Enhancement of awareness through feedback does not lead to interlimb transfer of obstacle crossing in virtual reality

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Abstract

Locomotor skill transfer is an essential feature of motor adaptation and represents the generalization of learned skills. We previously showed that gait adaptation after crossing virtual obstacles did not transfer to the untrained limb and suggested it may be due to missing feedback of performance. This study investigated whether providing feedback and an explicit goal during training would lead to transfer of adaptive skills to the untrained limb. Thirteen young adults crossed 50 virtual obstacles with one (trained) leg. Subsequently, they performed 50 trials with their other (transfer) leg upon notice about the side change. Visual feedback about crossing performance (toe clearance) was provided using a color scale. In addition, joint angles of the ankle, knee, and hip were calculated for the crossing legs. Toe clearance decreased with repeated obstacle crossing from 7.8±2.7cm to 4.6±1.7cm for the trained leg and from 6.8±3.0cm to 4.4±2.0cm ($p<0.05$) for the transfer leg with similar adaptation rates between limbs. Toe clearance was significantly higher for the first trials of the transfer leg compared to the last trials of the training leg ($p<0.05$). Furthermore, statistical parametric mapping revealed similar joint kinematics for trained and transfer legs in the initial training trials but differed in knee and hip joints when comparing the last trials of the trained leg with the first trials of the transfer leg. We concluded that locomotor skills acquired during a virtual obstacle crossing task are limb-specific and that enhanced awareness does not seem to improve interlimb transfer.

Keywords: obstacle crossing, motor adaptation, motor transfer, awareness, falls

Introduction

Challenges to stability during walking due to uneven floors, slippery surfaces, or obstacles require the neuromotor system to execute effective motor actions and rapidly adapt to provide safe locomotion. A widely used paradigm to assess locomotor adaptation is obstacle crossing during treadmill walking (Erni & Dietz, 2001; Lam et al., 2004; Van Hedel et al., 2004). Humans adapt their locomotor behavior with repeatedly practicing obstacle crossing as in using a smaller toe clearance and reducing lower extremity muscle activation (Kloter et al., 2012, Michel et al., 2018). An alternative method incorporates perturbations in virtual reality (VR), avoiding the need for complex mechanical equipment. This approach has recently been demonstrated to cause adaptations in stability and gait in different population groups (Delgado & Der Ananian 2020; Kim et al., 2019; Weber et al., 2021). However, contrary to the findings of an obstacle crossing paradigm in the physical world (Van Hedel et al. 2002; Kloter et al. 2012), no interlimb transfer was detected in VR obstacle crossing (Weber et al., 2021).

Previous studies have highlighted the significance of visual feedback in enhancing skill generalization (Taylor et al., 2013). Additionally, it has been suggested that optimizing performance via feedback can lead to improved transfer performance (Krishnan et al., 2017, 2018; Swinnen et al., 1997). As a result, it is anticipated that providing participants with feedback would grant them greater control over their actions and consequently improve interlimb transfer. Explicit performance feedback may have contributed to interlimb transfer in previous studies addressing mechanical obstacle crossing (van Hedel et al., 2002; Kloter et al., 2012). In our previous study we showed gait adaptation for VR training without feedback, but transfer to the untrained limb was absent (Weber et al., 2021). In the current study, we therefore decided to extend our investigations and aimed to evoke enhanced awareness by feedback as a factor influencing interlimb transfer. We hypothesized that additional feedback about obstacle crossing performance would increase awareness and hence support adaptation and transfer of movement kinematics.

Methods

Participants

Thirteen healthy young adults (7 males, 6 females; age 22.7±1.4yr; body height 175±9cm; body mass 73.1±9.6kg; means ± standard deviations) without prior experience in virtual obstacle crossing were recruited for this study. All participants had normal or corrected-to-normal vision, no neurological and musculoskeletal impairments, were right leg dominant (prior asked via kicking leg) and provided informed consent before any measurements were made. Using the effect size and power values from our previous study (Weber et al., 2021), the a priori sample size was computed using G*Power software (Faul et al., 2009), yielding a sample size of N=13 with a power of 0.99. The study was approved by the ethics committee of the University of Applied Sciences Koblenz and the protocol met all requirements for human experimentation in accordance with the Declaration of Helsinki (World Medical Association, 2013).

Experimental setup and procedures

This study is a direct continuation of our previous study (Weber et al., 2021) and characterized by the same experimental setup. In brief, upon familiarization to treadmill walking, participants wore a head-mounted VR display (Vive Pro, HTC Corporation, Taoyuan, Taiwan) and performed an obstacle crossing training in virtual environment while walking at 1.3m/s. The training consisted of crossing 50 unilateral virtual obstacles (height 10cm × depth 10cm × width 50cm) appearing at touch-down, 80cm in front of the participants' right (training) leg. After this session, participants performed 50 crossing trials with their left (transfer) leg upon notice about the change in legs. Participants were equipped with a 50-marker full body model (as in Weber et al., 2022; 120Hz, Qualisys, Gothenburg, Sweden) to visualize their body in VR and for kinematic analysis. Throughout all trials, participants wore a safety harness attached to the arch of the treadmill.

Obstacles were presented in the same sequence for all participants and for both legs. The explicit goal for the gait perturbation task was to 1) cross the obstacle within a given target range above the obstacle and 2) avoid crossing it below the target height. Enhanced awareness through feedback information about toe clearance was provided via a color scale presented in the participants' field of view (Fig. 1). A yellow section of the scale indicated 3-5 cm distance; a red section indicated a distance below the minimum target. A black, open circle on the scale indicated the clearance of the participant's toe above the front edge of the virtual obstacle for the previous crossing and remained displayed until the next obstacle crossing (Weber et al., 2022). Note that participants were not informed about the assignment of the colors to the corresponding height above the obstacle.

Insert Figure 1

Data Processing

Three-dimensional coordinates of markers from motion capture were filtered using a low-pass second-order zero-phase Butterworth filter with a 12Hz cut-off frequency. Foot take-off and touchdown were determined using the foot contact algorithm of Maiwald et al. (2009). Toe clearance was calculated as the difference between the height of the toe marker and the height of the obstacle when that marker was above the leading edge of the obstacle (Weber et al., 2022). Sagittal plane hip, knee and ankle angles of the trained and transfers legs were calculated for swing phases that were defined as the time between take-off and touchdown of the feet. Joint angles were calculated as in our previous study (Weber et al., 2022). In brief hip angle was calculated using the hip center, femoral head center and knee joint center. Knee angle was calculated using the hip joint center, knee joint center and ankle joint center. Ankle angle was calculated using the knee joint center, ankle joint center and fifth metatarsal. All calculations were performed using custom routines written in MATLAB (version 9.3.0, The Mathworks Inc, Natick, MA, USA).

Statistics

Trial data were pooled for obstacles 1-3, 24-26 and 48-50 and named *early, mid* and *late adaptation*, respectively (Weber et al., 2021). Obstacle crossing training was investigated statistically through one-way repeated measures ANOVA with three levels (early, mid and late adaptation) on toe clearance. Toe clearance data was normally distributed and heterogeneous in all adaptation phases of the trained leg and early adaptation of the transfer leg. Due to two outliers (one each for mid and late adaptation) parametric assumption could not be confirmed for these phases. These outliers were caused by natural variability hence we decided to consider respective data for further analyses. Bonferroni post-hoc tests were applied in cases of significance. Transfer effects were examined by comparing the data of early and late adaptation of toe clearance of the trained leg with early adaptation of the transfer leg in separate paired sample *t*-tests. Statistical Parametric Mapping (SPM; Pataky, 2010) *t*-tests were used to detect effects of obstacle crossing training on transfer in sagittal plane joint angles (obstacle crossing leg, swing phase) for early and late adaptation. Statistical analyses were performed using SPSS Statistics (version 27, IBM, Armonk, NY, USA) or open-source code SPM1d (version M.0.4.8, http://www.spm1d.org) in MATLAB, with α set at 0.05. All results in the text are presented as mean ± standard deviation.

Results

Locomotor adaptations with repeated VR obstacle crossing

Whilst there were virtual collisions between participants' feet and obstacles during some of the trials, these were not present in the statistically analyzed trials. Crossing virtual obstacles with the right leg resulted in adaptation effects indicated by a decrease in toe clearance (Fig. 2). The repeated measures ANOVA revealed statistically significant differences in toe clearance over repeated training for the trained right leg [*F*(1.24, 14.82)=13.78; *p*=0.001; Fig. 2]. Toe clearance decreased over repeated training between early and late adaptation (from 7.84±2.74cm to 4.56±1.67cm; *p*=0.005) and between early and mid adaptation (values for mid adaptation, 5.27±2.11cm; *p*=0.013) but there was no significant difference between mid and late adaptation (*p*=0.185; Fig. 2).

Transfer of locomotor adaptations to the untrained leg

Paired *t*-tests revealed statistically significant differences in toe clearance between trained leg late adaptation and transfer leg early adaptation (*p*=0.007) with higher values for the transfer leg (Fig. 2). Further, significantly greater knee joint extension during the swing phase between 0 and 21% and 65 and 84% (*p*<0.001), and hip joint extension between 0 and 65% (*p*<0.001; Fig. 3) were observed when comparing late adaptation (trained leg) with early adaptation (transfer leg). When comparing early adaption of the trained and transfer legs during obstacle crossing no significant or functionally relevant differences for toe clearance or any joint angle trajectories over time were determined; only in the initial period of the swing phase (0 to 12%) there were leg-differences in ankle joint angles (*p*=0.032). Similar to the trained right leg, ANOVA revealed statistically significant differences in toe clearance adaptation for the transfer leg [*F*(2, 24)=7.09; *p*=0.004]. Toe clearance decreased over repeated training between early and late adaptation (6.81±3.04cm and 4.35±2.03 cm; *p*=0.044) and between early and mid adaptation (mid values, 4.93±2.04cm; *p*=0.016) but there was no significant difference between the mid and late adaptation (*p*=1.00; Fig. 2). Both legs toe clearance of all adaptation phases was not significantly different between the trained and transfer leg (early, *p*=0.237; mid, *p*=0.574; late, *p*=0.694).

Insert Figure 2

Insert Figure 3

Discussion

This study investigated the effect of enhanced awareness of motor adaptation in young adults crossing virtual obstacles, and interlimb transfer of adaptation. The results indicate that crossing multiple virtual obstacles leads to locomotor skill adaptation but transfer between legs is limited even with constant feedback about crossing performance.

Motor adaptation effects in the current study are characterized by a reduction in toe clearance between early and late as well as between early and mid adaptation. This in line with our previous investigation in which participants did not receive feedback about their crossing performance (Weber et al., 2021). When visual feedback was available and an explicit performance target for toe clearance was set, toe clearance during the 25th and 50th obstacle were significantly smaller compared to the previous study (tested via an additional mixed ANOVA, $p<0.01$; current data vs. previous publication Weber et al., 2021: 25th: 4.86±2.01cm vs 11.69±7.20cm, 50th: 4.55±1.92cm vs. 8.96±4.18 cm) while baseline performance did not differ (1st: 12.49±10.55cm vs. 14.21±5.01cm). Thus combined with our previous findings the current study provides evidence that both rate and magnitude of refinements in locomotor skill using VR can be enhanced via feedback on one’s performance.

Although locomotor skill adaptation was improved and participants were informed about limb change before starting the transfer task, we were unable to detect any interlimb transfer of adaptive changes in obstacle crossing. Toe clearance of the transfer leg (early adaptation) revealed higher values when compared to the trained leg (late adaptation), which were on average close to the values of the trained leg during early adaptation (Fig. 2). Examination of the data for individual participants did not change the group-based conclusion for the absence of interlimb transfer. This might be further supported by our observations that acquisition was not enhanced i.e. there were no differences between legs in early, mid, and late adaptation. Moreover, lower extremity joint kinematics of the crossing limb were similar for early adaptation of both trained and transfer legs, with functionally relevant interlimb differences between late adaptation trained leg and early adaptation transfer leg. Though participants adapted faster and with a higher magnitude with feedback (current study) than without feedback (Weber et al., 2021) we found no interlimb transfer for both studies. Thus interlimb transfer was not elicited by enhanced awareness through feedback and information about limb change indicating that the acquisition of locomotor skills in a VR obstacle crossing task seems to be limb specific.

It remains unclear why some studies revealed interlimb transfer (e.g. Kloter et al., 2012 and Van Hedel and Dietz 2002) and others did not (e.g. Bhatt et al., 2008). Relevant factors might be the complexity and type of task, aspects of the cohort analyzed - including age, instructions that were given, practice-dose, or the experimental protocol (Carroll et al., 2016; Joiner et al., 2013; Krishnan et al., 2018, Stockel and Wang, 2011; Wang et al., 2011). However, based on our studies on VR obstacle crossing in two different sample groups (one with and the other without feedback), we have no evidence that adaptive changes in locomotion are transferred from one leg to the other in a VR condition. Thus, it remains controversial whether or not explicit goals and enhanced awareness lead to interlimb transfer (Wang et al., 2011; Werner et al., 2019). Since we recently identified limited locomotor skill transfer from the virtual to the physical world (Weber et al., 2022), we conclude that VR training using feedback enhances the effectiveness of limb-specific locomotor skill adaptation but should be considered carefully for applied settings given that transfer seems limited.

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: Experimental design, feedback and awareness procedure. Feedback was provided using a color scale with black open circle showing the position of the target area. Back view of the environment containing a corridor, a model of the treadmill, avatar of the participant, virtual obstacle and visual feedback about avoidance height. Participant crossing the 1st (a) and 50th (b) obstacle with the trained leg and the 1st (c) and 50th (d) obstacle with the transfer leg. By informing participants about leg change between (b) and (c) we enhanced their awareness of the task.

Figure 2: Adaptation of toe clearance for (a) trained leg and (b) transfer leg for obstacle crossing. Circles present mean values and grey shading presents standard deviations for all participants. Obstacles used to investigate adaptation (early, mid and late adaptation) are presented as white circles. (c) Mean and standard deviations (black) as well as individual values (grey circles) of early, mid and late adaptation for trained and transfer legs. + Significant difference to early adaptation for the corresponding leg. * Significant difference between late adaptation trained leg and early adaptation transfer leg ($p < 0.05$).

Figure 3: Sagittal plane ankle, knee and hip joint angle trajectories of the crossing leg during swing phase for early and late adaptation trained leg and early adaptation transfer leg as means and standard deviations (blue and red shadings respectively) for VR obstacle crossing. Grey areas indicate significant differences between late adaptation trained leg and early adaptation transfer leg. For comparison between early adaptation of the trained and transfer leg only the ankle joint showed significant differences at the initiation of the swing phase (0 to 12% period).