



Are there attentional demands associated with haptic modalities while walking in young, healthy adults?

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ABSTRACT

Study design: A prospective, observational study.

Objectives: To assess the attentional demands of using haptic modalities during walking using a multi-task paradigm in young, healthy adults.

Setting: Biomechanics of Balance and Movement (BBAM) Lab, University of Saskatchewan.

Methods: Twenty-two (12 male) young, healthy adults performed walking trials with and without a verbal reaction time (VRT) task, as well as with and without the use of haptic anchors and light touch on a railing. Walking performance was evaluated using normalized stride velocity and step width, and dynamic stability was evaluated using step width variability and medial-lateral margin of stability (ML MOS) and its variability.

Results: There were no significant differences in VRT when walking with and without added haptic input and no interactions between the added VRT task and added haptic input. Step width increased and variability of the ML MOS increased during trials with the VRT task compared to trials without the VRT task. The ML MOS decreased when using both haptic tools with a greater decrease when using light touch on the railing compared to when using the haptic anchors. Normalized stride velocity and step width decreased when using light touch on the railing only. *Conclusion:* Both haptic tools affected stability during walking. Using the railing to add haptic input had a greater effect on walking stability and was the only haptic tool to affect walking performance. Attentional demands should be considered in future research and applications of adding haptic input during walking.

1. Introduction

Walking is an important component of daily life that requires dynamic stability and sensorimotor integration for safe ambulation and independence (Simonsick, Guralnik, Volpato, Balfour, & Fried, 2005). Recently, there has been a rise in research investigating the use of haptic tools as a way of providing additional sensory input to improve stability while walking (Oates, Hauck, Moraes, & Sibley, 2017; Oates, Unger, Arnold, Fung, & Lanovaz, 2017; Kodesh, Falash, Sprecher, & Dickstein, 2015). The addition of haptic information from hand contact with an external surface provides the individual with information about their position relative to that surface, thereby enhancing awareness of where their body is in space (Oates, Unger et al., 2017; Rabin, Chen, Muratori, DiFrancisco-

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Donoghue, & Werner, 2013; Moraes et al., 2018). The addition of haptic input during walking is commonly provided through light touch (LT) on a rigid railing (Kodesh et al., 2015; Arora, Musselman, Lanovaz, & Oates, 2017; Bingenheimer et al., 2015; Jmker et al., 2015) or by dragging haptic anchors in each hand, which are light weights (~125 g) attached to a string (Costa, Mancio, Mauerberg-deCastro, & Moraes, 2015; Mauerberg-deCastro et al., 2014; Costa, Santos, Mauerberg-deCastro, & Moraes, 2018). The addition of sensory input in the form of LT with less than one newton (N) of force, or by dragging haptic anchors on the ground, has been observed to reduce sway parameters and step variability while walking among young, healthy participants (Oates, Unger et al., 2017; Hedayat, Moraes, Lanovaz, & Oates, 2017), suggesting the use of haptic modalities improves dynamic stability and balance control, without providing mechanical support. Walking aids can also improve mobility; however, the attentional demands of walking aids may interfere with balance control (Batani & Maki, 2005; Batistela, Oates, & Moraes, 2018). The attentional demands of haptic tools such as LT and anchors are currently unknown and need to be investigated to determine whether they are safe for individuals with reduced attentional capacity to use.

The framework for attention developed within cognitive psychology allows for investigation of how the allocation of attention may affect motor tasks, such as standing and walking (Lajoie, Teasdale, Bard, & Fleury, 1996). Dual- and multi-task paradigms can be used to investigate the attentional demands of the required tasks as well as understand which tasks are prioritized. In dual- and multi-task paradigms, tasks are added in sequence to observe how they interfere with each other (Al-Yahya et al., 2011). Interference occurs when a task that is added adversely affects the performance of the primary and/or the additional task(s) (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2012). Previous research found that even for healthy young adults, the addition of a secondary task can negatively affect walking performance, which may cause concern for safe ambulation (Al-Yahya et al., 2011). Understanding how attention is allocated to one or more tasks while trying to maintain balance control may provide insight into fall and accident prevention by addressing how individuals attend to and prioritize multiple tasks while walking.

A common test used during dual- and multi-task paradigms is the verbal reaction time (VRT) task (Abernethy, 1988). During a VRT task, participants are asked to respond verbally to an external cue and their reaction time is recorded. Difficulty of the VRT task can vary from simply saying when you hear a tone, to distinguishing whether the tone you hear is high or low-pitch. Usually, the VRT task is first administered while sitting or walking to determine the individual's baseline VRT, then other tasks are added to determine their effect on the VRT (Lajoie et al., 1996; Abernethy, 1988). VRT increases proportionally to the amount of attentional demand required by each subsequent task added (Abernethy, 1988). This suggests that, as the number of tasks (i.e., stimuli) increase, performance in either the VRT task or the primary task (e.g. sitting/walking) will decrease because less attention will be available to allocate between tasks causing greater interference among tasks.

Before we can responsibly recommend the use of added haptic input through LT on a railing or the use of haptic anchors as locomotor and balance enhancing tools, the attentional demands of each should be assessed. Previous literature has suggested that since the addition of haptic input through LT requires the individual to place their finger in a precise location on a surface, while simultaneously monitoring their application of force, it likely requires additional attentional resources (Vuillerme, Isableu, & Nougier, 2006). Using similar logic, it has also been suggested that since dragging haptic anchors does not require much accuracy they may pose minimal attentional demands (Mauerberg-deCastro et al., 2014). Previous work in standing balance control has shown reduced postural sway with both the addition of haptic input and a visual search task (Batistela et al., 2018; Chen, Chen, Tu, & Tsai, 2015; Chen & Tsai, 2015; Chen, Chu, Pan, & Tsai, 2018); however, the attentional demands of these tasks and their effect on walking balance control is not yet understood.

The primary objective of this study was to assess the attentional demands of walking with LT on a railing and walking with haptic anchors using a VRT-based multi-task paradigm in young, healthy adults. It was hypothesized that both haptic tools would require more attention than baseline walking (without either tool) as exhibited by a negative impact on either the primary task (walking) or the secondary task (VRT task performance) during conditions using the anchors and LT on the railing. Furthermore, based on previous literature, it was hypothesized that use of LT on a railing would require more attention than the use of the haptic anchors and that walking performance would be negatively affected by the addition of haptic input (Hedayat et al., 2017). The findings of this study will fill a critical knowledge gap regarding the attentional demands of haptic modalities during walking, and thus provide insight into their effect on dynamic stability.

2. Material and methods

2.1. Participants

Twenty-two young, healthy adults (12 males) with an average age of 24.5 ± 2.9 years, mass of 75.6 ± 17.5 kg, and height 1.71 ± 0.18 m participated in this study. Participants were eligible for the study if they were 18–30 years old and able to walk independently for at least 10 m. Participants were excluded if they had any pre-existing orthopaedic, psychological, or other neurological conditions affecting their ability to perform the tasks. Recruitment occurred through word of mouth, undergraduate classroom announcements, and postings on a campus-wide online board. All participants provided informed consent for the protocols that were approved by the institutional research ethics board.

2.2. Data collection

Participant height (m) and mass (kg) were measured with their shoes on and wore the same shoes during all walking trials. Hand and leg dominance was self-reported by each participant (Coren & Porac, 1978). Participants walked along a 10 m walkway while



Fig. 1. Examples of an individual using the haptic modalities: 1) Light touch (LT) on a rigid railing (Left) and 2) Haptic anchors, where the weighted bags are indicated by boxes (Right). Please note that this individual was not a participant of the study, they are simply demonstrating how each tool is used.

kinematic data were captured using a 3D motion capture system (VICON Nexus, Centennial, CO) with eight infrared cameras sampled at 100 Hz. Thirty-four reflective markers were placed on anatomical landmarks to create a 12-segment center of mass (COM) model. A verbal reaction time task (VRT) requiring participants to distinguish between a high (1000 Hz) or low (200 Hz) pitch 200 ms tone and respond verbally saying either “high” or “low” was used to assess the attentional demands of each condition. A force platform (OR6-7, AMTI, Watertown, MA; sampling rate of 2000 Hz) embedded in the walkway 2–3 m from the starting point was used to trigger the VRT task when it detected 10% of the participant’s body mass. The VRT task was presented only once per trial. The starting location for the walking trials was manipulated for each participant so they would naturally step on the force plate with their dominant limb. The VRT task was administered through a speaker located at the side of the walkway and tones and responses were captured using a wireless voice recorder (Philips Voice Tracer 2000) sampled at 44,100 Hz.

2.3. Haptic modalities

A custom-built 85 cm tall railing instrumented with load sensors (Futek Advance Sensory Technology, Inc., CA, USA; Range: 0–5 N) (Oates, Unger et al., 2017) was placed along the walkway in a location where participants could lightly run the index finger of their dominant hand along the railing while walking (Fig. 1). The amount of force applied was monitored to ensure participants were using light touch of less than 1 N of vertical force (Hedayat et al., 2017). The haptic anchors consisted of two 125 g weights that were attached to a string (Fig. 1) (Hedayat et al., 2017; Mauerberg-deCastro et al., 2014). The tension created in the strings provided additional sensory information allowing the individual to estimate the body orientation relative to the walking surface (Mauerberg-deCastro et al., 2014).

2.4. Experimental protocol

The VRT tasks were used to assess attentional demands of each walking condition. A significant decrease in performance of either the VRT or walking when performed either in a dual-task (VRT + walking OR haptic input + walking) or multi-task (VRT + walking + added haptic input) condition would indicate that the attentional capacity of the participant had been exceeded and interference had taken place (Woollacott & Shumway-Cook, 2002). In addition, the magnitude of impact on one or more outcome variables could indicate priority setting of the participant and give insight into which of the tasks was more important to complete properly. For example, an increase in VRT but no change in stride velocity could suggest the participant chose to “sacrifice” performance of the VRT to maintain stride velocity (Beauchet et al., 2008). Prior to any walking trials, eight baseline sitting VRT trials were collected while participants were seated. Participants then performed a series of familiarization walking trials (10 – 15 trials)

with and without the VRT task and; with and without the haptic modalities (LT and anchors). The main goal of these familiarization trials was to provide the participants with an opportunity to practice using the haptic modalities and familiarize them with the VRT task to minimize learning effects. Additionally, the familiarization walking trials were used to help the researchers determine where each participant should start their stride to best ensure consistent foot placement on the force plates, which was critical to trigger the VRT task.

Following the baseline VRT sitting and familiarization walking trials, participants began a randomized walking protocol whereby they walked under three conditions: 1) normal walking (no haptic modality), 2) walking with LT on the railing, and 3) walking while dragging the anchors. Trials were separated into two blocks based on condition (LT and anchors), with normal walking trials dispersed evenly throughout each block. The block order was counterbalanced between participants to minimize order effects. Participants completed 16 trials per condition, half with the VRT task and half without, and trial order was randomized within each block so that participants were unaware of whether the VRT task would be included in a given trial. Participants were instructed to walk at a comfortable pace and to try to keep equal focus on all tasks; walking, using the tools, and responding to the VRT task.

2.5. Data processing and analysis

Audio data files were processed using Audacity 2.1.2 (Audacity Team, Pittsburg, Pennsylvania) and Praat v6.0.19 (Boersma and Weenink, Amsterdam, Netherlands). VRTs were defined from the manually identified onset of the tone to the onset of a verbal response. Spectrograms were used to ensure onsets were correctly identified (Gould, Cummine, & Borowsky, 2012).

Kinematic data including total body COM location and positions of the heels and lateral aspects of the 5th metatarsals were calculated for the stride occurring immediately after the VRT task using custom MATLAB routines (R2006b, Mathworks, Natick, MA). For the trials with no VRT task, kinematic data were calculated for the stride occurring immediately after contact with the same force plate used to trigger the VRT task.

Dynamic stability was evaluated using step width variability, medial–lateral margin of stability (ML MOS), and the ML MOS variability. Step width variability was calculated using standard deviation between trials. Variability of gait parameters is a well-established indication of the dynamic control of balance during gait, where a narrow step and high step width variability are associated with impaired stability (Day, Kautz, Wu, Suter, & Behrman, 2012; Hausdorff, 2005). The ML MOS was calculated as the mean of the distances between the extrapolated COM position (xCOM) and the closest lateral edge of the BOS averaged over the entire stride (Hof, Gazendam, & Sinke, 2005). ML MOS is directly related to the impulse required to cause instability, thus a decrease in ML MOS is indicative of impaired stability (Hof et al., 2005). The standard deviation of ML MOS was calculated as another variability measure, where high amounts of ML MOS variability are associated with impaired stability (Kodesh et al., 2015; Hausdorff, 2005).

Stride velocity and step width were calculated to evaluate walking performance and understand changes observed in ML MOS. Stride velocity was calculated by dividing stride length over stride time and normalized to a Froude number using leg length (Hof, 1996). A decreased stride velocity would represent a negative effect on walking performance (Hedayat et al., 2017). Step width was calculated as the medial–lateral distance between the left and right heels and the lateral boundaries of an individual's base of support (BOS) were obtained using the 5th metatarsal locations (Oates, Unger et al., 2017). Step width was included to provide insight into potential changes observed in the ML MOS as a wider step would provide a greater ML MOS with the same COM position and velocity characteristics.

2.6. Statistical analysis

Outlier data points were defined as any value ± 2 SDs away from the calculated mean and were removed before conducting the remaining statistical analysis. Paired samples *t*-tests were used to examine differences between VRTs for the low and high tones, and between baseline sitting and baseline (no haptic input) walking VRT trials. To assess the attentional demands of haptic modalities during walking, a one-way RM ANOVA was conducted to compare VRT values between baseline walking (no modalities), walking with the haptic anchors, and walking with LT on the railing.

Separate 2×3 RM ANOVA tests were conducted to determine if there were any changes in walking (defined here as the primary task) due to adding both the VRT task (defined here as the secondary task) and use of the haptic modalities (defined here as the tertiary task). The 2 (VRT task present/absent) $\times 3$ (no modality/railing/anchors) RM ANOVA tests were conducted on the stability measures (step width variability, mean ML MOS, ML MOS variability) and walking performance measures (normalized stride velocity and mean step width). Mauchly's test was performed to check for sphericity and when necessary Greenhouse-Geisser corrections were used for the RM ANOVA results. Significant main effects were further investigated with post-hoc analyses of pairwise comparisons with Bonferroni corrections. Statistical Package for Social Sciences (SPSS) version 24.0 (SPSS INC., Chicago, IL) was used with significance set at $\alpha = 0.05$ for all statistical analyses.

3. Results

3.1. Verbal reaction time measures

There was no significant difference between the high and low VRT tasks and so the data from both tones were pooled for the remaining analyses. There was a significant increase in VRT while walking compared to sitting, $t(21) = -2.081, p = .050$ (Fig. 2).

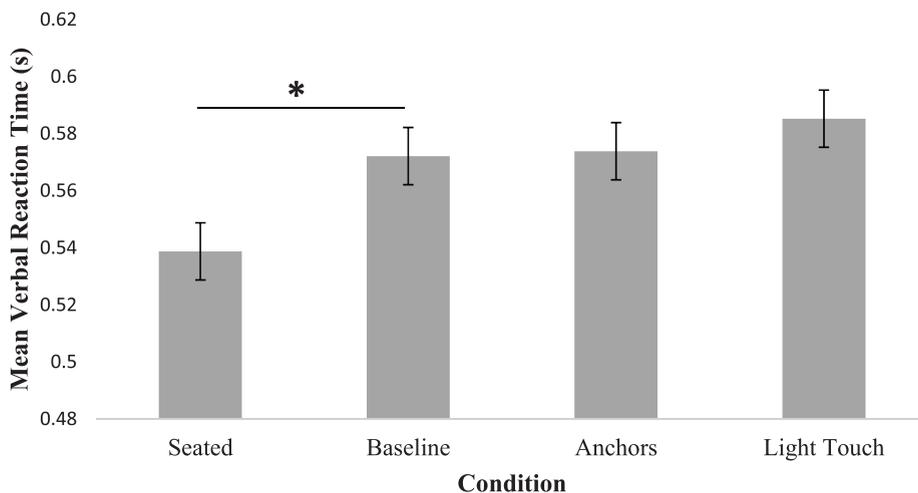


Fig. 2. Comparison of mean (\pm SE) verbal reaction times between different conditions; while seated, during baseline walking (no tools), while walking with haptic anchors, and while walking with light touch on a railing. * indicates a significant difference in VRT from the seated condition at the $\alpha = 0.05$ level.

The one-way RM ANOVA found no significant differences in VRT between baseline walking (with no modalities), walking with anchors, and walking with LT on the railing, $p = 0.506$ (Fig. 2).

3.2. Measures of gait & dynamic stability

Statistical results from the RM ANOVA tests are outlined in Table 1 and a summary of the pairwise comparisons between modalities, as well as the means (\pm SD) of each dynamic stability measure are reported in Table 2. There were no significant interactions between the VRT task (present or absent) and walking condition (baseline, LT, and anchors) for the dynamic stability and walking performance measures. However, there was a significant main effect of the VRT task on mean step width ($F(1, 21) = 6.602$, $p = .018$) and ML MOS variability ($F(1, 21) = 8.305$, $p = .009$). Pairwise comparisons showed that mean step width for trials with the VRT task (82.6 ± 6.2 mm) was significantly larger than trials with no VRT task (79.8 ± 6.2 mm). Additionally, ML MOS variability was significantly greater when the VRT task was present (14.85 ± 0.68 mm) compared to trials with no VRT task (14.23 ± 0.74 mm).

The RM ANOVA tests showed a significant main effect of walking condition on normalized stride velocity ($F(1.61, 24.374) = 12.976$, $p = .001$), mean step width ($F(1.951, 40.972) = 18.896$, $p < .001$), and mean ML MOS ($F(1.514, 32.996) = 16.154$, $p < .001$). Pairwise comparisons showed that normalized stride velocity was significantly lower for conditions using LT on the railing, compared to baseline walking conditions ($p < .001$) and walking while using the anchors ($p = .011$). There was no significant difference in normalized stride velocity values between baseline walking conditions and conditions using haptic anchors ($p > .05$). Mean step width was significantly smaller when walking using LT on the railing compared to baseline walking ($p < .001$) and walking while using the anchors ($p < .001$). There was no significant difference in mean step width between baseline walking and walking with the anchors ($p > .05$). The mean ML MOS was significantly larger during baseline walking conditions compared to walking with the anchors ($p = .030$), and walking using LT on the railing ($p < .001$). The mean ML MOS was also significantly larger during conditions using the anchors, compared to conditions using LT on the railing ($p = .006$).

4. Discussion

The primary objective of this study was to assess the attentional demands of walking with LT on a railing or walking with haptic anchors, using a multi-task paradigm in young, healthy adults. Results showed that both using the haptic modalities and completing the VRT task affected walking; however, the absence of interactions suggests that both tasks impacted walking in different ways. Our

Table 1

Results of 2×3 Repeated Measures ANOVA Tests. *Indicates significant F -value at the $\alpha = 0.05$ level.

Stability Measure	Main Effect of Verbal Reaction Time Task	Main Effect of Walking Condition (Baseline/LT/Anchors)	Interaction Effect
Normalized stride velocity	$p = .857$	$p = .001^*$	$p = .849$
Mean step width	$p = .018^*$	$p = .000^*$	$p = .551$
Step width variability	$p = .189$	$p = .061$	$p = .239$
Mean ML MOS	$p = .057$	$p = .000^*$	$p = .710$
ML MOS variability	$p = .009^*$	$p = .126$	$p = .923$

Table 2

Summary of Pairwise Comparisons between Modalities. Values are the estimated marginal means (\pm SE) where * indicates a significant difference from baseline walking (with no tools) at the $\alpha = 0.05$ level and + indicates a significant difference from walking with light touch (LT) on a railing at the $\alpha = 0.05$ level.

Stability Measure	Baseline	LT on Railing	Anchors
Normalized stride velocity	0.42 (0.03)	0.40 (0.03)*	0.42 (0.03)+
Mean step width (mm)	85.9 (6.6)	75.3 (5.9)*	82.4 (6.2)+
Step width variability	10.6 (1.2)	14.1 (1.3)	13.5 (1.5)
Mean ML MOS (mm)	110.8 (2.5)	105.8 (2.4)*	108.9 (2.4)*+
ML MOS variability	14.8 (0.68)	14.0 (0.81)	14.8 (0.73)

primary hypothesis that walking with anchors or with LT on a railing, would require more attention than walking without either haptic tool was partially supported. There were no changes in the VRT with the added haptic input but both walking performance and dynamic stability were affected in some way by the addition of haptic input. Our secondary hypothesis that use of LT on a railing would require more attention than the use of haptic anchors was supported as LT on a railing had a larger negative impact on the ML MOS than the haptic anchors and only the LT on the railing condition resulted in a significant decrease in stride velocity and step width. These results suggest that attentional demands should be considered regarding haptic modalities, especially when considering use of LT on a railing. The main findings of this study are discussed further below.

4.1. Significant main effect of VRT task

Interestingly, although there were no significant differences in VRT between the walking conditions, there was a significant main effect of the VRT task on individual's walking (step width) and stability (ML MOS variability). The performance of a discrete cognitive and motor task (VRT) may have interfered in the organization and control of the continuous motor task of walking leading to the changes observed in step width and ML MOS variability, despite participants being instructed to have an equal focus on all tasks. According to the functional integration hypothesis, postural control sub-serves the goal of additional supra-postural tasks (Chen et al., 2015; Riccio & Stoffregen, 1998). The results of the current study support this hypothesis as they suggest that the increase in step width could be interpreted as a positive change to improve the size of the base of support to maintain postural control and facilitate and prioritize the performance of the VRT task. Prior studies investigating the addition of haptic input during standing and performance of a cognitive task have also shown that modulating postural sway may facilitate the execution of the additional cognitive task (Batistela et al., 2018; Chen et al., 2015; Chen et al., 2018; Prado, Stoffregen, & Duarte, 2007). It is important to note that the change in ML MOS variability is quite small (0.62 mm difference between with and without the VRT) and; therefore, the impact on walking performance may have been minimal.

4.2. Significant main effect of walking condition

The second main effect found in this study was that of walking condition (LT on railing/anchors/baseline) on walking performance. Independent of whether the VRT task was present or absent, dynamic stability (as measured by ML MOS) significantly decreased while using the haptic modalities compared to baseline walking. In general, we found a greater effect when using the LT on a railing compared to using the anchors similar to previous research (Hedayat et al., 2017). The negative impact on the dynamic stability measure of ML MOS contrast somewhat with previous research (Costa et al., 2015; Hedayat et al., 2017) where the use of haptic modalities reduced trunk sway velocity interpreted as a positive effect for balance control. The differences between studies may be due to the outcome variables used: Previous work (Costa et al., 2015; Hedayat et al., 2017) used trunk-based parameters as a measure of dynamic stability whereas this study used the ML MOS. Because of the significant contribution of the trunk to the whole body COM, it is important to control the trunk movement to maintain balance control. The relationship of the COM with respect to the boundaries of the base of support, which is what the ML MOS evaluates, is another factor. While both outcome variables present important information about balance control during walking, the difference between the two perspectives is one possible explanation for the difference between results.

We propose that the accuracy demands required to successfully add LT on a railing with a small surface drew enough attentional resources to interfere with walking performance resulting in a slower walking velocity (Hedayat et al., 2017), decreased step width, and decreased ML MOS. In contrast to LT on a railing, use of haptic anchors may require minimal attentional demands since they do not restrict natural arm swing as much as LT on a railing, do not change the natural orientation of the arms, nor require a large amount of accuracy to drag them behind you (Mauerberg-deCastro et al., 2014). This is likely why we only found a significant difference in one of the dynamic stability measures (mean ML MOS) using haptic anchors when compared to baseline walking. Since step width and the ML MOS are often highly correlated, the presence of a decreased ML MOS and the absence of an effect on step width when using the haptic anchors may suggest a change in the postural control strategy when using anchors, which is different from the strategy needed for use of LT on a railing. Another interpretation of a reduced ML MOS and narrowed step could be a result of the participant's perception of improved stability with added haptic input, resulting in the individual decreasing their base of support to reduce metabolic costs, subsequently resulting in a decreased ML MOS (Matsubara, Wu, & Gordon, 2015).

4.3. Limitations

Despite the findings discussed above, there are limitations that should be acknowledged. The walking conditions may not have been sufficiently challenging to cause a multi-task effect large enough to detect a change in VRT in young, healthy adults. A more challenging walking task may have increased the attentional demands and/or interference for the young, healthy adults and subsequently provided a better representation of the impact of multi-tasking during walking for populations of individuals with balance impairments and/or with reduced attentional capacity. Although individuals were told to place equal amounts of attention on walking and the VRT task, we were not able to directly measure where attention was actually directed during each trial.

Another limitation of this study is that the use of LT on the railing and haptic anchors limit natural arm swing while walking by restricting the normal motion of the arms back-and-forth. Use of haptic anchors requires that the arms stay in place, but the orientation of the arms does not change. For that reason, the reduction in arm swing could be considered minimal when compared to the use of LT on a railing, which completely changes the orientation of the arm while walking. If arm swing was restricted too much by keeping a finger on the railing, it could result in decreased dynamic stability (Meyns, Bruijn, & Duysens, 2013), which would make it difficult to distinguish whether the negative effect on walking performance was due to reduced arm swing or interference effects attributed to the added attentional requirements of the haptic tool. However, the effects of arm placement while using anchors and LT on a railing have been investigated recently (Hedayat et al., 2017): The researchers suggested that the changes seen in balance control resulting from the use of LT on a railing are likely due to arm placement, since similar results were seen while actually using the railing and during placebo trials where participants walked with similar arm placement but received no haptic input (Hedayat et al., 2017). These findings imply that the limitation in arm swing may be a key factor while using LT on a railing to improve stability. Thus, further investigations into the impact of arm position and its effect on stability are required to provide insight into the results of our study. The restriction in arm swing seen in this study would be similar to real-world conditions while using a railing in a public space.

Finally, it is important to note that some of our outcome variables are correlated to each other such as step width and ML MOS as previously noted, which might reduce the power of our statistical analysis and limit confidence in our results. Despite this, these measures provide a holistic understanding of the individual's walking performance. For instance, step width and COM movement are two separate measures used to derive the MOS measure. Step width on its own would only provide us with a small piece of the puzzle regarding the individual's base of support while MOS provides additional information about how their COM moves within their base of support during a dynamic condition like walking. Therefore, although some of our measures are correlated, it was beneficial to include each one for the biomechanical analysis of gait and stability.

5. Conclusions

In conclusion, the results of this study suggest that it is important to consider the attentional demands of adding haptic input during walking, particularly when haptic input is added by light touch on a railing. Adding haptic input decreased the margin of stability when using either haptic tool. Light touch on a railing during walking decreased the margin of stability more than using the haptic anchors and only light touch on a railing reduced stride velocity and step width. We suggest that the potential positive impact of added haptic input on standing (Rabin et al., 2013; Arora et al., 2017; Bingenheimer et al., 2015) and walking balance control (Oates, Hauck et al., 2017; Oates, Unger et al., 2017; Kodesh et al., 2015; Hedayat et al., 2017) should be balanced with the attentional requirements of the walking aid to ensure safe ambulation and prevent falls. Poor performance of two or more tasks have been linked to recurrent falls, lower attentional capacity, and an inability to allocate attention appropriately in certain vulnerable populations (Beauchet et al., 2008). Thus, the attentional capacity of an individual should be taken into consideration when determining what type of walking aid would best improve their stability without limiting their attentional resources and posing a threat to their safety. Future research could examine whether practice walking with certain haptic tools could reduce the attentional demands required to use them while maintaining any benefits they have on stability.

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Declaration of Competing Interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.05.009>.

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