Obstacle crossing in a virtual environment transfers to a real environment

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Abstract:

Obstacle crossing, such as stepping over a curb, becomes more challenging with natural aging and could lead to obstacle-related trips and falls. To reduce fall-risk, obstacle training programs using physical obstacles have been developed, but come with space and human resource constraints. These barriers could be removed by using a virtual obstacle crossing training program, but only if the learned gait characteristics transfer to a real environment. We examined whether virtual environment obstacle crossing behavior is transferred to crossing real environment obstacles. Forty participants ($n = 20$ younger adults and $n = 20$ older adults) completed two sessions of virtual environment obstacle crossing, which was preceded and followed by one session of real environment obstacle crossing. Participants learned to cross the virtual obstacle more safely and that change in behavior was transferred to the real environment via increased foot clearance and alterations in foot placement before and after the real environment obstacle. Further, while both age groups showed transfer to the real environment task, they differed on the limb in which their transfer effects applied. This suggests it is plausible to use virtual reality training to enhance gait characteristics in the context of obstacle avoidance, potentially leading to a novel way to reduce fall-risk.

Keywords: foot clearance | foot placement | obstacle avoidance | peak foot elevation | skill transfer

Article:

Obstacles are a naturally occurring part of our daily environment when defined as any physical object that requires an individual to modulate their current gait pattern. Obstacles, such as stairs, curbs, and puddles, are stationary and allow for a slow and early adaptation of the gait pattern. Obstacles may also be dynamic and require a sudden adaptation, such as a ball rolling or an animal running into the gait path. The ability to avoid such obstacles is a crucial part of safe ambulation. High success rates of obstacle avoidance are due to an individual's ability to modify their limb trajectory within a step cycle (Patla, Prentice, Robinson, & Neufeld, 1991). Healthy able-bodied individuals contact obstacles 1–2% of the time (Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006), with the trail foot as the contact point 67–100% of the time (Heijnen, Romine, Stumpf, & Rietdyk, 2014; Mohagheghi, Moraes, & Patla, 2004; Rhea & Rietdyk, 2007, 2011; Rietdyk & Rhea, 2006). The probability of contact for the trail limb is higher than the lead limb due to the fact that online visual information can be used to guide the lead limb, but not the trail limb due to it being outside the visual field (Patla, 1998), and the observation that the movement trajectories of the leading and trailing limb are different because the lower limbs are independently controlled during obstacle crossing (Heijnen et al., 2014; Patla, Rietdyk, Martin, & Prentice, 1996; Rhea & Rietdyk, 2011).

Thirty-four percent of falls in older adults occur as a result of a trip, with the majority of these falls occurring during obstacle negotiation (Berg, Alessio, Mills, & Tong, 1997). Because of this, older adults exhibit a more careful strategy of obstacle crossing. Older adults cross obstacles at a slower speed, with a shorter step length and a shorter obstacle-heel strike distance (Chen, Ashton-Miller, Alexander, & Schultz, 1991; Muir, Haddad, Heijnen, & Rietdyk, 2015). The shortened step length is a result of the lead toe being raised more vertically after toe-off, which causes the foot to extend beyond the landing position during swing phase, thus overshooting before retracting backwards to the final landing position (Muir et al., 2015). This lead foot overshoot becomes progressively increased with aging (Muir et al., 2015). Additionally, older adults cross the obstacle so that it is 10% further forward in their obstacle-crossing step (Chen et al., 1991), a strategy likely used to keep the obstacle in sight longer relative to their limb. Understanding these typical obstacle crossing strategies adopted by healthy younger and older adults is useful in order to develop fall-prevention programs aimed at enhancing obstacle avoidance ability in individuals who are prone to falling.

Obstacle avoidance training programs have been developed using training with physical obstacles with some success. Patients post-stroke increased walking velocity and distance after four weeks of training with obstacles placed along a walkway (Bassile, Dean, Boden-Albala, & Sacco, 2003). Similarly, patients post-stroke with hemiplegia showed increases in gait velocity, stride length, walking endurance, and obstacle clearance capacity after two weeks of obstacle avoidance training (Jaffe, Brown, Pierson-Carey, Buckley, & Lew, 2004). Trip-training has also been used with some success as a way to enhance obstacle crossing behavior (Grabiner, Bareither, Gatts, Marone, & Troy, 2012; Lurie, Zagaria, Pidgeon, Forman, & Spratt, 2013). In this paradigm, a treadmill is typically used to provide a perturbation that simulates the foot hitting an obstacle in order to train the body to develop the appropriate neuromotor response. However, these training programs often require physical space, materials, and human resources which may not be available in some clinical settings.

To this end, clinicians have begun employing new and more advanced rehabilitation techniques, one of which is virtual reality. The use of virtual reality is defined as a simulation of a real environment that is generated through computer software and is experienced by the user through a human-machine interface (Holden, 2005). From a motor learning perspective, it has been suggested that virtual reality systems may enhance skill acquisition and retention by providing task specificity, repetition, and external real-time feedback (Wulf, 2007). Virtual reality gait training on a treadmill offers the advantage of providing a visually challenging task (i.e., ambulation over multiple virtual obstacles) in a relatively small and safe environment. Virtual reality training has been beneficial in increasing walking speed, stride length, walking distance, and obstacle crossing ability (Baram & Miller, 2006; Yang et al., 2008; Mirelman et al., 2010), while also lowering the incidence rate of falling (Mirelman et al., 2016). Additionally, virtual obstacles can be modified for a specific task. For example, previous literature has examined the clinical experience of a challenging virtual obstacle course environment with obstacles of various heights and sizes, resulting in improved functional mobility and obstacle negotiation (Shema et al., 2014). These clinical benefits were observed in patients with post-stroke hemiplegia (Yang et al., 2008), multiple sclerosis (Baram & Miller, 2006), Parkinson's disease (Mirelman et al., 2010), and older adults with poor mobility (Shema et al., 2014).

While the use of virtual obstacles during treadmill gait training appears promising, it is not yet clear how foot clearance over a virtual obstacle changes with increased training/exposures. It is also not clear whether these performance changes transfer to a real environment obstacle crossing task and the extent to which aging affects this transfer. Understanding these training and transfer effects is necessary prior to adopting virtual reality obstacle crossing into a clinical setting designed to decrease fall-risk. Thus, the purpose of this study was to (1) determine the biomechanical obstacle crossing behavior of adults within a virtual environment, (2) determine if a learning effect exists with virtual obstacle crossing, and (3) determine if the learning effect transfers to real environment obstacle crossing.

Three hypotheses were tested: (1) a training effect would be observed at the end of the virtual obstacle crossing training in the form of the adoption of a safer obstacle crossing strategy in the virtual environment; (2) a safer obstacle crossing strategy in the real environment would be adopted in the post-test relative to the pre-test; and (3) a higher pass rate in the virtual environment would be positively correlated with greater changes in performance between the pre- and post-test in the real environment, suggesting an association between motor learning in a virtual environment and transfer to a real environment task. A safer obstacle crossing strategy is defined as initiating crossing earlier (thus farther away from the obstacle) and stepping higher over the obstacle—each of which contribute to a decrease risk of obstacle contact, and subsequently, fall risk. It was also postulated that each hypothesized finding would be affected by age, with older adults showing less performance changes and transfer (albeit still significant) compared to the younger adults.

Methods

Participants

Forty healthy individuals (*n* = 20 younger adults, *n* = 20 older adults,) participated in the study (see Table 1 for demographics). All participants self-reported normal or corrected-to-normal vision, no current musculoskeletal injuries, no cognitive impairment, no current pregnancy, and able to walk unaided for 10 minutes. Each participant provided an informed consent, a basic healthy history, and physical activity questionnaire. All procedures for the study were approved by the local Institutional Review Board.

Instrumentation

Twenty-eight retro-reflective markers were placed bilaterally on the shoulders, anterior superior and posterior superior iliac crests, medial and lateral knee and ankles, medial first and lateral fifth metatarsals, and the most anterior superior position on the shoe toe and the calcaneus. Additionally, rigid plates of 4 markers each were placed on the shank and thigh segment of each limb. Lastly, 2 markers were placed on the top of the real environment obstacle. A 12-camera motion capture system (Qualisys AB, Gothenburg, Sweden) collected movement data at 100 Hz for each obstacle crossing session. Rating of Perceived Exertion (RPE) was also recorded throughout the study.

Table 1. Participant Demographics by Group [*M* (*SD*)]

Group	Foot Dominance	Age (yrs)	Mass (kg)	Height (m)
Younger Adults	20 Right	22.45 (3.65)	71.05 (13.68)	1.70 (0.08)
Older Adults	18 Right/2 Left	55.60 (5.98)	70.93 (13.92)	1.70 (0.09)

Experimental Design

After participants signed a consent form, they were put in a safety body harness to be utilized during the virtual obstacle crossing sessions. The retro-reflective markers were then applied to the participants' body. Preferred walking speed was determined on the treadmill (Symbex, Lebanon, NH) by starting at 0 m/s and incrementally increasing the speed (0.05 m/s) until the participant verbally indicated that speed was their preferred pace. Then, the participant was sped up to a fast walking pace (2.0 m/s) and incrementally slowed until they verbally indicated that speed was their preferred pace. The two speeds were then averaged to determine their preferred walking speed.

This study utilized a pre-test/training/post-test design (Figure 1). During the pre-test, participants walked overground and crossed a real environment obstacle. The obstacle was located at the halfway mark (4 m) along an 8 m pathway across the laboratory. The obstacle was made of Masonite board, painted flat black, and designed to easily tip over if contacted. The dimensions for the obstacle were 10 cm high (average curb height), 100 cm wide, and 0.5 cm deep. Participants were asked to "Walk at your normal pace and safely step over the obstacle with your dominant foot without stopping until you reach the end of the walkway." Foot dominance was determined via the question: "If you were to kick a ball for distance, which foot would you choose?" The answer given was determined to be their dominant foot.

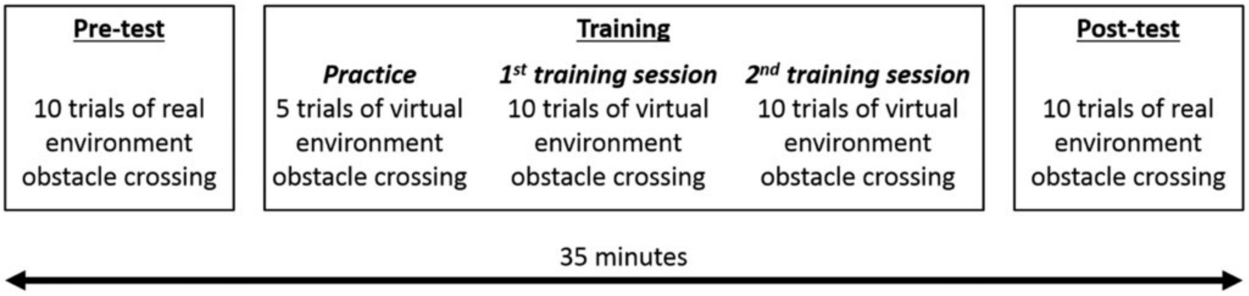

Figure 1. Testing protocol used in the study. A five-minute rest break was provided after the pre-test, 1st training session, and 2nd training session to minimize fatigue.

During the training, participants walked on a treadmill and crossed a virtual environment obstacle implemented in Vizard (WorldViz, Santa Barbara, CA). The virtual environment consisted of a grey and red walking path through a brown landscape with trees and a blue sky (Figure 2). A counter set in the top right corner of the display provided feedback on the number of obstacles hit and obstacles cleared during training. One obstacle appeared at a time in the foreground and moved toward the participant at a speed congruent with their preferred walking speed. The obstacle appeared at a distance that allowed the participant approximately 30 seconds of walking on the treadmill before they needed to step over it. Participants were instructed to continue walking and step over the obstacle normally as if it was something on the sidewalk. Once the obstacle was cleared, a new obstacle appeared in the foreground and this cycle continued for 10 obstacle crossings continuously. The obstacles were set to appear as 10 cm tall and covered the entirety of the pathway requiring the participant to step over it with both feet. The virtual environment also contained virtual feet that moved in real-time by corresponding to the participant's own foot movements via synchronization with the motion capture system. The toe, heel, medial, and lateral metatarsal markers on the participants' feet were portrayed as white markers on red feet in the virtual environment. If the obstacle was contacted [defined as the virtual foot hitting the obstacle in the virtual environment (Figure 2)], the specific foot marker that was hit turned red to indicate a collision, while the other markers that cleared the obstacle remained white. If the foot successfully cleared the obstacle, all markers turned green.

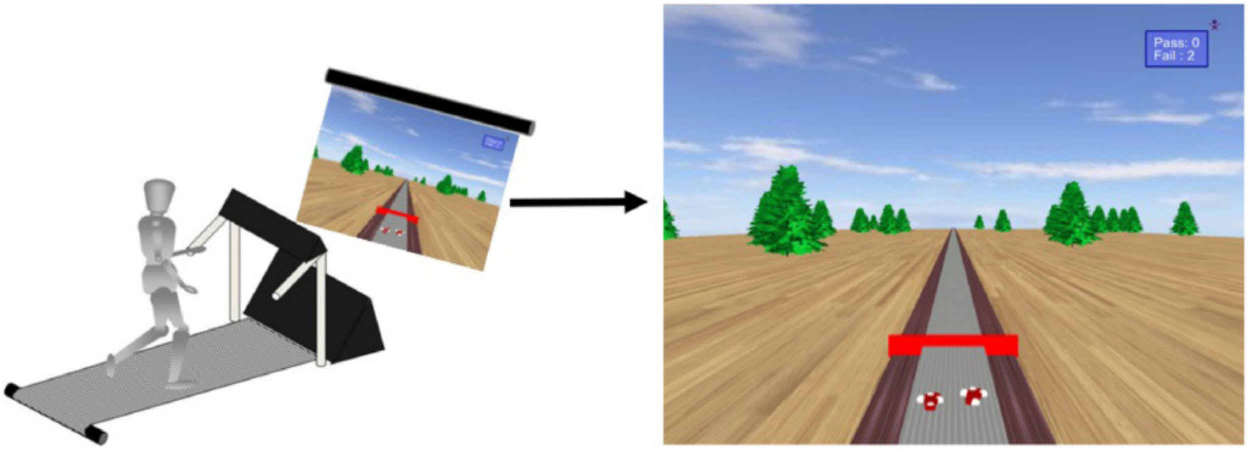

Figure 2. Virtual environment used for obstacle crossing training.

The post-test was identical to the pre-test and was used to test for transfer of obstacle crossing behavior from the virtual to the real environment. In total, participants' obstacle crossing behavior was measured 40 times—10 real environment obstacle crossings in the pre-test, 20 virtual environment obstacle crossings during training, and 10 real environment obstacle crossings in the post-test. Participants were asked to provide their RPE before and after each set of 10 trials.

Data Reduction

To measure the obstacle crossing performance in the real environment, we used the following metrics for both leading and trailing limbs: (1) foot placement before and after obstacle crossing (Figure 3), (2) toe and heel clearance during crossing (Figure 4), and (3) toe and heel peak elevation during crossing. Foot distance to the obstacle was calculated as distance from a point to a plane, where the point was the 3D coordinate of the heel/toe marker of each limb and the plane was the vertical 2D plane defined by the markers placed on the obstacle. Foot placement before and after the obstacle was calculated for each marker based on the segment where the marker remained stationary. Toe and heel clearance were quantified as distance from a point to vector, where the point was the 3D coordinate of the toe/heel marker and the vector spanned the top of the obstacle. Radial clearance was defined as the shortest distance between the foot marker and the top of the obstacle during crossing, whereas vertical clearance was the shortest distance at the moment when the foot marker was immediately above the obstacle. In addition to these clearance metrics, we calculated peak elevation of the toe/heel marker during obstacle crossing in order to directly compare crossing performance in the real environment. A delta score was calculated for each of the aforementioned metrics to measure the change from pre-test to post-test in the real environment. A positive delta score indicated a greater value in post-test compared to pre-test.

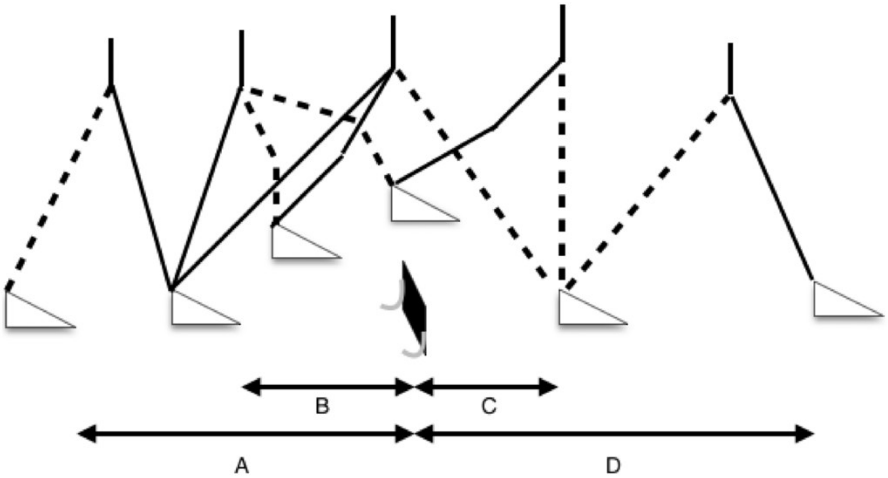

Figure 3. Depiction of the foot placement measurements. The foot placement for the lead limb (dotted limb) is shown in A (before the obstacle) and C (after the obstacle). The foot placement for the trail limb (solid limb) is shown in B (before the obstacle) and D (after the obstacle). Figure adapted from Said et al. (2005).

To measure the obstacle crossing performance in the virtual environment, we measured peak elevation of the toe/heel when crossing the virtual obstacle. Due to technical difficulties, we were not able to record the foot placement or clearance relative to the virtual obstacle. We also recorded the pass rate (percent of successful virtual obstacle crossings defined as all foot markers crossing over the top of the virtual obstacle). A delta score was calculated for each of the aforementioned metrics to measure the change from the 1st training session to the 2nd training session in the virtual environment. All calculations were performed using MATLAB 2015b (MathWorks Inc., Natick, MA).

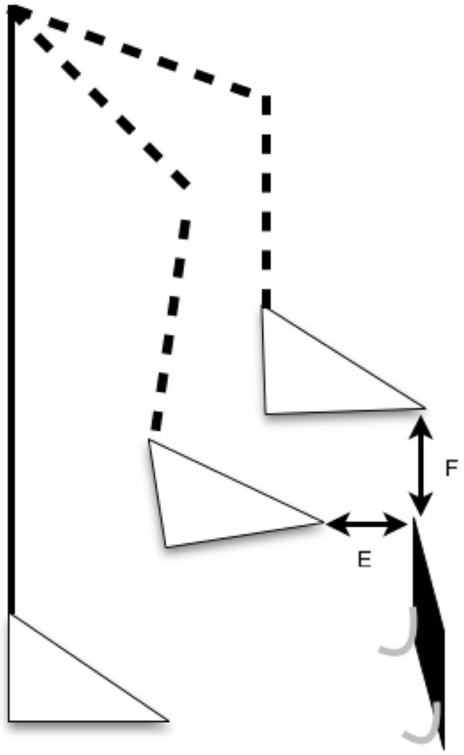

Figure 4. Depiction of the foot clearance measurements. The radial clearance is shown in E (closest distance to the obstacle) and the vertical clearance is shown in F (distance directly over the obstacle). Peak elevation (not depicted) was determined to be the highest elevation exhibited during crossing.

Statistical Approach

The average value of each metric was calculated across the 10 trials in each session. To address hypothesis 1, we used a 2 Age (younger vs. older adults) × 2 Session (1st vs. 2nd training session) repeated measures MANOVA for pass rate and peak elevation of the lead and trail limb in the virtual environment. To address hypothesis 2, two separate Age (younger vs. older adults) × Test (pre- vs. post-test) repeated measures MANOVAs were run: one for foot placement in the real environment and one for foot clearance in the real environment. Finally, to address hypothesis 3, Pearson correlation coefficients were calculated between the number of successful obstacle passes in the virtual environment and the delta scores for each obstacle crossing metric in the real environment. The alpha level was set *a priori* to 0.05 for all statistical tests.

Results

While preferred waking speed was slower for the older adults ($M = 0.43$, $SD = 0.08$ m/s) compared to the younger adults ($M = 0.96$, $SD = 0.18$ m/s; $t(38) = 2.37$, $p = .02$), there was no difference in RPE between the age groups at any of the time points ($p > .05$).

Table 2. Summary of Results

	Group	Pre-Test	Post-Test	Delta Score
Real Environment				
Lead Limb PBO	Older	0.889 (0.128)	0.929 (0.122)	0.043 (0.104)
	Younger	0.802 (0.119)	0.855 (0.181)	0.053 (0.137)
Trail Limb PBO	Older	0.234 (0.061)	0.272 (0.075)	0.040 (0.050)
	Younger	0.197 (0.055)	0.227 (0.086)	0.030 (0.063)
Lead Limb PAO	Older	0.293 (0.041)	0.276 (0.049)	−0.018 (0.034)
	Younger	0.308 (0.070)	0.282 (0.069)	−0.026 (0.043)
Trail Limb PAO	Older	1.003 (0.080)	0.997 (0.084)	−0.003 (0.030)
	Younger	1.009 (0.132)	0.968 (0.123)	−0.040 (0.074)
Lead FC (Radial)	Older	0.124 (0.032)	0.134 (0.031)	0.012 (0.022)
	Younger	0.141 (0.039)	0.151 (0.050)	0.010 (0.023)
Trail FC (Radial)	Older	0.102 (0.043)	0.124 (0.056)	0.023 (0.023)
	Younger	0.094 (0.034)	0.114 (0.041)	0.020 (0.024)
Lead FC (Vertical)	Older	0.138 (0.040)	0.152 (0.042)	0.016 (0.021)
	Younger	0.163 (0.050)	0.180 (0.067)	0.017 (0.025)
Trail FC (Vertical)	Older	0.123 (0.061)	0.145 (0.069)	0.021 (0.027)
	Younger	0.121 (0.054)	0.145 (0.055)	0.024 (0.024)
Lead Limb PE	Older	0.403 (0.058)	0.420 (0.064)	0.018 (0.019)
	Younger	0.405 (0.040)	0.421 (0.048)	0.015 (0.022)
Trail Limb PE	Older	0.480 (0.099)	0.497 (0.096)	0.017 (0.033)
	Younger	0.499 (0.063)	0.525 (0.062)	0.027 (0.023)
	Group	**Session 1**	**Session 2**	**Delta Score**
Virtual Environment				
Lead Limb PE*	Older	0.466 (0.095)	0.468 (0.114)	0.022 (0.115)
	Younger	0.460 (0.143)	0.447 (0.099)	−0.013 (0.069)
Trail Limb PE	Older	0.360 (0.119)	0.387 (0.124)	0.028 (0.088)
	Younger	0.382 (0.208)	0.423 (0.209)	0.041 (0.077)
Pass Rate (%)	Older	37.00 (21.55)	46.00 (27.22)	9.00 (13.71)
	Younger	33.50 (22.31)	43.50 (23.68)	10.00 (13.38)

Note. Results Include Lead and Trail Limb Position Before the Obstacle (PBO), Lead and Trail Limb Position After the Obstacle (PAO), Lead and Trail Limb Foot Clearance (FC) in the Radial and Vertical Directions, Lead and Trail Limb Peak Elevation (PE), and Pass Rate. Asterisk Indicates Non-Significance for Session, $p < .05$.

Pass Rates

For the pre-test in the real environment, participants contacted the obstacle 0% [0 out of 400 trials] of the time for the lead limb and 0.0025% [1 out of 400 trials] of the time for the trial limb. Similar obstacle contact rates were observed for the post-test with a 0% [0 out of 400 trials] contact rate for the lead limb and a 0% [0 out of 400 trials] contact rate for the trial limb. Collectively, the percentage of successful passes for all participants/limbs was 99.94% [1599 out of 1600 trials] for the real environment obstacles. For the 20 trials in the virtual environment, there was a limb difference ($p = .03$ in the pass rate; 64% for the lead limb and 74% for the trail limb) and the overall pass rate (defined as a successful clearance of the obstacle for both limbs) was 40%. Age-related changes and the relation between the real and virtual environment obstacle crossing are explored in the hypothesis testing below. The pass rate for the virtual obstacle crossing trials and their relation to the real environment obstacle crossing behavior are reported in the hypothesis 3 results. The statistics addressing each hypothesis are presented below and the values for each dependent variable are presented in Table 2. Significant delta scores that were related to pass rate are visualized and presented in Figure 5. Due to technical difficulties, data were not available for one participant (an older adult) in the real environment. Thus, the degrees of freedom are slightly different between the real and virtual environment statistics.

> Hypothesis 1: A training effect would be observed at the end of the virtual obstacle crossing training in the form of the adoption of a safer obstacle crossing strategy in the virtual environment.

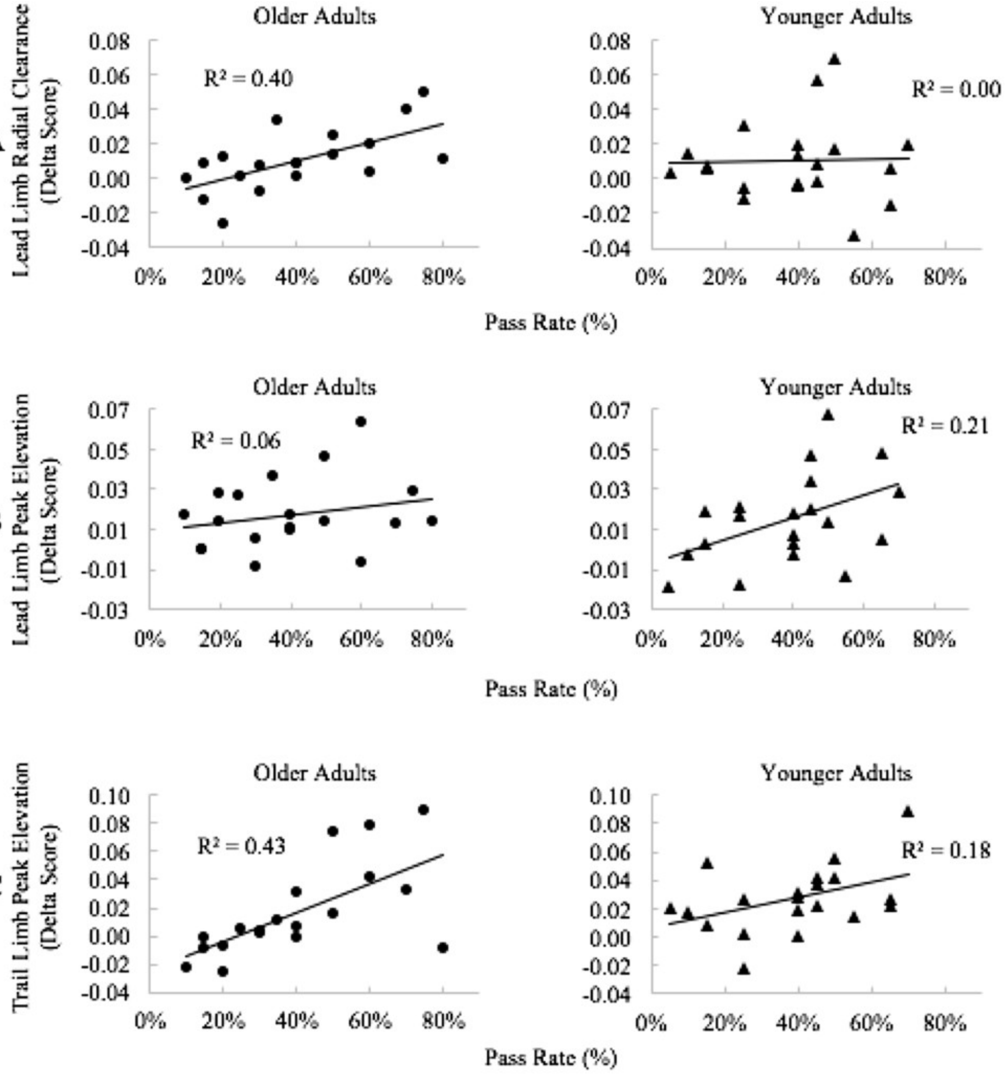

Figure 5. The relationship between the delta score of lead limb radial clearance and pass rate separated by age (panel a), the delta score of lead limb peak elevation and pass rate separated by age (panel b), and the delta score of trail limb peak elevation and pass rate separated by age (panel c).

There was a multivariate main effect for Session ($F[3,36] = 5.10$, $p = .01$, partial $\eta^2 = 0.30$), but not Age ($F[3,36] = 0.51$, $p = .68$, partial $\eta^2 = 0.04$). Follow-up univariate tests showed that trail limb clearance peak elevation ($F[1,38] = 8.92$, $p = .01$, $\eta^2 = 0.19$) and pass rate

($F[1,38] = 5.58$, $p = .02$, partial $\eta^2 = 0.13$) drove this multivariate effect of Session. Follow-up pairwise comparisons confirmed there is a significant difference in trail limb peak elevation between the 1st and 2nd session, $t(39) = 3.01$, $p = .01$. Follow-up pairwise comparisons also confirmed there was a significant difference in pass rate between the 1st and 2nd session, $t(39) = 2.39$, $p = .02$. Further, the pass rate was significantly higher for the trail limb compared to the lead limb across all 20 trials $t(39) = 2.29$, $p = .03$. There was no Age × Session interaction ($F[3,36] = 0.80$, $p = .50$, partial $\eta^2 = 0.06$) for pass rate and lead and trail limb clearance peak elevation in the virtual environment.

> Hypothesis 2: A safer obstacle crossing strategy in the real environment would be adopted in the post-test relative to the pre-test.

The results show that after virtual obstacle training, both older and younger adults tended to place the leading and trailing limbs further away from the obstacle prior to crossing, crossed with higher clearance in the leading and trailing limb, and then placed both limbs closer to the obstacle after crossing over (Table 2). Multivariate main effects were identified for Test ($F[4,34] = 4.42$, $p = .01$, partial $\eta^2 = .34$), but not Age ($F[4,34] = 1.05$, $p = .39$, partial $\eta^2 = 0.11$) for foot position metrics. There was no Age × Test interaction for lead and trail limb position before and after the obstacle ($F[4,34] = 1.77$, $p = .16$, partial $\eta^2 = 0.17$). Follow-up univariate tests showed each metric of foot placement drove the multivariate effect for Test: lead limb position before the obstacle ($F[1,37] = 5.73$, $p = .02$, $\eta^2 = 0.13$), trail limb position before the obstacle ($F[1,37] = 13.79$, $p = .001$, $\eta^2 = 0.27$), lead limb position after the obstacle ($F[1,37] = 11.50$, $p = .002$, $\eta^2 = 0.237$), and trail limb position after the obstacle ($F[1,37] = 6.50$, $p = .02$, $\eta^2 = 0.15$). Follow-up pairwise comparisons confirmed there was a significant difference from pre-test to post-test for lead limb position before the obstacle ($t[38] = 2.44$, $p = .02$), trail limb position before the obstacle ($t[38] = 3.74$, $p = .001$), lead limb position after the obstacle ($t[38] = 3.43$, $p = .001$), and trail limb position after the obstacle ($t[38] = 2.52$, $p = .02$).

A multivariate main effect for Test was identified ($F[4,34] = 13.09$, $p < .001$, partial $\eta^2 = 0.61$), but not Age ($F[4,34] = 2.14$, $p = .10$, partial $\eta^2 = 0.20$) for foot clearance metrics. Follow-up univariate tests showed each variable of foot clearance drives this multivariate effect for Test: radial lead limb clearance ($F[1,37] = 9.24$, $p = .004$, $\eta^2 = 0.20$), radial trail limb clearance ($F[1,37] = 31.49$, $p < .001$, $\eta^2 = 0.46$), lead limb peak elevation ($F[1,37] = 24.54$, $p < .001$, $\eta^2 = 0.40$), and trail limb peak elevation ($F[1,37] = 22.13$, $p < .001$, $\eta^2 = 0.37$). Follow-up pairwise comparisons confirm there was a significant difference from pre-test to post-test, for radial lead limb clearance ($t[38] = 3.08$, $p = .004$), radial trail limb clearance ($t[38] = 5.67$, $p < .001$), lead limb peak elevation ($t[38] = 5.01$, $p < .001$), and trail limb peak elevation ($t[38] = 4.72$, $p < .001$). No Age × Test interactions for the variables of radial lead and trail limb clearance and lead and trail limb peak elevation in the real environment ($F[4,34] = 1.35$, $p = .27$, partial $\eta^2 = 0.14$) were identified.

> Hypothesis 3: A higher pass rate in the virtual environment would be positively correlated with greater changes in performance between the pre- and post-test in the real environment.

The relationship between pass rate in the virtual environment and delta score of radial lead limb clearance in the real environment yielded a weak positive correlation trending towards significance ($r = 0.30$, $n = 39$, $p = .06$). When separated by age group, this relationship was driven by the older adults, as the older adults exhibited a statistically significant strong correlation ($r = 0.64$, $n = 19$, $p = .003$) compared to the very weak, non-significant correlation exhibited by the younger adults ($r = 0.03$, $n = 20$, $p = .89$) (Figure 5a). In addition, the relationship between pass rate in the virtual environment and delta score of lead limb peak elevation in the real environment yielded a weak positive correlation ($r = 0.36$, $n = 39$, $p = .03$). When separated by age group, this relationship was driven by the younger adults, as the younger adults exhibited a moderate positive correlation ($r = 0.46$, $n = 20$, $p = .04$) compared to the weak, non-significant correlation exhibited by the older adults ($r = 0.24$, $n = 19$, $p = .32$) (Figure 5b). Lastly, the relationship between pass rate in the virtual environment and delta score of trail limb peak elevation in the real environment yielded a moderate positive correlation ($r = 0.55$, $n = 39$, $p < .001$). When separated by age group, this relationship was driven by the older adults, as the older adults exhibited a strong correlation ($r = 0.66$, $n = 19$, $p = .002$) compared to the moderate correlation exhibited by the younger adults ($r = 0.43$, $n = 20$, $p = .06$) (Figure 5c).

Discussion

This study examined the extent to which changes in gait during a virtual obstacle crossing task on a treadmill transferred to overground gait obstacle avoidance in a real environment. Further, this study examined whether age influenced the learning and transfer of the obstacle crossing strategy. In general, our hypotheses were supported, as participants did adopt a safer obstacle crossing strategy in the virtual environment with training, and that newly learned behavior was transferred to the real environment. Furthermore, both age groups similarly altered their foot placement and increased foot clearance in the real environment as a result of virtual environment training, but employed different adaptive strategies to successfully avoid the obstacles.

Younger and older adults learned to enhance their obstacle crossing in the virtual environment via trail limb peak elevation and pass rate, evidenced by an increase in these variables from 1st to 2nd session of the virtual environment training. This suggests that participants chose an obstacle crossing strategy of increasing their trail limb's overall peak elevation after focusing on the lead limb clearing the obstacle to try to ensure that the trail limb would not contact the obstacle. These findings are congruent with previous work with real obstacles showing that after contact with an obstacle, clearance and peak elevation remain elevated for multiple subsequent obstacle crossings (Heijnen, Muir, & Rietdyk, 2012; Rhea & Rietdyk, 2011), highlighting the ecological validity of a virtual obstacle crossing paradigm. Participants in our study were not particularly successful at the virtual obstacle crossing task. They hit the virtual obstacle with their lead limb 36% of the time and 26% of the time with their trail limb—contact rates that are much higher than observed in repeated real environment obstacle crossing (Heijnen et al., 2012). Further, their overall pass rate—defined as both limbs successfully clearing the obstacle—was 40%. These high failure rates could be due to the novelty of the task or from a lack of accurate depth perception, as the virtual environment is presented on a projection screen and is not immersive or represented similarly to real environment obstacle encounters. Regardless, this repeated unsuccessful behavior led to the adoption of alternate movement strategies during the training in order to increase success rates, similar to the manner in which toe elevation is increased after contact with an obstacle in the real world in order to attempt to avoid a subsequent contact (Heijnen et al., 2012; Rhea & Rietdyk, 2011). As participants frequently contacted the obstacle within the virtual environment training sessions, their toe elevation progressively increased during training and remained increased during the real environment post-test. Additionally, increases in the virtual environment pass rate from the 1st to the 2nd training session suggest that the participants became progressively more successful at crossing the obstacles from session 1 to session 2, furthering the evidence for learning within the virtual environment, which was positively associated with post-test performance in the real environment.

It is plausible that the increases in toe elevation in the real environment post-test could have been due to contacting the obstacle more often during those obstacle crossings, which can then cause the person to increase their toe elevation on subsequent trials (Heijnen et al., 2012). However, our participants were remarkably successful at the real-world obstacle crossing task, hitting the obstacle only 1 out of 1600 trials when accounting for 40 participants, 2 limbs, and 20 trials (10 pretest- and 10 post-test). This 99.94% success rate is higher than reported in previous literature, where participants contacted a 10 cm obstacle 0.8% of the time (leading to a 99.2% success rate)(Rhea & Rietdyk, 2011). Similarly, a 99.4% success rate has been observed with obstacles whose height was normalized to leg length (Heijnen et al., 2012). Our observation of a higher success rate is likely due to the fact that our participants only completed 10 real world obstacle crossings at a time, which may not have allowed for the gradual lowering of the limb during obstacle crossing. This postulate is supported by the observation that the lead and trail limb linearly decrease 0.4 mm and 1.0 mm respectively per trial in repeated obstacle crossings (Heijnen et al., 2012). Based on our data in Table 1, it would have taken ∼100 obstacle crossings (range of 94–141 crossings) in the pre-test before an obstacle contact would be expected to occur, congruent with previous findings (Heijnen et al., 2012). After the increase in foot clearance attributed to the virtual obstacle training, participants could cross a real obstacle an extra 10–20 times (range of 114–151 crossings) before an obstacle contact would be expected to occur. Thus, our data suggests that the change in behavior was due to the virtual obstacle crossing training rather than a consequence from hitting the obstacle in the real environment. Further, it shows that as few as 20 trials of virtual obstacle crossing have a positive effect on real environment obstacle crossing behavior. These findings highlight the idea that virtual obstacle training can lead to the adoption of a safer real environment obstacle crossing strategy.

Both younger and older adults adjusted their adaptive obstacle crossing strategies via foot position, clearance, and elevation in the real environment following virtual obstacle crossing training. Previously, distance between foot placement and the obstacle has been related to foot contact with the obstacle (Chou & Draganich, 1998; Patla & Greig, 2006). A main effect was observed in all foot position variables in the real environment from pre- to post-test. Participants increased their foot position away from the obstacle before crossing and placed their foot closer to the obstacle after crossing. This was the case for both the lead limb and the trail limb, and suggests an obstacle crossing strategy of initiating an earlier crossing to ensure proper time for increasing foot clearance and successful obstacle crossing. Additionally, a main effect was observed for all foot clearance and peak elevation variables in the real environment from the pre- to post-test. Participants increased radial foot clearance between their foot and the obstacle, which may be a function of the overall increase in peak foot elevation that was observed.

Increasing foot clearance decreases the chance of contacting the obstacle, but this may come at the cost of increased metabolic energy demand and decreased biomechanical stability. There is likely a specific range of foot clearance that will optimize the ratio of increased metabolic cost to decreased obstacle contact. However, this ratio may be specific to person and context. Future research may test this optimization using perturbation and physiological testing.

Lastly, younger and older adults were able to transfer the learning obtained from the virtual environment to the real environment as evidenced by the positive relationships between pass rate in the virtual environment and delta scores in the real environment. After separating the correlations by age, it was observed that younger and older adults each applied separate adaptive obstacle strategies which transferred to the real environment. Younger adults adopted an increase in lead limb peak elevation in the real environment. This suggests that the younger adults focused on increasing the overall elevation of the lead limb in the virtual environment to increase the success of obstacle crossing, while allowing the trail limb to cross with relatively less modulation. Conversely, older adults adopted an increase in radial lead limb clearance and trail limb peak elevation. This may suggest that after increasing the clearance of the lead limb over the obstacle, older adults increased the overall trail limb elevation due to lack of confidence in the trail limb to successfully clear the obstacle. Due to the fact that the trail limb is the main obstacle contactor at 67–100% of the time (Heijnen et al., 2014; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007, 2011; Rietdyk & Rhea, 2006) and older adults are at an increased fall risk, adopting an elevated clearance of the trail limb is a strategy for older adults to decrease contact and also fall-risk. Increasing clearance and elevation may be metabolically costly, but it may be argued that the benefit of decreasing obstacle contact, and thus fall-risk, outweighs the increase in metabolic cost for older adults.

There are some important differences to note between the virtual and real environments. First, the virtual environment lacked the tactile information of obstacle contact. Thus, participants had to rely on proprioception regarding limb position and visual information in both a feedforward and a feedback manner to modify limb trajectory. In the real environment, the visual information of the trail limb is typically absent because it is out of the visual field. However, our virtual environment provided visual information of both the lead and trail limbs via the real-time feedback from seeing both feet move relative to the obstacle. This experience is different than the real environment experience and likely participants used this visual information to modify the trajectory of their trail limb.

This study is limited by the fact that it did not include a group which walked on the treadmill in the virtual environment without the virtual obstacles. As such, it is difficult to ascertain that the changes seen in the real environment were due solely to the virtual environment obstacles and not to the potential practice effect from crossing the real environment obstacle a total of 20 trials. Additionally, the variables of foot placement and clearance, which were analyzed in the real environment, were not analyzed in the virtual environment due to technical difficulties. The ability to compare all variables across environments help better understand how training in a virtual environment may transfer to a real environment.

In conclusion, our data show that obstacle crossing training in a virtual environment can influence real environment obstacle crossing behavior. These changes were not limited to age, as each age group responded similarly to the training. This study sets up the foundation to employ virtual reality training for patients with pathology who may exhibit decreased gait adaptability, reduced ability for obstacle negotiation, and an increased fall-risk—ultimately taking advantage of the benefits of virtual reality training with respect to safety and specificity.

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