j.jbiomech.2020.110135.

[22] G. Yogev-Seligmann, Y. Rotem-Galili, A. Mirelman, R. Dickstein, N. Giladi, J. M. Hausdorff, How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability, Phys. Ther. 90 (2010) 177–186, https://doi.org/10.2522/ptj.20090043.

[23] C.T. Bonnet, S. Baudry, A functional synergistic model to explain postural control during precise visual tasks, Gait Posture 50 (2016) 120–125, https://doi.org/10.1016/j.gaitpost.2016.08.030.

[24] P.M. McAndrew Young, J.B. Dingwell, Voluntary changes in step width and step length during human walking affect dynamic margins of stability, Gait Posture 36 (2012) 219–224, https://doi.org/10.1016/j.gaitpost.2012.02.020.

[25] S.M. Bruijn, J.H. van Dieën, Control of human gait stability through foot placement, J. R. Soc. Interface 15 (2018) 20170816, https://doi.org/10.1098/rsif.2017.0816.