Obstacle avoidance training in virtual environments leads to limb-specific locomotor adaptations but not to interlimb transfer in healthy young adults

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Abstract

Obstacle avoidance is one of the skills required in coping with challenging situations encountered during walking. This study examined adaptation in gait stability and its interlimb transfer in a virtual obstacle avoidance task. Twelve young adults walked on a treadmill while wearing a virtual reality headset with their body state represented in the virtual environment. At random times, but always at foot touchdown, 50 virtual obstacles of constant size appeared 0.8 m in front of the participant requiring a step over with the right leg. Early, mid and late adaptation phases were investigated by pooling data from trials 1-3, 24-26 and 48-50. One left-leg obstacle appearing after 50 right-leg trials was used to investigate interlimb transfer. Toe clearance and the anteroposterior margin of stability (MoS) at foot touchdown were calculated for the stepping leg. Toe clearance decreased over repeated practice between early and late phases from 0.12 ± 0.05 m to 0.09 ± 0.04 m (mean ± SD, $p < 0.05$). MoS increased from 0.05 ± 0.02 m to 0.08 ± 0.02 m ($p < 0.05$) between early and late phases, with no significant differences between mid and late phases. No differences were found in toe clearance and MoS between the practiced right leg for early phase and the single trial of the left leg. Obstacle avoidance during walking in a virtual environment stimulated adaptive gait improvements that were related in a nonlinear manner to practice dose, though such gait adaptations seemed to be limited in their transferability between limbs.

Keywords: obstacle avoidance, falls, gait stability, motor transfer, motor adaptation

Introduction

Walking in daily-life situations is challenging due to terrain variations that may cause falls, e.g. surface friction and height. Tripping over obstacles during locomotion has been reported to be among the most frequent causes of falls in the elderly population (Berg et al., 1997; Blake et al., 1988; Overstall et al., 1977). But the frequency of falls at leisure time and work is also high among younger and middle-aged adults; internationally every fifth work accident is associated with falls including tripping over obstacles (Bureau of Labor Statistics, 2019; Eurostat, 2019). Those accidents can lead to serious injuries (e.g. hip fractures and head injuries, even death) with hospital admission resulting in high costs for health insurances and a reduced quality of life for those with long-lasting impairment.

Perturbation training is among potential preventive measures to reduce the severity of fall accidents. Training through repeated gait perturbations has been shown to be an effective way to improve balance control across the adult lifespan and it has been established that balance gains are retained over months or even years (Bhatt et al., 2006; Epro et al., 2018; Grabiner et al., 2012; Karamanidis et al., 2020; König et al., 2019; Pai et al., 2007). However, a nonlinear practice dose-response relationship in healthy old as well as participants with neuropathology means that a specific threshold is required to reach a steady state (Karamanidis et al., 2020). Thus, short periods of task specific perturbation training improving fall resisting skills may contribute to a reduction in the incidence and severity of future falls. However, the above-mentioned studies, as well as other research in human balance control, have mostly employed elaborate mechatronic devices (e.g. cable-trip systems or treadmill belt accelerators/decelerators), which are expensive and call for dedicated facilities and extensive training for healthcare. In recent years simulation techniques such as virtual reality (VR) have found increasing popularity and use in training of human gait and balance control (Canning et al., 2020; Mirelman et al., 2020). A virtual environment (VE) provides safe but also challenging training conditions with controlled stimulus delivery while reducing the amount of required training equipment. Some studies have already applied VR techniques to support investigations in obstacle avoidance. For example, in a recent study participants acquired a strategy for skilled virtual obstacle negotiation, which they were able to transfer to overground walking and retain for 24 hours (Kim et al., 2019).

Transfer of motor skills to the various motor tasks and conditions of real life is an essential component of learning. Interlimb transfer, for which improvements in limb actions from repeated practice of a unilateral motor task can be transferred to the contralateral limb (Poh et al., 2016; Ruddy and Carson, 2013), is an important property of learning. It represents generalization of skill learning (Ruddy and Carson, 2013) and is useful because it reduces the duration of training. Various factors (e.g. aging, duration of training and type of task) have been shown to influence the extent of interlimb transfer (Carroll et al., 2016; Joiner et al., 2013; Krishnan et al., 2018, Stockel and Wang, 2011; Wang et al., 2011). Regarding an obstacle avoidance gait task, Van Hedel and colleagues (2002) as well as Kloter and Dietz (2012) reported interlimb transfer if participants were aware of the change in limbs (i.e. they were informed that they had to cross the next obstacles with the other limb) and received explicit feedback about their performance while training. However, whether similar generalization of skill learning between limbs in an obstacle avoiding task can be observed in VE is currently unknown.

Our study examined adaptation to avoid suddenly appearing obstacles in a VE, as well as the transfer of adaptation from the trained to the untrained leg in healthy young adults. We used toe clearance as a measure of the effectiveness of obstacle avoidance, and margin of stability (MoS) as an indicator of dynamic stability while walking. We hypothesized: (1) that our participants in crossing multiple obstacles in a VE would progressively improve dynamic balance and effectiveness, with a nonlinear relation between response and practice dose; and (2) that these adaptations would be transferable from the trained to the untrained leg.

Methods

Participants

Twelve healthy young adults (six males, six females; age 21.6 ± 1.5 yrs; height 175 ± 10 cm; mass 70.3 ± 9.5 kg; mean ± standard deviation, SD) voluntarily participated in the present study after providing their written informed consent. They had normal or corrected-to-normal vision and were free of neurological and musculoskeletal impairments that might have affected gait or cognitive function. The study was approved by the ethics committee of the University of Applied Sciences Koblenz and met all requirements for human experimentation in accordance with the Declaration of Helsinki (World Medical Association, 2013).

Experimental setup and procedures

Participants walked on a treadmill (pulsar, h/p/cosmos, Nussdorf-Traunstein, Germany) while gait kinematics were measured using an 8-camera motion capture system (Oqus 7/Oqus 5, Qualisys, Gothenburg, Sweden). Kinematic data were recorded at 120 Hz using a 48-marker full body model (Qualisys animation marker set). Markers were additionally placed on the head mounted display (HMD; Vive Pro, HTC Corporation, Taoyuan, Taiwan; four markers) and the treadmill (four markers). The VE included a geometrically accurate model of the treadmill and its handrails. The motion capture system logged movements of the participant and supplied marker position data dynamically to the VR software system Unity (Version 2019.2.7f2, Unity Technologies, San Francisco, CA, USA). Unity allowed the participant's body to be visualized in the VE and simulated the virtual obstacles presented via the HMD.

Before training, participants were familiarized with the set-up for about 10 minutes in a three-part procedure. They walked on the treadmill (1) without wearing the HMD, (2) wearing the HMD whilst holding the treadmill handrails, and (3) letting go of the handrails whilst wearing the HMD. Treadmill walking velocity was set to 1.3 m/s. For safety reasons, participants wore a harness attached to the safety arch of the treadmill. During training, participants walking on the treadmill saw an endless corridor displayed in the HMD. They had to cross and avoid 50 unilateral virtual obstacles (height 0.1 m × depth 0.1 m × width 0.5 m) with their right leg (see Fig. 1A). We chose unilateral virtual obstacles in order to avoid the contralateral trailing limb from adapting to obstacle crossing (as seen in Kloter and Dietz, 2012), which would have biased the investigation of interlimb transfer. Obstacles always appeared at touchdown of the right leg (i.e. at the same time in the gait cycle) 0.8 m in front of the participant's right heel on the right-hand side (Fig. 1A). They appeared at random times which were fixed in the same sequence for all participants. At the end of the training session with the right leg, one obstacle was presented to the untrained left leg, at the touchdown of that leg. Only one virtual obstacle was used to test interlimb transfer in order to avoid rapid learning effects of the untrained limb as previously shown with physical obstacles (Kloter and Dietz, 2012). The change of leg was not announced beforehand. When a participant did hit an obstacle, it was displayed in the VE but no further feedback about crossing performance was provided.

Insert Figure 1

Data Processing

The three-dimensional coordinates of the markers were filtered using a low-pass, second-order, zero-phase Butterworth filter with a 12 Hz cut-off frequency. Toe clearance was calculated as the difference between the height of the toe marker when that marker was above the leading edge of the obstacle and the height of the obstacle (Fig. 1B). Foot touchdown was determined using the foot contact algorithm of Maiwald et al. (2009; i.e. using the local maxima in the vertical acceleration curve of the corresponding target marker (heel or fifth metatarsal) within an approximation interval). Center of mass (CoM) was calculated as the average position of the four pelvis markers (left and right anterior and posterior superior iliac spines). CoM velocity was defined as the mean of the first derivatives of the CoM and C7 positions plus the treadmill belt speed (Süptitz et al., 2013). The anteroposterior MoS at touchdown was calculated as the anteroposterior distance between the anterior boundary of the base of support (BoS, anteroposterior component of the toe projection to the ground) and the extrapolated CoM (X_{CoM}; adapted from Hof et al., 2005) for each touchdown of the obstacle stepping limb (Fig. 1C). All calculations were performed using a customized routine written in MATLAB (version 9.3.0, The Mathworks Inc, Natick, MA, USA).

Statistics

The adaptation of participant responses to practice dose was examined by pooling trials. Trial data were combined for obstacles 1-3, 24-26 and 48-50 and were named *early*, *mid* and *late adaptation*, respectively. Obstacle crossing training was investigated statistically through one-way, repeated-measures ANOVA with four levels (early, mid and late adaptation, and transfer) and for each of toe clearance, BoS, X_{CoM} and MoS. Tukey *post hoc* tests were applied in cases of significant main effects. Partial eta-squared (η_p^2) as normalized effect size measures were calculated to evaluate the strength of effects, with cut-off values of 0.01 denoting small, 0.06 moderate and 0.14 large effects, respectively (Cohen, 1988). Statistical analyses were performed using RStudio software (version 1.2.5042, RStudio, Boston, MA, USA) with α set at 0.05. All results in text are presented as mean ± SD.

Results

Figure 2 shows changes in toe clearance (Fig. 2A) and MoS (Fig. 2B) as mean values of all analyzed participants for crossing 50 obstacles with their right leg and a single obstacle with their left leg (transfer). Crossing virtual obstacles resulted in adaptation effects indicated by a decrease in toe clearance and an increase in the MoS (i.e. more stable body configurations).

Insert Figure 2

The repeated measures ANOVA revealed statistically significant differences in toe clearance over repeated practice [$F(3, 30) = 3.35$; $p = 0.032$, $ɲ_p^2 = 0.251$]. Toe clearance decreased over repeated practice between early and late adaptation phases (0.13 ± 0.05 m and 0.09 ± 0.04 m, respectively; $p = 0.039$) but there was no significant difference between the early and mid phases (mid value, 0.12 ± 0.05 m; $p = 0.97$; Fig. 3A). For BoS, a significant main effect was found [$F(3, 24) = 3.28$; $p = 0.038$, $ɲ_p^2 = 0.291$]. *Post hoc* comparisons showed significant differences between early and late adaptation phases ($p = 0.048$) with increasing BoS values with repeated practice (early 0.62 ± 0.07 m; mid 0.66 ± 0.05 m; late 0.69 ± 0.03 m). There was no significant main effect for X_{CoM} [$F(3, 24) = 2.30$; $p = 0.102$, $ɲ_p^2 = 0.214$], with values of 0.57 ± 0.08 m, 0.59 ± 0.09 m and 0.61 ± 0.04 m for early, mid and late adaptation respectively. According to the adaptation effects of BoS, ANOVA revealed statistically significant differences for MoS [$F(3, 33) = 8.09$; $p < 0.001$, $ɲ_p^2 = 0.424$]. MoS progressively increased from one adaptation phase to the next (early 0.05 ± 0.02 m; mid 0.07 ± 0.02 m; late 0.08 ± 0.02 m) with differences between early and mid adaptation phases ($p = 0.048$) and between early and late phases ($p < 0.001$) but not between mid and late ($p = 0.52$; Fig. 3B). The single trial of the untrained leg resulted in values of 0.13 ± 0.07 m (toe clearance), 0.53 ± 0.05 m (X_{CoM}), 0.59 ± 0.08 m (BoS) and 0.05 ± 0.02 m (MoS). There were no significant differences between the single trial values compared to the early adaptation phase of the trained leg in any of the analyzed outcomes (toe clearance, $p = 0.99$; BoS, $p =0.63$; MoS, $p = 0.99$; see also Fig. 3).

Insert Figure 3

Discussion

This study investigated learning and interlimb transfer effects in young adults in response to crossing unexpected virtual obstacles while walking on a treadmill. Our first hypothesis, that young adults progressively decrease their toe clearance and increase their MoS, with a nonlinear relationship between response and practice dose, was confirmed. However, we did not find evidence to support our second hypothesis, namely that these adaptations can be transferred from the trained leg to the untrained leg.

Trained motor adaptations to cross obstacles - a complex task requiring precise inter-leg coordination - could prevent various accidents in challenging daily life situations. Results of the present study suggest that treadmill training in a VE leads to adaptation of gait stability and gait effectiveness when crossing multiple obstacles. The MoS of the crossing leg was significantly higher for mid and late adaptation phases when compared to the early adaptation phase. Since BoS, in contrast to X_{CoM}, showed adaptation effects after repeated practice, we may argue that the main mechanism responsible for the increment in MoS was performing a longer step after crossing the obstacle. However, adaptation of MoS appeared to plateau at approximately the 25th obstacle as there were no significant differences between mid and late adaptation. This might be a dose threshold of the nonlinear practice dose-response relationship which is in accordance with previous mechanical perturbation studies (Karamanidis et al., 2020). Kim and colleagues (2019) also found a plateau beginning after approximately 30 obstacles and participants needed on average 21 obstacles to achieve 66% of their total reduction in toe clearance. In the current study, toe clearance of the crossing leg also showed learning effects between early and late phases but with a slightly lower learning rate compared to the results of Kim and colleagues (2019).

Humans often prefer to walk in ways that minimize energetic cost (Donelan et al., 2001) and can also optimize energetic cost in real time (Finley et al., 2013; Selinger et al., 2015). Despite the absence of instruction to reduce toe clearance in this study, participants combined lower toe clearance with an increase in BoS when adapting their crossing strategy with repeated practice. They thus crossed the obstacle with a lower but longer step, which reflects a change to a more effective and stable movement. However, compared to investigations by van Hedel and Dietz

(2004) and Kim et al. (2019), with participants instructed to cross obstacles with as little clearance as possible and given feedback about task performance, the final magnitude of toe clearance in the present study after training in a VE was substantially higher. Since Kim and colleagues (2019) also investigated crossing obstacles in a VE, we believe that these differences in study outcomes may have occurred due to differences in instructions, or the absence of performance feedback and the unexpected appearance of obstacles in our study. Regarding the initial toe clearance, our results are comparable to Kim and colleagues (2019) with an average value for all participants of 0.13 m for both investigations. However, missing feedback about toe clearance in the current study may explain the higher final toe clearance after repeated practice compared to other studies (van Hedel and Dietz, 2004; Kloter and Dietz, 2012) and the variation in individual responses to obstacle crossing resulting in high standard deviations of the parameters. The results of the analysis may therefore be influenced by the variability within and between participants. Irrespective, however, these findings suggest that VR techniques can be used as tools to support training of locomotor skills since our participants adapted their MoS and toe clearance through training in VE.

Whether the identified adaptive changes can be retained long term over several months, or transferred to physical obstacles and/or different conditions (e.g. obstacle avoidance during overground gait), cannot be answered from the current investigation. There are indications in the literature to date that adaptive changes in predictive VR obstacle avoidance can be partly retained in the short term (i.e. within 24h) and transferred to predictive overground physical obstacle avoidance (Kim et al., 2019). Further investigation is needed as to whether improvements in VR obstacle avoidance can be retained in the long term and whether avoidance of unexpected virtual obstacles can be beneficial in coping with suddenly appearing physical obstacles or for recovery responses to trip- or slip-like perturbations.

Although participants notably adapted when crossing 50 obstacles with their right leg, interlimb transfer was not detected. Differences between early adaptation and transfer trials occurred neither for toe clearance nor for MoS. Malfait and Ostry (2004) postulated that cognitive awareness of the perturbation is required for interlimb transfer to occur. In studies of van Hedel et al. (2002) and Kloter and Dietz (2012) cognitive awareness may have been pronounced by explicit performance feedback after crossing the obstacle and consequently resulted in interlimb transfer. In contrast, McCrum et al. (2018, 2019) and Bhatt et al. (2008), neither of whom provided feedback about performance, found only partial interlimb transfer. Thus previous findings seem to support the view of Malfait and Ostry (2004) and suggest that interlimb transfer of motor adaptation depends on whether tasks involve explicit goals and cognitive awareness. The absence of cognitive awareness (i.e. no feedback given to the subjects about crossing performance) and explicit goals as well as the lack of awareness of limb change in this investigation may explain why no interlimb transfer occurred in the VE. Accordingly, it seems possible that if limb change had been announced we may also have seen partial interlimb transfer. It must be acknowledged furthermore that we cannot exclude that repeated testing of the left (transfer) limb may have resulted in a partial interlimb transfer regarding a faster adaptation in comparison to the right limb. It would be of interest for future studies to determine how the awareness of limb change influences the ability to transfer the learned adaptations to the untrained leg and if the transfer limb shows faster learning when crossing multiple obstacles in comparison to the trained limb.

One might argue that using a single trial for the transfer task (see Methods section) as opposed to averaging multiple trials may lead to less robust data due to the variability of the motor response. However, when comparing the single data points of the transfer task with each of the three data points within the mid and late adaptation phases for the MoS of each participant, the transfer task was lower in 82% of the cases (i.e. in 59 out of 72 analyzed trials). Therefore despite trial-to-trial variability in task execution when crossing virtual obstacles, we are confident that the current findings are not affected by use of single-trial transfer.

In conclusion, our findings revealed that repeated practice of obstacle avoidance during treadmill walking in a VE can stimulate adaptive improvements in MoS and toe clearance up to a certain threshold of practice dose. However, the lack of explicit information to increase cognitive awareness for movement performance may have hindered transfer of improved adaptation between legs. VR techniques are an innovative method to support training locomotor skills, providing challenging stimuli in a safe and controlled environment while reducing the requirements for training equipment.

Disclosure of interest

The authors declare no conflicts of interest.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figure Legends

Figure 1: Virtual environment (VE) consisting of an endless corridor with a 3D model of the treadmill and an avatar representing the participant. The avatar represents the connections between markers on anatomical landmarks of the participant. (A) Perspective of the participant when the obstacle appears 0.8 m in front of the participant’s right heel. (B) Toe clearance is calculated as the vertical distance between the toe marker and the leading edge of the obstacle. (C) The anteroposterior margin of stability (MoS) is calculated for the moment of foot touchdown as the anteroposterior distance between the base of support (anteroposterior

component of the toe projection to the ground) and the extrapolated center of mass (X_{CoM}) adapted from Hof et al., (2005). Center of mass (CoM) is defined as the average position of the four pelvis markers and CoM velocity (V_{CoM}) is calculated as the mean of the first derivatives of the CoM position and C7 position, plus the treadmill belt speed.

Figure 2: (A) Toe Clearance and (B) Margin of Stability for crossing obstacles 1 to 50 with the right leg presented as means (circles) with standard deviations (shaded) for all participants. Obstacles used to investigate adaptation (early, mid and late) are presented as open circles. The black triangle and error bars after the dashed vertical line represent the mean and standard deviation of the transfer trial (left leg). During repeated obstacle avoidance training of the right leg (50 perturbation trials) two participants hit one virtual obstacle. However, those two trials were outside our observation windows for the analysis of early, mid and late adaptation and, therefore, did not affect the statistical analysis. As there were no consequences on motor task execution or dynamic stability, those two trials are included in the figure. No participant hit the obstacle for the transfer task.

Figure 3: (A) Toe Clearance and (B) Margin of Stability at early (obstacles 1-3), mid (obstacles 24-26) and late adaptation phases (obstacles 48-50) and for the single trial of the untrained leg (transfer). Values are expressed as means ± standard deviations of the 12 analyzed subjects, along with data values for all analyzed obstacles (grey dots). Tukey *post hoc* tests revealed statistically significant differences compared to early phase (* $p < 0.05$, ** $p < 0.001$).