Journal of Electromyography and Kinesiology 39 (2018) 142–148

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Impacts of using a head-worn display on gait performance during level walking and obstacle crossing

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ARTICLE INFO

Keywords:
Head-worn display
HWD
User interface
Gait kinematics

ABSTRACT

Use of a head-worn display (HWD) may affect gait performance and increase slip and trip risks, though there is a lack of information on such effects. This study investigated how different display technologies (monocular and binocular HWDs, and a paper list) and visual information presentation modes affect gait performance. Twelve gender-balanced participants completed walking and obstacle crossing trials on a linear walking track under all experimental conditions and a baseline control (without using a technology). During these trials, information relevant to a simulated light assembly task was provided, as representative of a potential occupational application. Gait performance was assessed based on minimum foot clearance (MFC), required coefficient of friction, foot placement locations around the obstacle, and/or walking/obstacle crossing speed. Use of a HWD had no substantial effects on level walking performance. A more conservative/cautious obstacle crossing strategy was, however, observed with HWD use, including a decrease (~3%) in obstacle crossing speed (compared to the baseline). Gender-specific foot control strategies (lead foot MFC) were also observed that depended on the specific display technology and information modes. Foot placements around the obstacle were not influenced by use of the binocular HWD, yet a conservative strategy was observed with the monocular HWD.

1. Introduction

Wearable technology, such as “smart glasses” or more generally augmented reality head-worn displays (HWDs), has been drawing increasing attention, including for potential occupational use in sectors such as logistics (Reif and Günthner, 2009; Weaver et al., 2010) and maintenance/assembly (Caudell and Mizell, 1992). When using a HWD, the wearer can employ both hands freely while accessing information projected within their field of view, which is thus potentially beneficial in performing a work task. However, having a display in front of one (monocular) or both eyes (binocular) raises practical concerns, such as distraction and reduced situational awareness (Kim et al., 2016). HWDs can cause reduced visual performance (Longley and Whitaker, 2015), inaccurate depth perception (Drascic and Milgram, 1996), and less sensitive detection of unexpected events (Krupenia and Sanderson, 2006; Liu et al., 2009). Further, Mustonen et al. (2013) found that performing a cognitive task (working memory) administered via a monocular HWD negatively affects paced gait performance, as indicated by an increase in path overruns. Reading via a monocular HWD (vs. a handheld device) also required more time and was considered to be more demanding (Vadas et al., 2006).

In addition, there is broader evidence that an increase in attentional demands and/or cognitive distraction can negatively affect gait performance (e.g., Dubost et al., 2008; Bock and Beurskens, 2011; Soangra and Lockhart, 2017). Such effects could, in turn, increase the risks of slips, trips, and falls (STFs) especially in challenging environments (e.g., floor obstacles present). STFs are a major cause of occupational injuries and fatalities in many countries. In the U.S., for example, STFs accounted for ~ 28% of lost workday cases (BLS, 2016b) and ~17% of fatal occupational injuries (BLS, 2016a) in 2015. In the UK, ~25% of cases with more than seven lost workdays in 2016 were due to STFs (UNISON National, 2017). Previous work (e.g., Bentley, 2009; Chang et al., 2016; Leclercq et al., 2017) has identified multiple factors contributing to STFs, including working environments, organizational factors, job characteristics, and individual characteristics. Given the expanding interest in occupational use of HWDs, we believe there is a need to understand the potential impacts of HWD use on gait performance related to slip- and trip-related fall risks.

This exploratory study aimed to assess the influence of HWD use on gait performance during level walking and obstacle crossing. Specifically, and not limited to occupational implementations, using a HWD will likely involve evidence-based decision making regarding the type of HWD and methods for information presented on the display. We considered two different HWD types (binocular vs. monocular) and

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https://doi.org/10.1016/j.jelekin.2018.02.007
Received 11 December 2017; Received in revised form 7 February 2018; Accepted 19 February 2018

information-presentation modes (text- vs. graphic-based). The latter was included given that information-presentation mode can influence perceptual and information processes (Speier, 2006). Gait performance was assessed when participants concurrently processed information relevant to a simple assembly task during level waking or obstacle crossing. We hypothesized that HWD use would worsen gait performance and that this influence would be more pronounced during the more challenging obstacle crossing activity vs. level walking. We also hypothesized that the magnitude of adverse effects would depend on the specific HWD type, information-presentation mode used, and potential gender-related differences. The latter was considered since gender differences have been observed in gait and upper body kinematics during level walking (Chumanov et al., 2008; Mazzà et al., 2009), including greater hip abduction among females and greater head accelerations among males. Further, females and males exhibited different body turning preferences when navigating in a virtual environment while wearing a HWD (Bowman et al., 2002).

2. Methods

2.1. Participants

A convenience sample of 12 gender-balanced participants were recruited from the university and local community. Their mean (SD) age, stature, and body mass were 25.3 (6.0) yrs, 177.2 (6.2) cm, and 74.2 (8.3) kg, respectively for the males; and 30.2 (14.3) yrs, 164.2 (4.8) cm, and 55.8 (5.4) kg, respectively, for the females. All participants reported having normal or corrected-to-normal vision (with contact lenses only), and having no recent (past 12 months) or current musculoskeletal disorders or injuries. Prior to any data collection, participants gave written informed consent following procedures approved by the Virginia Tech Institutional Review Board.

2.2. Experimental design and procedures

We used a repeated-measures design to assess the effects of different technology types and information-presentation modes on gait performance during level walking and obstacle crossing. The three levels of *Technology Type* (*Tech Type*) were: a paper list, binocular HWD, and monocular HWD (Fig. 1). Two levels of *Information-presentation Mode* (*Info Mode*) were text- vs. graphic-based information that was required to complete a simulated assembly task using a Purdue Pegboard (Fig. 2). This assembly task involved pins, washers, and collars of a given quantity and in a given sequence.

Level walking and obstacle crossing trials were performed on a linear walking track (1.5 m wide × 15.5 m long). For both level walking and obstacle crossing trials, participants were asked to first stand at a starting position, walk across the track at a "purposeful" walking speed (Beringer et al., 2014), and cross any obstacle when it was presented as they would in the real-life situations. Participants completed the assembly task upon reaching the end of the track. Over the middle region of the walking track, information required to complete the assembly task was provided according to a given experimental condition. For obstacle crossing trials, a rectangular-shaped foam object was used (1.5 m wide × 5 cm long × 6 cm high), and was placed between two force platforms (AMTI, OR-6, Watertown, MA) embedded in the middle of the walking track.

Upon arrival to the laboratory, participants were provided identical model of shoes, in their own size, and were asked to do repeated trials of level walking and obstacle crossing on the gait track at their purposeful walking speed. These initial trials were done without using any of the noted technology types, serving as a baseline condition, and then for a total of at least 30 min under all experimental conditions for familiarization. During this initial familiarization, the starting foot position was adjusted for the baseline and each of the experimental conditions, to ensure that participants stepped on each of the two force platforms, without visible adjustments to their gait patterns. We marked the final starting foot positions on the walking track, and also marked the locations that were two steps ahead/after the first/second force platform. Only between these locations was visual information (required to complete the simulated assembly task) presented on a HWD, and which was controlled using a tablet computer that was wirelessly mirrored to the HWD. For the paper list condition, a "beep" sound was played when entering and leaving the region; participants were asked to look at the paper list when hearing the first beep, and were allowed to stop looking at any time before the second beep. Participants then completed the assembly task, based on the memorized task information. To ensure that participants paid attention to the information, we checked if the assembly task was completed correctly, and provided feedback to participants if otherwise.

After the familiarization period, participants completed level walking and obstacle crossing trials in the baseline and each of the experimental conditions. All conditions were replicated three times, and a minimum of 30 s rest was provided between both replications and conditions. For the baseline trials, the presentation order of level walking and obstacle crossing (namely, obstacle presence conditions) was alternated between participants. For the experimental trials, the presentation order of *Tech Type* was counterbalanced using 3 × 3 Balanced Latin Squares, and within a given *Tech Type* condition the order of *Info Mode* and obstacle presence conditions was counterbalanced using 4 × 4 Balanced Latin Squares.

2.3. Data collection and analysis

Triaxial ground reaction forces (GRFs) were sampled at 1 kHz from the two force platforms, and subsequently low-pass filtered (36 Hz cutoff; 6th order Butterworth; bidirectional). Bilateral foot kinematics were captured at 100 Hz, using a 10-camera optical motion capture camera (Vicon Motion Systems Ltd., Vero, Denver, CO), and were subsequently low-pass filtered (9 Hz cutoff; 4th order Butterworth; bidirectional). After the familiarization period, we placed passive reflective markers bilaterally, or in the mid-sagittal plane, over several anatomical landmarks: calcaneus, first and fifth medial metatarsal heads, second toe distal phalange, lateral and medial malleoli, anterior and posterior iliac superior spines. In addition, and based on Startzell and Cavanagh (1999), eight reflective markers were placed around the

Fig. 1. Technology types: paper list (Left; text font size = 18 pt.), commercially available binocular (Middle; Epson Moverio BT-200), and monocular head-worn display (HWD) (Right; Vuzix M100).

Fig. 2. Illustration of text-based (Left) and graphic-based (Middle) information, and the simulated assembly task involving a Purdue Pegboard (Right). In the information displays, "Bin" indicates the column of the pegboard in which washers, collars, and pins are assembled, while "Build" indicates the sequence of washers (W) and collars (C) on a pin.

shoe outsole. These latter markers were removed before data collection, and were reconstructed for each walking trial, using foot markers (Veldpaus and Woltring, 1988). In obstacle crossing trials, four reflective markers were placed on each top corner of the obstacle.

Similar to previous work (Merryweather et al., 2011; Chang et al., 2016), gait performance was assessed in the context of slip- and trip-related fall risks respectively using the required coefficient of friction (RCOF) and minimum foot clearance (MFC) between the foot and the floor surface. RCOF was obtained from each force platform as the ratio of resultant shear forces to the normal force. Maximum RCOF was then extracted for each trial, according to the method described by Chang et al. (2011).

In conditions without the obstacle, MFC was defined as the lowest location among the reconstructed shoe outsole markers, near the mid-swing phase of gait in a given swing phase. MFC was calculated for each foot when participants walked across the force platforms (1999). In conditions with the obstacle, MFC was calculated separately for the lead and the trail foot over the obstacle (Startzell and Cavanagh, 1999). The location of foot placement around the obstacle was also obtained to examine obstacle crossing strategies (Chen et al., 1991), by deriving the trail-foot horizontal toe distance and the lead-foot horizontal heel distance (Fig. 3). Walking speed was estimated as the mean velocity of the four reflective markers on the pelvis during ~3 steps across the force platforms. Finally, obstacle-crossing speed was derived as the mean velocity of the same pelvis markers during the obstacle crossing step.

2.4. Statistical analysis

All statistical analyses were performed separately for level walking and obstacle crossing. First, descriptive statistics were obtained for level walking and obstacle crossing performance measures in the baseline condition, and gender-related differences in the measures were tested using one-way analyses of variance (ANOVAs). To achieve normally-distributed and homogenous residuals, lead-foot heel horizontal distance was log transformed prior to analysis. To determine if gait performance was affected by *Tech Type* and *Info Mode*, and if such effects were moderated by gender, separate three-way, repeated measures ANOVAs were performed on each gait performance measure. In these ANOVAs, change scores (Δ = measure in a given experimental condition – baseline measure) served as dependent measures, with walking (or obstacle crossing) speed included as a covariate. We observed no substantial violation of parametric model assumptions, and examined significant effects further using *post hoc* pairwise comparisons (Tukey's HSD) and simple effects analyses as relevant. All statistical analyses were complete using JMP® Pro 13.0 (SAS Institute Inc., Cary, NC) with statistical significance determined when $p < 0.05$, and effect sizes are reported using partial eta-squared (η_p^2). All summary statistics are presented as least-squares means (95% confidence intervals) unless stated otherwise.

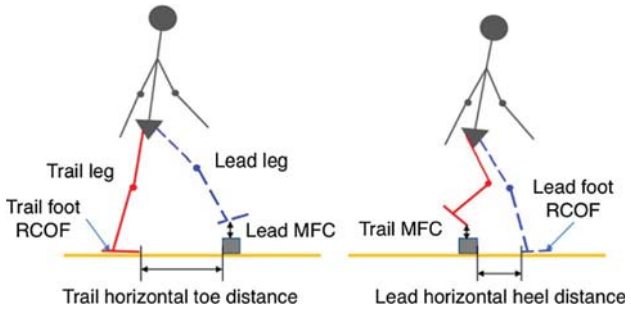

Fig. 3. Gait performance measures obtained during obstacle crossing: required coefficient of friction (RCOF), minimum foot clearance (MFC), and foot placement locations.

3. Results

3.1. Baseline condition

Summary measures are presented in Table 1 for level walking and obstacle crossing. No statistically-significant gender differences were evident (Table 1).

3.2. Level walking

A summary of ANOVA results regarding level walking performance

Table 1
Means (SDs) of baseline gait performance measures for level walking and obstacle crossing.

		Male	Female	*p* value
Level walking	MFC (mm)	16.08 (6.21)	14.62 (8.60)	0.688
	RCOF	0.22 (0.03)	0.22 (0.05)	0.863
	Walking speed (m/s)	1.40 (0.15)	1.40 (0.10)	0.931
Obstacle crossing	MFC_{LEAD} (mm)	67.94 (34.50)	72.18 (32.34)	0.704
	MFC_{TRAIL} (mm)	83.40 (40.39)	92.48 (42.73)	0.837
	$RCOF_{LEAD}$	0.27 (0.06)	0.23 (0.07)	0.318
	$RCOF_{TRAIL}$	0.21 (0.02)	0.23 (0.03)	0.309
	Lead-foot heel horiz. distance (mm)	306.67 (236.74, 376.59)	308.24 (238.31, 378.16)	0.973
	Trail-foot toe horiz. distance (mm)	157.89 (90.99)	136.27 (48.88)	0.855
	Obstacle crossing speed (m/s)	1.33 (0.15)	1.34 (0.09)	0.895

MFC = minimum foot clearance; RCOF = required coefficient of friction.
Subscripts, LEAD and TRAIL respectively indicate the lead and the trail foot.
Least square means (95% confidence intervals) were reported for the lead-foot heel horiz. distance.

Table 2
Summary of ANOVA results [F value (p value, η_p^2)] regarding the main and interaction effects of *Tech Type*, *Info Mode*, and *Gender* on level walking performance change scores. Note that walking speed was not included as a covariate for walking speed change scores.

	ΔWalking speed	ΔRCOF	ΔMFC
Gender (G)	0.17 (0.693, 0.06)	0.56 (0.462, 0.03)	1.02 (0.337, 0.08)
Tech Type (TT)	2.31 (0.125, 0.26)	0.16 (0.846, 0.001)	0.03 (0.976, 0.002)
Info Mode (IM)	0.15 (0.692, 0.003)	0.52 (0.483, 0.002)	0.19 (0.670, 0.004)
G × TT	0.29 (0.751, 0.04)	0.45 (0.636, 0.003)	0.46 (0.639, 0.007)
G × IM	0.11 (0.748, 0.002)	0.03 (0.751, 0.0001)	0.05 (0.822, 0.0001)
TT × IM	0.31 (0.737, 0.01)	1.07 (0.358, 0.007)	0.04 (0.959, 0.0002)
G × TT × IM	1.62 (0.241, 0.06)	0.71 (0.503, 0.004)	3.17 (0.064, 0.02)
Walking speed	·	0.03 (0.872, 0.00001)	0.57 (0.453, 0.001)

MFC = minimum foot clearance; RCOF = required coefficient of friction.

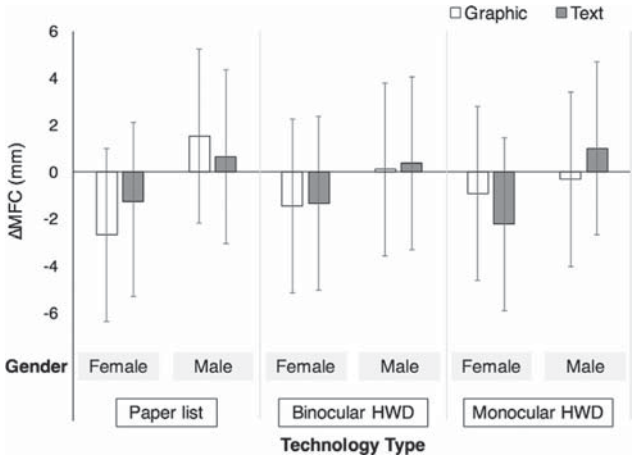

Fig. 4. *Tech Type* × *Info Mode* × *Gender* interaction effects ($p = 0.06$) on minimum foot clearance change values (ΔMFC) during obstacle crossing. Note that 0 in the vertical axis is the baseline, and that error bars indicate 95% confidence intervals.

is presented in Table 2. There were no significant effects of *Tech Type*, *Info Mode*, or *Gender* (all p values ≥ 0.125), with the potential exception of one three-way interaction described below. Qualitatively, the change scores suggested that all level walking performance measures were comparable to those in the baseline condition. The *Tech Type* × *Info Mode* × *Gender* interaction effect, however, approached significance on MFC change scores (ΔMFC; $p = 0.064$, $\eta_p^2 = 0.02$). Gender differences were more pronounced for the two conditions involving a paper list + graphic-based information and a monocular HWD + text-based information (Fig. 4).

3.3. Obstacle crossing

A summary of ANOVA results for obstacle crossing performance is presented in Table 3. *Tech Type*, *Info Mode*, and *Gender* were not significant for either obstacle crossing speed or RCOF change scores (all p values ≥ 0.068). Though not statistically significant ($p = 0.068$, $\eta_p^2 = 0.26$), both HWD conditions were associated with reduced obstacle crossing speed relative to the baseline: ΔObstacle crossing speed = 0.006 (−0.03, 0.04) m/s for the paper list condition, −0.03 (−0.06, 0.009) m/s for the binocular HWD, and −0.04 (−0.07, −0.001) m/s for the monocular HWD. *Info Mode* × *Gender* interaction effects on $RCOF_{LEAD}$ change scores ($\Delta RCOF_{LEAD}$; $p = 0.09$, $h^2 = 0.02$) indicated that gender differences in $\Delta RCOF_{LEAD}$ were more evident with text-based information [males = −0.013 (−0.087, 0.06);

Table 3
Summary of ANOVA results [F value (p value, η_p^2)] regarding the main and interaction effects of *Tech Type*, *Info mode*, and *Gender* on obstacle crossing performance change scores. Note that significant effects are highlighted using bold font, and that obstacle crossing speed was not included as a covariate for obstacle crossing speed change scores.

	ΔObstacle crossing speed	$\Delta RCOF_{LEAD}$	$\Delta RCOF_{TRAIL}$	ΔMFC_{LEAD}	ΔMFC_{TRAIL}	$\Delta Heel_{LEAD}$	ΔToe_{TRAIL}
Gender (G)	0.11 (0.752, 0.02)	1.43 (0.261, 0.36)	0.25 (0.630, 0.02)	3.67 (0.084, 0.31)	0.002 (0.967, 0.0003)	0.79 (0.396, 0.12)	0.99 (0.345, 0.23)
Tech Type (TT)	3.09 (0.068, 0.26)	0.26 (0.77, 0.008)	0.03 (0.971, 0.004)	3.44 (0.0507, 0.16)	1.85 (0.183, 0.06)	1.35 (0.281, 0.07)	0.79 (0.467, 0.04)
Info Mode (IM)	0.01 (0.912, 0.0001)	0.01 (0.905, 0.0001)	3.08 (0.110, 0.02)	0.43 (0.530, 0.003)	0.07 (0.794, 0.0007)	0.95 (0.354, 0.003)	0.38 (0.549, 0.002)
G × TT	1.00 (0.384, 0.10)	0.94 (0.406, 0.04)	1.04 (0.371, 0.03)	1.05 (0.370, 0.07)	0.53 (0.599, 0.02)	0.81 (0.460, 0.03)	1.14 (0.341, 0.04)
G × IM	0.02 (0.888, 0.0002)	3.52 (0.090, 0.02)	1.29 (0.282, 0.01)	0.002 (0.967, 0.0001)	0.48 (0.503, 0.003)	2.13 (0.178, 0.007)	0.45 (0.518, 0.002)
TT × IM	0.70 (0.497, 0.009)	0.03 (0.969, 0.001)	1.08 (0.359, 0.01)	0.84 (0.445, 0.007)	1.04 (0.372, 0.02)	**3.37 (0.0369, 0.04)**	**3.50 (0.0324, 0.04)**
G × TT × IM	0.57 (0.564, 0.007)	0.009 (0.991, 0.0001)	1.07 (0.363, 0.01)	**4.62 (0.0223, 0.04)**	0.64 (0.538, 0.009)	0.82 (0.441, 0.01)	2.45 (0.089, 0.03)
Obstacle crossing speed	·	0.90 (0.345, 0.01)	**5.36 (0.0248, 0.04)**	0.19 (0.667, 0.008)	0.77 (0.381, 0.002)	0.77 (0.381, 0.0003)	**12.98 (0.0004, 0.11)**

MFC = minimum foot clearance; RCOF = required coefficient of friction.
$Heel_{LEAD}$ = Lead-foot heel horizontal distance; Toe_{TRAIL} = Trail-foot toe horizontal distance.

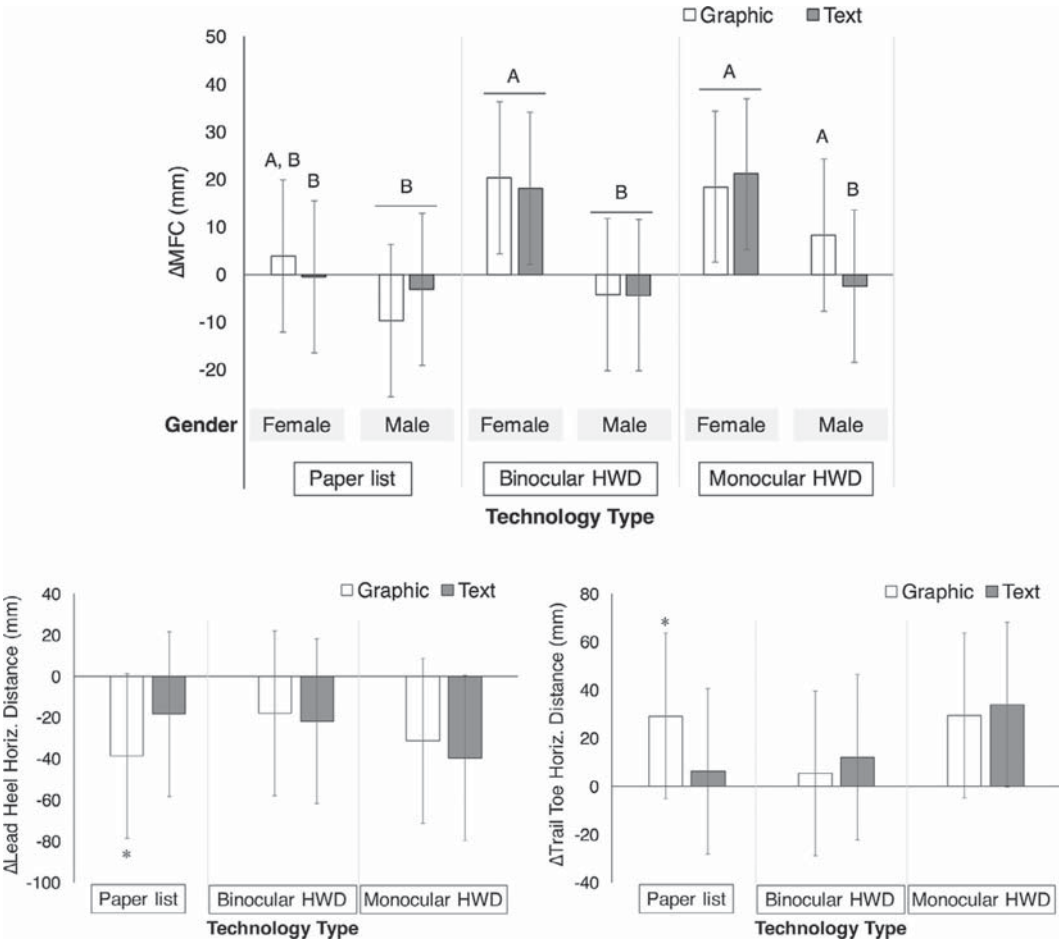

Fig. 5. *Tech Type* × *Info Mode* × *Gender* interaction effect on minimum foot clearance change values (ΔMFC) of the lead foot over the obstacle (Top), and *Tech Type* × *Info Mode* interaction effects on changes of lead heal (Bottom Left) and trail toe horizontal distance change values (Bottom Right) during obstacle crossing. Note that 0 in the vertical axis is the baseline, pairs of values with different characters are significant different, and error bars indicate 95% confidence intervals.

females = 0.053 (−0.02, 0.13)] than with graphic-based information [males = −0.003 (−0.08, 0.07); female = 0.041 (−0.032, 0.11)]. Furthermore, mean $\Delta RCOF_{TRAIL}$ was positive under all experimental conditions, suggesting a potential increase in $RCOF_{TRAIL}$ compared to the baseline [$\Delta RCOF_{LEAD}$ = 0.01 (−0.001, 0.027) for males, and 0.008 (−0.006, 0.022) for females].

ΔMFC_{LEAD} was significantly affected by the *Tech Type* × *Info Mode* × *Gender* interaction ($p = 0.0223$, $\eta_p^2 = 0.04$). When wearing a HWD, females (but not males) increased MFC_{LEAD} values when crossing the obstacle (Fig. 5). The *Tech Type* × *Info Mode* interaction effect was also significant on change scores of the lead-foot heel ($\Delta Heel_{LEAD}$; $p = 0.0369$, $\eta_p^2 = 0.04$) and trail-foot toe horizontal distances (ΔToe_{TRAIL}; $p = 0.0324$, $\eta_p^2 = 0.04$). Compared to baseline values, using the paper list with graphic-based information and the monocular HWD increased Toe_{TRAIL} and decreased $Heel_{LEAD}$ (Fig. 5).

4. Discussion

Processing visual information via a HWD while walking, such as in a workplace, may compound the risk of slips or trips. Such adverse effects of HWD use on gait performance were hypothesized, which was partially supported by our results. Use of a HWD or the paper list led to no substantial changes in level walking performance, compared to measures of baseline performance (i.e., without using a HWD or the paper list). HWD use, however, reduced obstacle crossing speed and yielded changes in obstacle crossing strategies that may be gender-specific and dependent on specific technology types and/or information modes being used.

Use of HWDs (vs. the paper list) may induce a more conservative/cautious obstacle-crossing strategy. Specifically, reducing obstacle crossing speed can be viewed as a conservative strategy to maintain postural stability when concomitant attentional demands increase (e.g., Chen et al., 1996; Harley et al., 2009). The monocular and binocular HWDs both reduced obstacle crossing speed here, respectively by −0.04 (−0.07, −0.001) m/s and −0.03 (−0.06, 0.009) m/s from the baseline obstacle crossing speed – on average ~3% slower than baseline. Though not directly comparable, obstacle crossing speed was reported to respectively decrease by ~3% and ~4% when healthy, young individuals performed a visual Stroop test (Worden et al., 2016) and a word generation task (Harley et al., 2009) during obstacle crossing. Using the paper list here, however, did not yield a consistent decrease in obstacle crossing speed; mean change in obstacle crossing speed was 0.006 (−0.03, 0.04) m/s. Walking and obstacle crossing require visual and visuospatial information to control limb trajectories (Patla and Rietdyk, 1993), and this information can be acquired with central and peripheral vision (Bardy et al., 1999). We thus suggest that acquiring such information may be more attentionally demanding with a HWD vs. paper list, even though the HWDs allowed participants to see the walking path and information on the display simultaneously, and the paper list required participants to look down to read (i.e., potentially limiting central and peripheral vision). Such an increase in attentional demands may have workplace safety implications, in that recent studies have demonstrated that performing attentionally-demanding tasks (e.g., texting while walking) can deteriorate an individual's awareness of surroundings and events (Lim et al., 2015; Lin and Huang, 2017).

This effect may mean that using a HWD could reduce the situational awareness of a user in the workplace, such as of safety hazards or safety-related events.

A measure of the control of foot trajectory (i.e., MFC_{LEAD}) over and placement around the obstacle also suggested conservative obstacle crossing strategies, with the specific strategy dependent on technology type, information mode, and gender. Common conservative strategies to reduce trip risks include increasing MFC_{LEAD}, and/or increasing the trial toe distance while reducing the lead heel distance (Chen et al., 1996; Harley et al., 2009). When a HWD was used here, females increased MFC_{LEAD} compared to the baseline (Fig. 5). Males showed some evidence of adopting such a strategy, but only with the monocular HWD + graphic-based information, while MFC_{LEAD} decreased with the paper list + graphic-based information. Worden et al. (2016) reported partially comparable findings, in that an increase in MFC_{LEAD} and MFC_{TRAIL} was observed during obstacle crossing when performing a visual Stroop test (with a computer screen located at the end of a walking track). We also found potential gender differences in $\Delta RCOF_{LEAD}$, though these depended on the specific *Info Mode*. Especially with text-based information, females appeared to increase $RCOF_{LEAD}$ relative to the baseline, while males reduced it, suggesting gender-specific strategies in foot contact dynamics (Heiden et al., 2006). Note that these gender-related differences remained evident even after accounting for participant stature (as a covariate). Though subsequent investigation is required to better understand such differences, one possible explanation is that males and females had different levels of perceived risks with a HWD, depending on information modes, and adopted different obstacle crossing strategies.

Interestingly, use of the binocular HWD had no substantial effects on foot placement control around the obstacle, while the monocular HWD and the paper list with graphic-based information caused a conservative foot placement strategy – increasing the trail toe distance while reducing the lead heel distance (Fig. 5). The difference in foot placement control when using the binocular vs. monocular HWD may be attributable to binocular rivalry with the latter, since processing different visual information presented to each eye requires more attention (Zhang et al., 2011).

Three study limitations should be acknowledged. First, our results are based on a limited sample of young participants. It is well documented that gait performance decreases with aging, leading to an increased risk of STFs, and that gait performance of older individuals can deteriorate further as attentional demands increase. Second, only a relatively optimal walking condition was considered. In reality, individuals walk on diverse and often suboptimal walking surfaces, with varying walking speeds, and while making directional changes. Third, participants were exposed to HWDs for only a short duration. Though a familiarization period was provided, participants may develop other gait strategies specific to HWD use with longer and/or more frequent use. Potentially related to this, some participants noted that they felt more “natural” using the paper list (i.e., looking down to read).

In summary, this study examined the effects of HWD use, with different technologies and information-presentation modes, on gait performance during level walking and obstacle crossing. Using a HWD to acquire task information for the light assembly task considered here had no evident effects on level walking performance. However, use of a HWD appears to induce conservative obstacle crossing strategies, likely to minimize trip risks. HWDs resulted in a slight decrease (~3%) in obstacle crossing speed compared to the baseline, and an adjustment in the control of the lead foot MFC and foot placement. Importantly, the magnitude of such adjustments depended on HWD type, information mode, and/or gender. From a workplace safety perspective, our findings support that caution should be given when incorporating a HWD in work processes that require the worker to walk around, since specific HWD types and UI implementations can induce behavioral changes. Given the limitations discussed above, future efforts are needed to further understand how HWD use affects gait performance in terms of slip- or trip-risks such as, for example, differences in attentional allocation depending on HWD type and information mode, and detection of slip or trip risks.

Acknowledgement

This work was sponsored by the Center for Excellence in Logistics and Distribution (CELDi), a National Science Foundation Industry/University Cooperative Research Center, under award #0732686. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Conflict of interest

The authors have no conflicts of interest.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jelekin.2018.02.007.

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