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Virtual reality obstacle crossing: adaptation, retention and transfer to the physical world

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Statutory declaration

Hereby I declare that the current thesis and the work presented in it is my own original work. This material has not been submitted either in whole or in part for a degree at this or any other institution. All materials used and paraphrased from other sources are clearly indicated as references. I further declare that I took the guidelines for qualified scientific work of London South Bank University into account.

London, April 30th 2023

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Summary

Virtual reality (VR) paradigms are increasingly being used in movement and exercise sciences with the aim to enhance motor function and stimulate motor adaptation in healthy and pathological conditions. Locomotor training based in VR may be promising for motor skill learning, with transfer of VR skills to the physical world in turn required to benefit functional activities of daily life. This PhD project aims to examine locomotor adaptations to repeated VR obstacle crossing in healthy young adults as well as transfers to the untrained limb and the physical world, and retention potential of the learned skills. For these reasons, the current thesis comprises three studies using controlled VR obstacle crossing interventions during treadmill walking.

In the first and second studies we investigated adaptation to crossing unexpectedly appearing virtual obstacles, with and without feedback about crossing performance, and its transfer to the untrained leg. In the third study we investigated transfer of virtual obstacle crossing to physical obstacles of similar size to the virtual ones, that appeared at the same time point within the gait cycle. We also investigated whether the learned skills can be retained in each of the environments over one week. In all studies participants were asked to walk on a treadmill while wearing a VR headset that represented their body as an avatar via real-time synchronised optical motion capture. Participants had to cross virtual and/or physical obstacles with and without feedback about their crossing performance. If applicable, feedback was provided based on motion capture immediately after virtual obstacle crossing. Toe clearance, margin of stability, and lower extremity joint angles in the sagittal plane were calculated for the crossing legs to analyse adaptation, transfer, and retention of obstacle crossing performance.

The main outcomes of the first and second studies were that crossing multiple virtual obstacles increased participants' dynamic stability and led to a nonlinear adaptation of toe clearance that was enhanced by visual feedback about crossing performance. However, independent of the use of feedback, no transfer to the untrained leg was detected. Moreover, despite significant and rapid adaptive changes in locomotor kinematics with repeated VR obstacle crossing, results of the third study revealed limited transfer of learned skills from virtual to physical obstacles. Lastly, despite full retention over one week in the virtual environment we found only partial retention when crossing a physical obstacle while walking on the treadmill.

In summary, the findings of this PhD project confirmed that repeated VR obstacle perturbations can effectively stimulate locomotor skill adaptations. However, these are not transferable to the untrained limb irrespective of enhanced awareness and feedback. Moreover, the current data provide evidence that, despite significant adaptive changes in locomotion kinematics with repeated practice of obstacle crossing under VR conditions, transfer to and retention in the physical environment is limited. It may be that perception-action coupling in the virtual environment, and thus sensorimotor coordination, differs from the physical world, potentially inhibiting retained transfer between those two conditions. Accordingly, VR-based locomotor skill training paradigms need to be considered carefully if they are to replace training in the physical world.

Publications in peer-reviewed journals

1. **Weber, A.**, Hartmann, U., Werth, J., Epro, G., Seeley, J., Nickel, P., & Karamanidis, K. (2023). Enhancement of awareness through feedback does not lead to interlimb transfer of obstacle crossing in virtual reality. Journal of Biomechanics, In Press.
2. **Weber, A.**, Hartmann, U., Werth, J., Epro, G., Seeley, J., Nickel, P., & Karamanidis, K. (2022). Limited transfer and retention of locomotor adaptations from virtual reality obstacle avoidance to the physical world. Scientific Reports, 12(1), 1-9.
3. **Weber, A.**, Werth, J., Epro, G., Friemert, D., Hartmann, U., Lambrianides, Y., Seeley, J., Nickel, P. & Karamanidis, K. (2022). Head-mounted and hand-held displays diminish the effectiveness of fall-resisting skills. Sensors, 22(1), 344.
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5. **Weber, A.**, Friemert, D., Hartmann, U., Epro, G., Seeley, J., Werth, J., Nickel, P. & Karamanidis, K. (2021). Obstacle avoidance training in virtual environments leads to limb-specific locomotor adaptations but not to interlimb transfer in healthy young adults. Journal of Biomechanics, 120, 110357.

Publications in congress proceedings

1. Schneider M., **Weber A.**, Kaufmann M., Kluge A., Hartmann U., Karamanidis K., Ellegast R. (2023). Generation of consistent slip, trip and fall kinematic data via instability detection and recovery performance analysis for use in machine learning algorithms for (near) fall detection. 25. International Conference on Human-Computer Interaction, Copenhagen, Sweden
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Scenarios for the Prevention of Slip, Trip, and Fall (STF) Accidents. In Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Human Body and Motion (pp. 210–219). 21. International Conference on Human-Computer Interaction, Orlando, United States https://doi.org/10.1007/978-3-030-22216-1_16

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List of figures

those two trials are included in the figure. No participant hit the obstacle for the transfer task.

Figure 6: (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 (* $p < 0.05$, ** $p < 0.001$).

Figure 7: 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 8: 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 9: 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).

Figure 10: Experimental protocol illustrating the days of measurement (T1 session 1; T2 session 2), tasks within sessions and type and number of obstacles for the two groups.

Figure 11: (A) Virtual environment containing a corridor, a model of the treadmill, avatar of participant, virtual obstacle and visual feedback about avoidance height. (B) Participant avoiding the virtual obstacle. (C) Participant avoiding the physical obstacle.

Figure 12: Adaptation of toe clearance for (A) first VR-based training (T1) and (B) second VR-based training (T2) for avoiding obstacles with the right leg (1-50) presented as means (circles) with standard deviations (grey shading) for all IG participants. Obstacles used to investigate adaptation (early and late) are presented as open circles. *: significant difference between early and late adaptation ($p < 0.05$). No differences were detected between late T1 and early T2.

Figure 13: Sagittal plane ankle, knee and hip joint angle trajectories of the avoiding leg during swing phase for T1 (day 1) and T2 (post 7-10 days) for early and late adaptation as mean and standard deviation (blue and red shading) during VR obstacle avoidance. Vertical grey areas indicate significant differences between early and late adaptation.

Figure 14: Sagittal plane ankle, knee and hip joint angle trajectories of the avoiding leg during swing phase for T1 (day 1) and T2 (post 7–10 days) for intervention group (IG) and control group (CG) as mean and standard deviation (blue and red shading) during the first physical obstacle avoidance (trial 1). The vertical gray area indicates a significant difference between groups.

Figure 15: Mean and standard deviation of toe clearance for all participants of the intervention group (IG, circles; $n = 14$) and control group (CG, triangles; $n = 14$) for avoiding the three physical obstacles of each transfer task on T1 (first transfer), and T2 (retained transfer and second transfer). * Significant difference between IG and CG for obstacles 1–3 in T1 ($p < 0.05$), † significant

difference between third obstacle T1 and first obstacle T2 IG ($p < 0.05$), # significant difference between first and third obstacle T1 CG.

Figure 16: Left: Schematic illustration of the trained leg while crossing a virtual obstacle during swing phase in early and late adaptation. Right: ankle, knee and hip sagittal plane angle for early and late adaptation as mean and standard deviation (blue and red shading) for VR obstacle avoidance. Vertical grey areas indicate significant differences between early and late adaptation ($p < 0.05$).

Figure 17: Toe clearance of the 1st, 25th and 50th obstacle of the trained leg and 1st obstacle of the transfer leg for participants without feedback (black) and with feedback (grey), individual data, mean and standard deviation. *: significant differences between with and without feedback groups ($p < 0.05$). +: significant differences between 50th obstacle right and 1st obstacle left for both groups ($p < 0.05$).

Figure 18: Schematic illustration of the findings: virtual reality obstacle avoidance training, can stimulate adaptive changes within the locomotor system that are enhanced with visual feedback. These changes can be retained in the virtual environment. Transfer and retention to the physical environment are, however, limited. Transfer from the virtual to the physical environment may be influenced by distance/size perception, sensory-motor information, task specificity, kinematics and sense of presence.

Figure 19: Virtual environment displayed in the game engine Unity containing the endless corridor, the model of the treadmill and the avatar streamed by Qualisys.

Figure 20: Left: view of markers and bones (yellow) used for avatar streaming and treadmill markers (blue). Middle: view of the virtual environment with the streamed avatar and treadmill position. Right: real treadmill and its virtual model.

Figure 21: Obstacle setup for virtual and physical environments. In the physical environment, a foam obstacle with the same dimensions as those in the virtual environment was attached to an electromagnet which released the obstacle at foot touchdown of the crossing leg.

List of abbreviations

AIM	Automatic identification of markers
C7	Seventh cervical vertebra
CG	Control group
cm	Centimetre
CoM	Center of mass
F	Value of F-statistic
h	Hours
HMD	Head mounted display
Hz	Hertz
IG	Intervention group
kg	Kilogram
m	Metre
m/s	Metre per second
MoS	Margin of Stability
MTP	Motion-to-Photon
p	Probability value
PBT	Perturbation-based training
SD	Standard deviation
SPM	Statistical parametric mapping
t	Value for hypothesis test statistic t-test
T1	Measurement day 1
T2	Measurement day 2
VCoM	Center of mass velocity
VE	Virtual Environment
VR	Virtual Reality
XCoM	Extrapolated centre of mass
yr or yrs	Years
η_p^2	Partial eta-squared

Table of contents

1. Introduction

Virtual reality (VR) has become increasingly popular in training human gait and balance control. It provides a safe yet challenging training environment with controlled stimulus delivery, while minimizing the need for elaborate training equipment. Studies have already used VR techniques to investigate locomotion and balance in different population groups and training settings. For VR perturbations to be useful in everyday life, it must be understood how they can be used most effectively and whether the training leads to a generalisation of the skills (transfer within limbs and from VR to physical situations). Furthermore, it is important that the skills can be maintained to achieve sustainable effects. To extend knowledge of VR training paradigms this thesis will focus on virtual reality locomotor skill adaptation, transfer and retention. The following introduction will provide a brief overview of the history of VR development and the current knowledge about balance/locomotor training in VR, including a general introduction to adaptation, transfer and retention by different training paradigms.

1.1 Virtual reality (VR)

1.1.1 VR history and technology

There are many definitions of VR but all of them have several things in common, including the aspect of a display or projection, sensory stimulation (i.e., visual, audio), and an environment. In this thesis I would like to define VR as a “computer-generated simulation of a three-dimensional environment, in which the user is able to both view and manipulate the contents of that environment” (Stampe et al. 1993). VR is a technology that has been in development for several decades, with roots tracing back to 1835 with the development of the first stereoscope by Charles Wheatstone. By using this stereoscope it was possible to arrange two images in such a way that the human brain perceived them as one 3D image. Even today, the principles of the stereoscope are still used in low-budget VR, e.g. in smartphone-based VR. Another milestone in the development of VR was Morton Heilig’s Sensorama in the mid-1950s (Figure 1). Sensorama was designed as a seated VR environment and it integrated various technologies to provide a multisensory experience. The immersive encounter comprised high-quality, full-colour 3D video, audio elements, haptic feedback, scent delivery, and wind simulation. In 1960 the first head-mounted display (HMD) was developed by Morton Heilig and in 1961 the first motion tracking HMD was invented where the image changed with head movement. In the early 1980s the first consumer VR systems were introduced, such as the VPL Research Data Glove (Figure 1), and in the 1990s VR became popular in the gaming industry, with the release of systems such as arcade machines like the Virtuality and Sega VR. However, these early systems were expensive, bulky, and often provided only low-quality experience. Despite these limitations, the technology continued to evolve, and in 2012 a new generation of VR systems emerged with the Oculus Rift and HTC Vive (Figure 1). These systems offered high-quality visuals, better tracking, and more intuitive interfaces, making them more accessible and user-friendly. These consumer devices set a new standard for quality and price, resulting in widespread adoption. As a result, VR technology is now widely available, and numerous software developers are creating VR experiences across a variety of application domains, for example health and medicine, simulation and training, engineering and construction, and education. In 2022 approximately 74 million people were using VR and it is estimated that over 120 million people worldwide will use VR in 2027 (Richter 2022).

Figure 1: Development of virtual reality (VR). Left: Sensorama (1956) [mortonheilig.com], middle: VPL DataGlove (1985) [therealmccrea.com], right: modern head-mounted display Oculus Quest 2 (2020) [meta.com]

To differentiate VR from other technologies such as augmented reality (AR), Milgram (1995) developed the Reality-Virtuality Continuum (Figure 2), which orders different realities on a continuous scale. This continuum allows for the classification of all worlds between the purely real and purely virtual as Mixed Reality.

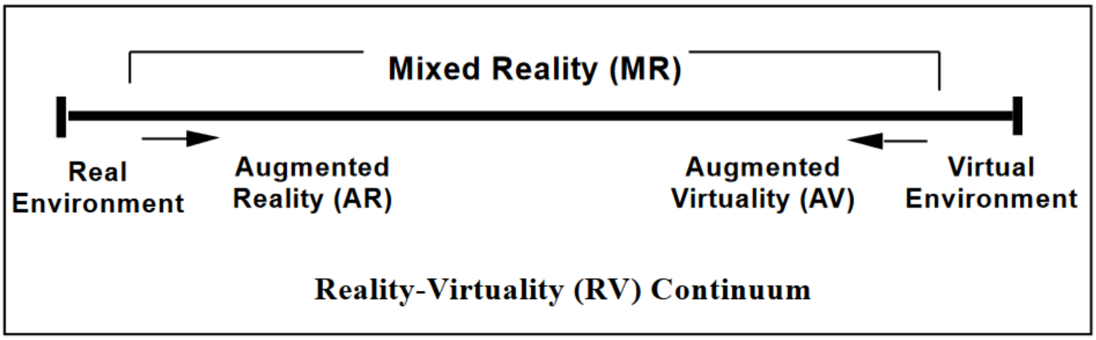

Figure 2: Reality-Virtuality Continuum (Milgram 1995)

Because of the many and varied definitions of VR, there are also many different VR technologies that lie at different points on the Reality-Virtuality Continuum. Although VR is commonly associated with HMDs, there are alternative technologies, such as smartphones, Wii, or Kinect, as well as specialized systems like the Cave Automatic Virtual Environment (CAVE) and the Computer Assisted Rehabilitation Environment (CAREN). These technologies primarily diverge in their methods of presenting the virtual environment (VE), ranging from basic displays (e.g., those found on Wii or Kinect) to HMDs to expansive projections utilized in CAVE and CAREN systems. Depending on the system and display technology used, the VR environments differ in their level of *immersion*, which is “[...] a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences” (Witmer and Singer 1998). VR systems can be categorized as fully immersive, semi-immersive, or non-immersive, depending on the degree to which they block out perception of the physical world. Fully immersive systems use 3D environments that completely exclude perception of the physical world, whereas semi-immersive and non-immersive systems allow varying degrees of perception of both the physical world and the VE. The degree of immersion plays a vital role in achieving embodied simulations and inducing a sense of presence, which is the feeling of being physically present in the VE. To increase immersion, VR systems can provide multimodal stimulus control, such as adjusting the users' field of view based on their head position (Rose et al. 2018). This allows for more realistic user-environment interactions. Accordingly, immersive VR was used to conduct all studies reported in this thesis.

The immersivity of a VR application is further dependent on the Motion-to-Photon (MTP) latency. MTP latency quantifies the temporal delay between the physical movement of a tracked object and the corresponding rendering of that movement in computer-generated images. In VR applications, high MTP latency can significantly degrade performance and can also induce cybersickness, which comes with symptoms such as nausea, dizziness, and discomfort (see Staufert et al. 2020 for a review). In the context of VR motor training, the MTP latency assumes additional importance due to its potential impact on the alignment between proprioceptive perception of a participant's own movements and the corresponding visual feedback observed in the VR environment. If there are noticeable discrepancies between the perceived and viewed movements caused by MTP latency, it can have implications for the effectiveness of motor training interventions. Studies have demonstrated that latencies exceeding 75 ms can have an impact on motor performance (Ware and Balakrishnan 1994; Waltermate et al. 2016). Previous research has proposed that there exists an optimal range of latencies for visual feedback, typically falling between 40 ms and 70 ms, although the precise optimal latency may vary depending on the nature of the motor task involved (Waltermate et al. 2015).

1.1.2 Current applications of VR

VR technology has advanced rapidly over the years, and with it the potential for a wide range of applications has emerged. One of the well-known applications for VR is the gaming and entertainment industry, where users are allowed to fully immerse themselves in virtual worlds and interact with them in ways that were previously impossible. This has opened up new possibilities for storytelling and gaming, allowing developers to create experiences that are more engaging, captivating and satisfying (Shelstad et al. 2017). The perceived interactivity, realism and spatial presence, are strong predictors of enjoyment (Shafer et al. 2011, 2014). The use of VR headsets has made gaming more exciting, and many gamers have embraced it as the future of gaming.

In addition to gaming, VR has also been used in the field of education and workforce training. Educational games refer to games that are intentionally created, implemented, and assessed to aid in the teaching or learning of a subject or specific skill within a formal or informal setting (Oyelere et al. 2017; Pavlidis and Markantonatou 2018). Several studies have demonstrated the educational advantages of VR, including its capacity to aid students with different learning styles in achieving cognitive development (Lee et al. 2010), enhancing spatial thinking (Cohen and Hegarty 2014), teaching object-oriented programming concepts (Bouali et al. 2019), and promoting collaborative learning (Greenwald et al. 2017). An example of VR workforce training is a collaborative learning game, targeted at medical trainees, to acquire the skills in triaging and treating a patient (Tsoy et al. 2019). Through simulation training inexperienced surgeons can improve their endovascular skills (Aggarwal et al. 2006) or develop spatial cognition in medical ultrasound imaging (Byl et al. 2018). Furthermore, there is an application used for training expertise in occupational hazard prevention, specifically fire safety in buildings (Diez et al. 2016). The platform simulates fires throughout a building and requires trainees to find the safest evacuation route or put out the fire. The simulated fires react to the environment and the trainee's response in real-time. VR can also be used for occupational health and safety training. For example, it can be used to raise awareness of health and safety issues amongst construction workers (Hafsia et al. 2018) and to showcase various pieces of personal protective equipment such as helmets and belts for fall protection (Plonsker 2019). The user is incentivized to choose appropriate measures for fall protection such as closing scaffold flaps, attaching cross-braces and wearing personal protective equipment.

In recent decades the architectural, engineering, and construction industry has increasingly acknowledged the potential of VR technology to create multisensory 3D environments. This technology has been particularly useful during various stages of designing, engineering, constructing, and managing the built environment (Nikolić and Whyte 2021). A major focus of VR research for the built environment is optimizing architectural design and its processes, especially design collaboration, review and building safety management. Typically, VR technology is employed in a visualization-based and experience-based scenario, allowing users to rehearse, examine, and validate construction activities and operations without exposing themselves to any risks. By pre-planning and training with VR technology, safety-related risks can be identified, and potential solutions can be selected.

In healthcare, VR can be used to help patients with phobias or anxiety disorders to confront and overcome their fears. The effectiveness of VR has been verified for example in the treatment of different phobias, panic disorder, body image disturbances, and fear of flying (Maples-Keller et al. 2017). Similarly, patients with chronic pain manage their symptoms with immersive distractions (Ahmadpour et al. 2019). VR therapy can help to treat post-traumatic stress disorder in veterans, allowing them to confront traumatic memories in a safe and controlled environment. It is anticipated that over time the patient will lose the feelings of anxiety caused by their condition (Gonçalves et al. 2012). Another VR application is rehabilitation, which aims to help patients who have experienced physical or cognitive impairments to recover their lost abilities. VR systems provide users with the ability to interact with various sensory environments and receive real-time feedback on their performance. These applications provide functional goals in virtual reality interactive games, creating a fun and engaging therapy experience that helps patients rebuild neurological pathways and achieve necessary physical workouts. Additionally, VR tools can record accurate measurements of user performance and provide greater therapeutic stimulation.

1.1.3 Distance perception in physical and virtual environments

Perception refers to the conscious sensory experience of one's surroundings. The human visual system employs various depth cues (information about the spatial relations of the objects) to perceive three-dimensional space from two-dimensional images in physical-world environments. These depth cues include occlusion, relative object size and density, height in the visual field, and aerial perspective in static settings (also known as pictorial depth cues; Cutting and Vishton 1995). In addition, distance information can be gathered from non-pictorial depth cues such as motion parallax, the oculomotor system (convergence and accommodation), and binocular disparity as a result of visual input from two eyes. Despite several proposed models for integrating depth cues, such as the linear cue combination model (Landy et al. 1995; Landy et al. 2011) or intrinsic constraint model (Domini and Caudek 2011), none of them can fully account for all empirical findings (Proffitt and Caudek 2012). Furthermore, environmental context and personal variables, such as intention and effort, can influence distance perception. For example, the perceived distance can be affected by the effort required for walking, but only when observers intend to walk the distance (Witt et al. 2004).

Although egocentric distances are accurately perceived in full-cue physical environments (Loomis and Philbeck 2008; Rieser et al. 1990), they are often underestimated by 50 – 80% in complex VEs (see Creem-Regehr et al. 2015; Renner et al. 2013 for reviews). Kenyon et al. (2007) suggested that errors in hardware, software, and human perception may contribute to this phenomenon known as "depth compression," which has been deemed "inevitable" (Jones et al. 2001). Renner et al. (2013) identified *technical*, *compositional*, and *human* factors that could impact distance estimates in VR. *Technical factors* include hardware limitations like restricted field of view, weight of the head-mounted display, distortions of the stereoscopic image, missing but also distorted non-pictorial depth cues and limitation in the number of depth cues (Buck et al. 2018; Hornsey and Hibbard 2021; Kelly 2022). Perspective cues like linear perspective, foreshortening, and texture gradient have been shown to improve distance perception (Surdick et al. 1997). *Compositional factors* refer to the features of the VE, such as the presence of avatars or floor texture. It has previously been proposed that adding an avatar to a VR environment presented through a head-mounted display enhances the sense of presence and improves distance perception (Mohler et al. 2010; Phillips et al. 2010; Ries et al. 2009). *Human factors* cover psychological characteristics, such as individual differences between users and changes in perception through adaptation.

Distance estimates can improve over time without feedback (Jones et al. 2012), and familiarization with the VE before a task has been suggested to correct distance perception (e.g. Altenhoff et al. 2012; Waller and Richardson 2008). However, the transferability of training effects to physical environments is crucial for most VR applications. The carry-over effect (users perceive reality differently after adapting to a VE) can limit the usefulness of feedback and practice in VR (Altenhoff et al. 2012; Witmer and Sadowski 1998). Carry-over effects can persist for at least several minutes in the absence of feedback in the physical environment (Waller and Richardson 2008). However, when users get feedback in their interaction with the physical environment the carry-over effects will disappear faster.

In contrast to the extensive work on egocentric distance perception in VEs, there is relatively limited work on absolute size perception in VEs in comparison to physical-world size estimates. Regardless of the type of perceptual information (Vision-only, Haptics-only, Vision and Haptics) size is overestimated in the VE (Siqueira et al. 2021). The strength of the overestimation of height and length depends on the design of the VE and the amount of visual cues (Park et al. 2021). Luo et al. 2007 showed that scene complexity and stereovision could have a significant impact on judgments on the size of virtual objects. Furthermore field of view, image resolution, scene contrast and target distance can influence the perception of size in VR (Eggleston et al. 1996).

1.2 Locomotor adaptations to perturbations

Walking in daily life often represents challenges for the human neuromotor system due to variations in terrain such as uneven surfaces and obstacles. Therefore effective locomotor adjustments are required to reduce fall risk, both feedforward- (Bhatt et al. 2006; Bohm et al., 2012) and feedback-driven (Bierbaum et al. 2011; Pai et al. 2003). Incidence of falls increases with age (Peden et al. 2002). However, falls generally, and those associated with tripping over obstacles, also occur frequently among younger and middle-aged adults during leisure activities and work-related tasks. In fact, about one in five work-related accidents internationally are attributed to falls (Bureau of Labor Statistics, 2019; Eurostat, 2019). Obstacle-induced trips have been recognized as a factor frequently contributing to falls in the elderly population (Berg et al. 1997; Blake et al. 1988; Overstall et al. 1977). These accidents can result in severe injuries, leading to hospitalization and significant associated costs on health insurance systems (Florence et al. 2018). Furthermore, individuals who experience long-lasting impairments due to such accidents may also face a reduced quality of life (Talbot et al., 2005). Given these circumstances, there is a pressing need to develop and implement training programs aimed at enhancing individuals' ability to prevent falls and navigate obstacles safely.

Perturbation-based training (PBT) is a type of balance training that utilizes sudden, unpredictable disturbances or perturbations to stimulate rapid postural responses that, to some extent, restore balance. In this thesis, PBT is defined as a type of balance training that employs repeated perturbations to elicit postural responses and restore stability. The primary aim of PBT is to enhance the ability to recover from destabilizing situations that can lead to falls in daily life. During PBT, external perturbations are applied repeatedly to challenge the individual’s balance control system (Mansfield et al. 2015). These perturbations can be delivered in various ways, such as through the use of treadmill acceleration/deceleration, cable-pulls, movable platforms, obstacles and visual perturbations (Grabiner et al. 2012; König et al. 2019; Okubo et al. 2019). Motor adaptations can be induced by predictive or reactive training approaches. Predictive adaptation uses anticipatory mechanisms to adjust locomotor output e.g. by weight shifting, thereby reducing the magnitude of recovery responses needed (Carty et al. 2015). Conversely, reactive adaptation refers to a modification in motor responses to unexpected perturbations, leading to neuromechanical reorganization that induces e.g. faster recovery initiation or rapid stepping responses. PBT differs from traditional balance training, which typically involves static or predictable exercises, in that it requires the individual to react rapidly to sudden perturbations, thereby improving the ability to respond to unexpected balance challenges.

To operate PBT, treadmill paradigms are frequently employed to facilitate gait adaptation and its investigation. The appeal of treadmills stems from the ability to establish controlled conditions, such as regulation of gait velocity, and the convenience of presenting a large number of perturbations within a comparatively small space. Nevertheless, it is important to consider the limitations associated with treadmill training. For instance, participants are required to continue walking even after experiencing a perturbation, which may not mimic real-life scenarios when stopping or adjusting one’s gait pattern is necessary. In addition, differences exist between treadmill and overground walking (in visual flow for example), which leads to differences in gait characteristics (Hollmann et al. 2015). Such differences need to be considered when interpreting and applying findings from treadmill-based studies to natural walking environments. The subsequent sections provide comprehensive insights into three crucial aspects of perturbation training, namely mechanical perturbations, VR perturbations, and obstacle crossing perturbations.

1.2.1 Mechanical perturbations

Mechanical PBT has been shown to be an effective intervention for improving balance control and reducing the risk of falls in older adults and individuals with neurological conditions (see Gerards et al. 2017; Mansfield et al. 2015; McCrum et al. 2022 for reviews). There is evidence that a single session of repeated mechanical perturbations can facilitate rapid acquisition (i.e. in three to five trials) of fall-resisting skills across diverse age groups and tasks (Bhatt and Pai 2008; McCrum et al. 2016). Enhancements in the ability to recover from destabilizing perturbations are linked to modifications in proactive and reactive regulation of postural stability. These alterations include the anterior repositioning of the body’s center of mass (by, for example, changing trunk angle and velocity), as well as enhancing limb support (length and velocity of recovery step), resulting in more effective recovery stepping responses (Mansfield et al. 2010; Shimada et al. 2004; Pater et al. 2015). Participating in one or multiple sessions of PBT can decrease the occurrence of falls in everyday situations in both healthy and frail/pathological older adults over a period of one to twelve months (see Gerards et al. 2017 for review).

Humans have the ability to rapidly adjust their gait patterns in response to environmental changes in ways that are both reactive (König et al. 2019; McCrum et al. 2018) and predictive (Michel et al. 2008; van Hedel and Dietz 2004). Various factors influence motor adaptation, such as the amount of practice, type of feedback, and variability and specificity of practice (Fonseca et al. 2012; Song 2019; Matsuda and Abe 2023). Although learning improves with an increase in the number of practice trials, the law of practice indicates that the effect is most significant during the early stages of learning and diminishes over time (Schmidt and Lee 2011). Performance feedback, which is a process that provides individuals with information about their task performance, is a critical aspect of motor learning and can facilitate the adaptation and improvement of motor skills. It can be obtained from internal or external sources and can involve various sensory modalities such as visual or auditory input (Schmidt and Lee 2011; Magill 2011). Numerous studies have demonstrated that in addition to receiving external feedback, adopting an external focus of attention, where individuals direct their attention to the external effects of their movements, rather than their own body movements, can significantly improve learning outcomes (Shea and Wulf 1999; Pascua et al. 2015; Wulf 2013). In contrast, an internal focus of attention may interfere with the automatic control processes regulating movement. By adopting an external focus of attention, the motor system can self-organize naturally, resulting in more efficient movement patterns.

Motor training should not solely focus on promoting immediate performance improvements but should also aim to ensure long-term learning by facilitating transfer and retention of skills. Skills acquired in one locomotor task or environmental condition can often be transferred to another task or condition (Bieryla et al. 2007; Long et al. 2015; Torres-Oviedo and Bastian 2010). Interlimb transfer is another relevant component of research on motor learning. This involves the transfer of enhanced performance on a unilateral motor task to the opposite untrained limb (Poh et al. 2016; Ruddy and Carson 2013). This type of transfer is beneficial because it can reduce the overall duration of training and represents the generalization of skill learning (Ruddy and Carson 2013).

The magnitude of interlimb transfer can be affected by multiple factors including age, the duration of training, and the type of task being practiced (Carroll et al. 2016; Joiner et al. 2013; Krishnan et al. 2018; Stöckel and Wang 2011; Wang et al. 2011). Earlier studies have emphasized the importance of visual feedback in facilitating interlimb transfer and generalization of visuomotor adaptation in manual tasks (Cohen 1973; Taylor and Ivry 2013). Optimizing performance through feedback may also optimize transfer performance (Krishnan et al. 2018; Swinnen et al. 1997). Malfait and Ostry 2004) proposed that awareness of perturbations can facilitate interlimb transfer. Studies by van Hedel et al. (2002) and Kloter and Dietz (2012) on mechanical obstacle avoidance showed that explicit performance feedback, contributing to task awareness, can lead to interlimb transfer. In contrast, studies by McCrum et al. (2018) and Bhatt et al. (2008) on tripping and slipping training (respectively) that did not provide feedback about performance only observed partial interlimb transfer. Overall, previous research supports Malfait and Ostry’s (2004) view that awareness of perturbations may facilitate interlimb transfer. However, some subsequent studies, such as the ones conducted by Wang et al. (2011) and Lefumat et al. (2015), have not been able to replicate the findings of Malfait and Ostry (2004). These contrasting results suggest that the relationship between awareness and interlimb transfer may not be straightforward or may be task dependent, and further research is needed to clarify the issue.

The neuromotor system can adapt and learn to cope with destabilizing situations through repetitive exposure to perturbations (Pai et al. 2014). These acquired adaptations have the potential to provide long-term prevention against falls. In research settings, retention of locomotor skills over prolonged time periods is often examined after adaption to external perturbations or conditions, such as trip-like perturbations (König et al. 2019; McCrum et al. 2016), tracking tasks (Krishnan et al. 2018) but also in VR based training (Kim et al. 2019). In a study by Krishnan and colleagues (2018), participants were instructed to accurately match target hip and knee trajectories during the swing phase of gait. The reduction in tracking error achieved through practice was retained after 24h (Krishnan et al. 2018). Previous studies on mechanical PBT with older adults have shown that the neuromotor system exhibits high plasticity in response to repeated unexpected perturbations, and these adaptations can be retained over a prolonged period, up to approximately 1.5 years (Epro et al. 2018). The use of mechanical perturbation was found to have long-term effects with low training volume, reducing subsequent risk of fall injury (Epro et al. 2018).

1.2.2 Virtual reality perturbations

Simulation techniques such as VR have increasingly been used in training research and for the development of training programs. This is due to easy access to physical training using VR and greater flexibility of training programs in terms of location, time and content. The realistic context of training scenarios may result in possibilities for the implementation of training content in clinical and research settings (see Delgado and Der Ananian 2021 and Juras et al. 2019 for reviews). The main advantage of using VR for locomotion training is that it allows individuals to practice and improve their skills in a safe, controlled environment. Due to the automated nature of many virtual systems, tasks can be consistently repeated with ease, and adjusted with respect to training intensity and volume (Adamovich et al. 2009; Lange et al. 2012; Weiss and Katz 2004). Additionally, Ves may decrease the perception of exertion (Thornton et al. 2005) and motivate users to engage in more repetitions or longer practice durations compared to traditional exercises (Holden 2005). VR can also provide feedback and data can be used to monitor progress and adjust training responsively (e.g. to include different levels of difficulty and complexity).

VR training has shown promising results in enhancing motor learning (for example, gait quality) for individuals with neurological disorders such as stroke, Parkinson’s disease or multiple sclerosis (Bohil et al. 2011; Canning et al. 2020; Jaffe et al. 2004; Mirelman et al. 2020; Peruzzi et al. 2016). VR technology has facilitated the creation of various training programs that are relevant and effective for locomotor and balance training, benefiting not only individuals who are neurologically or physically impaired, but also healthy individuals.

VR environments can be manipulated in ways that are impossible in the physical world. This can be realized for example by changing visual flow or creating challenging walking conditions through virtual snowfall, pets suddenly crossing walkways or simulating fall scenarios, such as slipping on a wet surface, tripping over an obstacle, or losing balance on a narrow surface (Parijat et al. 2015a; Nyberg et al. 2006; Peterson et al. 2018; Giotakos et al. 2007). Such training programs can reduce fear of falling in the elderly population (Giotakos et al. 2007).

Participants exhibit more cautious walking behaviour in VE compared to the physical world. This was indicated by a decrease in gait speed, shorter strides, longer double support, and higher step width (Parijat et al. 2015b; Menegoni et al. 2009; Riem et al. 2018; Peterson et al. 2018). It can be inferred that simply walking in a VE, without any virtual perturbations, poses a challenge to gait stability and coordination. However, the integration of virtual perturbations, such as medio-lateral or anterior-posterior tilting of the virtual environment during walking in virtual reality, has been shown to enhance gait and coordination parameters (Menegoni et al. 2009; Peterson et al. 2018). Transient visual perturbations can be used to simulate slipping while walking, allowing for safe training and assessment of user responses.

Training in VE has been shown to produce comparable results to training programs with a movable platform in fall interventions (Liu et al. 2015). While both environments had similar effects in reducing fall frequencies, differences in body motion were observed between the two environments. In conventional moveable platform slip training, the first response utilizes the lower extremities, followed by hip and trunk responses. However, virtual slips first cause a reaction in the upper body, followed by the lower extremities. Thus, although recovery actions appear superficially to be comparable between the moving platform and VE (Liu et al. 2015), differences in component movement order indicate different compensatory strategies. While visual perturbations directed medio-laterally elicit greater balance responses than perturbations directed along the anterior-posterior axis (Martelli et al. 2019), the latter do elicit reactive and proactive adjustments. Even without training in physical situations, the adaptations led to reductions in fall rates when transferred to physical slip situations (Parijat et al. 2015a, 2015b). If this training program can demonstrate prolonged retention and be implemented in physical-world settings such as rehabilitation or prevention centres, it could mitigate the risk of severe accidents.

The above-mentioned studies mostly focus on training reactions to slip situations by rotating the VE. However, it is also important to train fall-resisting skills in situations involving tripping. Therefore VE has also been used to train obstacle avoidance, for which participants occasionally cross virtual obstacles while walking through a virtual corridor (Kim et al. 2019). This study involved providing feedback to participants in the form of pleasant or unpleasant sounds depending on the distance between their foot and the obstacle after each crossing, thereby encouraging the user to cross the obstacle as close as possible. The study reported successful reduction in foot clearance, transfer of reduced foot clearance to physical obstacles, and retention over 24 hours (Kim et al. 2019). Unfortunately, this study only focused on toe clearance and did not investigate dynamic stability control. Participants were instructed to hold lightly onto a handrail while walking on the treadmill, which clearly has a direct effect on dynamic balance control. Furthermore, the virtual obstacles appeared far away, making the task highly predictive and giving the participants time to adjust their gait cycle.

While previous studies have demonstrated that VR-based perturbations may represent a cost-effective method for locomotor training, the development of comprehensive and reliable training programs still present significant challenges in this context. It should be aimed to improve the effectiveness of VR training programs with investigation of gait stability and gait coordination in situations for which the virtual perturbation arrives unexpectedly. Furthermore, transfer of training effects to real life situations and long-term retention should be investigated.

1.2.3 Obstacle crossing perturbations

Compared to perturbation-based balance training, which focuses on reactive responses to tripping, obstacle avoidance training aims to prevent tripping altogether by addressing the protective mechanisms in human gait. Human gait is a complex motor task that requires precise coordination between different muscle groups and joint movements. One of the challenges of walking is avoiding obstacles, which often requires rapid adjustments in gait to prevent tripping and falling. Just walking over a zero-thickness tape on the ground increases foot clearance and reduces translation speed compared to walking without obstacles (Chen et al. 1991). As the height of the obstacles increases, foot clearance also increases and crossing speed becomes lower (foot clearance and crossing speed correlate with obstacle height; Chen et al. 1991). In addition to obstacle height, obstacle width also influences crossing patterns (Patla et al. 1991). It has been suggested that there are two main obstacle avoidance strategies: first, elevation of the ipsilateral pelvis (hip joint) which biases the swing limb trajectory; and second, increased swing limb flexion to elevate the limb as an obstacle is crossed (Patla et al. 1991). The choice of which strategy or combination of strategies to use depends on the reaction time (i.e. the time from seeing the obstacle to crossing it) and obstacle height (Patla et al. 1991). Crossing an obstacle during walking requires coordinated movements of multiple joints, particularly precise control of the swinging foot and coordination between the stance and swinging limbs, but also arm coordination (Kloter and Dietz 2012; Michel et al. 2008; Yen et al. 2009). During this movement, the body’s center of mass must be balanced over one foot while the other foot crosses the obstacle by swinging forward. Older adults increase the motion of their body center of mass (CoM) in the medio-lateral direction, suggesting a compensatory adjustment of the swinging limb to counterbalance perturbations in the frontal plane (Chou et al. 2003).

When approaching an obstacle, step planning involves optimizing the movement of one’s CoM and various body segments, e.g. the foot (Yamagata et al. 2020; Yiou et al. 2016) to ensure a smooth traversal with minimal disruption. Typically, young adults begin adjusting their foot placements two steps prior to crossing the obstacle (and older adults three steps) as evident through changes in step length (Chen et al. 1994). The final placement of the trailing leg, just in front of the obstacle, demonstrates the least variability and is consistently positioned at a fixed horizontal distance of approximately 25 cm between the front edge of the foot and the front edge of the obstacle (Patla et al. 2004). This behavioural strategy is believed to help in avoiding contact with the obstacle.

Complex cognitive processes, such as executive function, attention, visuospatial processing and motor planning must be employed in obstacle crossing (Chen et al. 2017; Mirelman et al. 2017; Yogev-Seligmann et al. 2008). To successfully navigate obstacles while walking, individuals typically rely on their visual, vestibular, and other sensory systems to assess the obstacle and adjust their gait accordingly (Galna et al. 2009; McFadyen et al. 2007; Reynolds and Day 2005). The role of vision in obstacle crossing is of paramount importance. Visual exteroceptive information is utilized to ascertain key attributes of the obstacle, such as its dimensions, location, and solidity, while exproprioception input regarding the body's position in relation to the surroundings is also crucial. Research on visual field manipulation has demonstrated that on-line visual exproprioceptive information is utilized to refine the trajectory of the lower limbs during obstacle avoidance while visual exteroceptive information may primarily contribute to feedforward control (Rhea and Rietdyk 2007). Furthermore, visual information derived from optic flow, is crucial for accurate foot positioning with respect to the obstacle during the approach phase (Menuchi and Gobbi 2012).

Research investigating obstacle avoidance has provided insights into the role of visual fixation during different phases of the process. Regarding the approach phase, studies have observed visual fixations on the obstacle itself (Patla and Vickers, 1997) or the area behind the obstacle, indicating the initiation of limb movement for obstacle crossing (Di Fabio et al. 2003). However, it has been found that peripheral vision is sufficient for successful obstacle crossing itself, as fixation is directed towards the landing area (Patla and Vickers 1997; Marigold et al. 2007). Alternatively, fixation is in a forward-looking direction (Di Fabio et al. 2003), rather than on the obstacle, during the actual crossing phase. Consequently, peripheral vision, which captures the sudden appearance of an obstacle in the path of travel, is adequate for successful avoidance of the obstacle, and visual fixation is generally not redirected towards either the obstacle itself or the landing area (Marigold et al. 2007).

Obstacle avoidance training is a form of gait training that aims to improve ability to cross obstacles by teaching people how to adjust their gait patterns to reduce the risk of tripping. By repeatedly practicing obstacle avoidance, humans can adjust their locomotor commands and use lower toe clearance to decrease active musculature in the lower extremities. This leads to more efficient obstacle crossing, but also lowers the safety margin (Kloter and Dietz 2012; Michel et al. 2008). A typical crossing strategy and changes in hip, knee and ankle angle over repeated obstacle crossing can be seen in Figure 3. Studies have shown that these adaptive changes in the lower extremities can be partially transferred to other walking conditions (e.g. downhill walking, walking with weighted legs; Lam and Dietz 2004) and to the untrained leg if participants were informed of the change in limbs and received explicit feedback about their performance during training (Kloter and Dietz 2012; van Hedel et al. 2002).

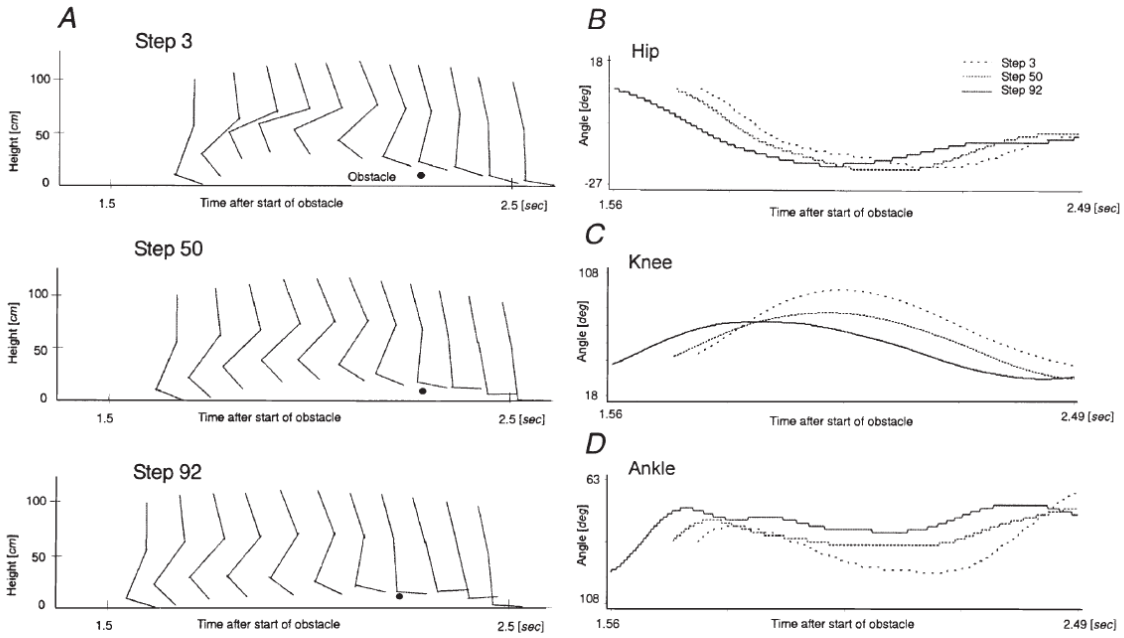

Figure 3: Stick diagrams of the right leg while stepping over the obstacle (A), and hip (B), knee (C) and ankle (D) joint movements during step 3, 50 and 92 over the obstacle (i.e. swing phase of the right leg) [Erni and Dietz 2001].

2. Aims of the dissertation

The use of VR training paradigms to stimulate motor adaptations has become increasingly common and it shows great potential for enhancing motor skill acquisition. Transferring and retaining the skills acquired in the virtual world to the physical world are crucial for enhancing locomotion and daily life activities. However, physical world transfer and retention of VR locomotor skills has rarely been investigated.

This thesis therefore examined the effects of a VR obstacle crossing training on locomotor adaptations, retention and transfer between limbs and to the physical world. The **first study** investigated locomotor skill adaptations to crossing 50 unexpectedly appearing virtual obstacles with one limb and its interlimb transfer to the untrained limb (one obstacle). We hypothesised a progressive adaptation in locomotor kinematics with a nonlinear relation between practice dose and response and that the learned skills can be transferred from trained to the untrained limb. In the **second study** we elaborated on adaptation with repeated practice and on interlimb transfer by examining the influence of feedback and awareness of limb change. We hypothesised that providing participants with additional feedback about their performance while crossing obstacles and awareness about limb change would promote adaptive changes in locomotion kinematics and enhance transfer. The **third study** investigated transfer of the learned locomotor skills from virtual to physical environments and its retention over one week in the virtual and physical environment. We hypothesised that after a single session of VR-based obstacle avoidance training, participants would exhibit adaptive changes in human locomotion, including a modulization in lower extremity joint kinematics and a reduced toe clearance over obstacles. We expected that adaptive changes stimulated via repeated VR obstacle crossing would be transferred to physical obstacle conditions and could be retained in both VR and physical environments after one week.

The three studies conducted are presented separately in the following chapters in the format submitted to the corresponding journal but with the citation style amended to the format of this thesis, following permission granted by the respective journal.

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

Journal of Biomechanics (2021, v. 120, p. 110357 DOI: 10.1016/j.jbiomech.2021.110357)

3.1 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.

3.2 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 VR have found increasing popularity and use in training of human gait and balance control (Canning et al. 2020; Mirelman et al. 2020). A 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; Stöckel 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.

3.3 Methods

3.3.1 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).

3.3.2 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 x depth 0.1 m x width 0.5 m) with their right leg (see Figure 4A). 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 (Figure 4A). 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.

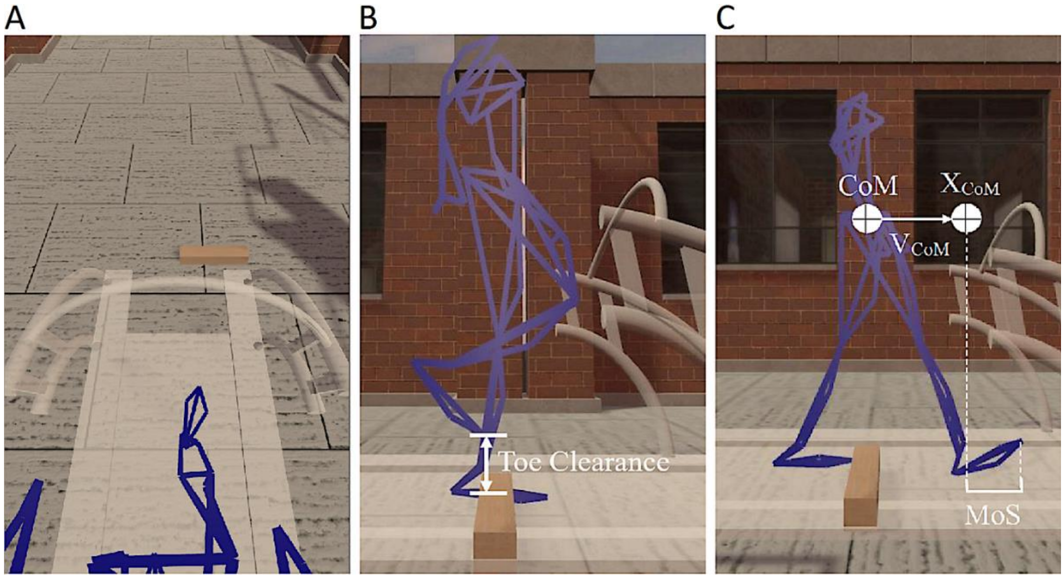

Figure 4: Virtual environment (VE) consisting of an endless corridor with a 3D model of the treadmill and an avatar representing the participant. The avatar represents the connections between markers on anatomical landmarks of the participant. (A) Perspective of the participant when the obstacle appears 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 (XcoM) adapted from Hof et al. (2005). Center of mass (CoM) is defined as the average position of the four pelvis markers and CoM velocity (VcoM) is calculated as the mean of the first derivatives of the CoM position and C7 position, plus the treadmill belt speed.

3.3.3 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 (Figure 4B). 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 (XcoM; adapted from (Hof et al. 2005) for each touchdown of the obstacle stepping limb (Figure 4C). All calculations were performed using a customized routine written in MATLAB (version 9.3.0, The Mathworks Inc, Natick, MA, USA).

3.3.4 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, XcoM 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.

3.4 Results

Figure 4 shows changes in toe clearance (Figure 5A) and MoS (Figure 5B) 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).

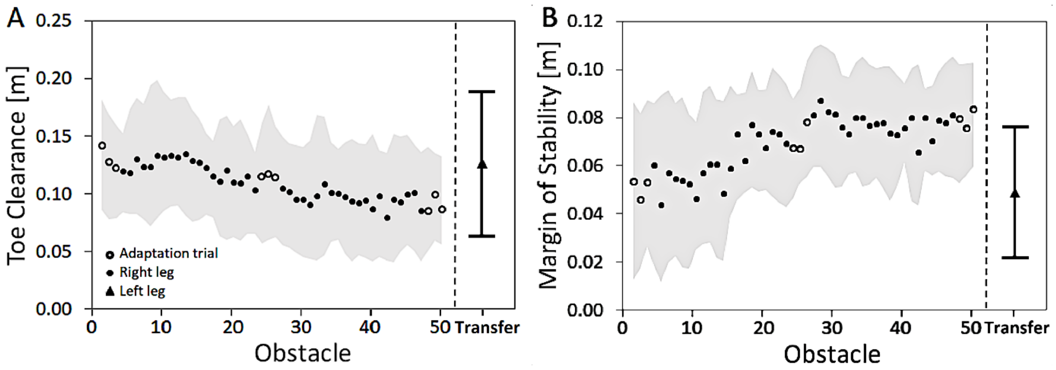

Figure 5: (A) Toe Clearance and (B) Margin of Stability for crossing obstacles 1 to 50 with the right leg presented as means (circles) with standard deviations (shaded) for all participants. Obstacles used to investigate adaptation (early, mid and late) are presented as open circles. The black triangle 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.

The repeated measures ANOVA revealed statistically significant differences in toe clearance over repeated practice [$F(3, 30) = 3.35$; $p = 0.032$, $\eta_p^2 = 0.251$]. 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; Figure 6A). For BoS, a significant main effect was found [F(3, 24) = 3.28; p = 0.038, $\eta_p^2 = 0.291$]. 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 XcoM [F(3, 24) = 2.30; p = 0.102, $\eta_p^2 = 0.214$], 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, $\eta_p^2 = 0.424$]. 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; Figure 6B). The single trial of the untrained leg resulted in values of 0.13 ± 0.07 m (toe clearance), 0.53 ± 0.05 m (XcoM), 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 Figure 6).

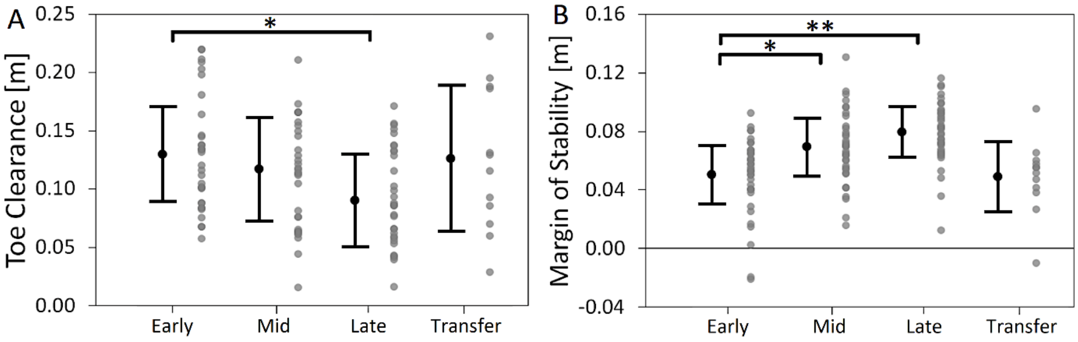

Figure 6: (A) Toe Clearance and (B) Margin of Stability at early (obstacles 1-3), mid (obstacles 24-26) and late adaptation phases (obstacles 48-50) and for the single trial of the untrained leg (transfer). Values are expressed as means ± standard deviations of the 12 analyzed subjects, along with data values for all analyzed obstacles (grey dots). Tukey post hoc tests revealed

statistically significant differences compared to early phase (* $p < 0.05$, ** $p < 0.001$).

3.5 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 XcoM, 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 (Kloter and Dietz 2012; van Hedel and Dietz 2004) 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 and Bhatt and Pai 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.

3.6 Acknowledgements

A scholarship grant from the German Social Accident Insurance (DGUV), Germany, for the first author (A.W.) is gratefully acknowledged.

4. Second study: Enhancement of awareness through feedback does not lead to interlimb transfer of obstacle crossing in virtual reality

Journal of Biomechanics (In Press, DOI: 10.1016/j.jbiomech.2023.111600)

4.1 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 ± 2.7 cm to 4.6 ± 1.7 cm for the trained leg and from 6.8 ± 3.0 cm to 4.4 ± 2.0 cm ($p < 0.05$) 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.

4.2 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 and Dietz 2001; Lam and Dietz 2004; van Hedel and Dietz 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 and Dietz 2012; Michel et al. 2008). 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 and Der Ananian 2021; Kim et al. 2019; Weber et al. 2021). However, contrary to the findings of an obstacle crossing paradigm in the physical world (Kloter and Dietz 2012; van Hedel et al. 2002), 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 and Ivry 2013). Additionally, it has been suggested that optimizing performance via feedback can lead to improved transfer performance (Krishnan et al. 2017; Krishnan et al. 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 (Kloter and Dietz 2012; van Hedel et al. 2002). 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.

4.3 Methods

4.3.1 Participants

Thirteen healthy young adults (7 males, 6 females; age 22.7 ± 1.4 yr; body height 175 ± 9 cm; body mass 73.1 ± 9.6 kg; 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).

4.3.2 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 1.3 m/s. The training consisted of crossing 50 unilateral virtual obstacles (height 10 cm × depth 10 cm × width 50 cm) appearing at touch-down, 80 cm 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; 120 Hz, 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 (Figure 7). 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.

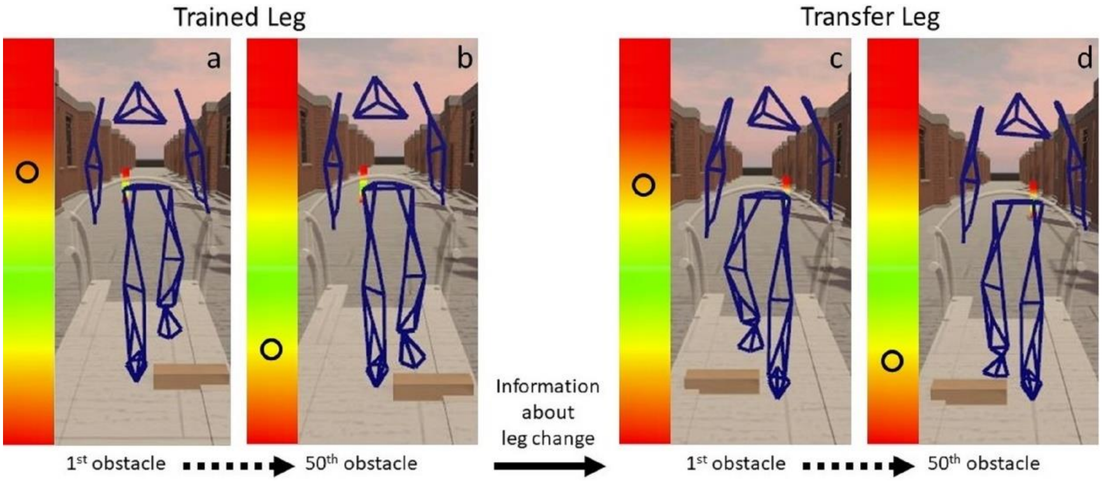

Figure 7: Experimental design, feedback and awareness procedure. Feedback was provided using a color scale with black open circle showing the position of the target area. Back view of the environment containing a corridor, a model of the treadmill, avatar of the participant, virtual obstacle and visual 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.

4.3.3 Data processing

Three-dimensional coordinates of markers from motion capture were filtered using a low-pass second-order zero-phase Butterworth filter with a 12 Hz 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).

4.3.4 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, https://www.spm1d.org) in MATLAB, with α set at 0.05. All results in the text are presented as mean ± standard deviation.

4.4 Results

4.4.1 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 (**Figure *8***). 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; **Figure *8***]. Toe clearance decreased over repeated training between early and late adaptation (from 7.84 ± 2.74 cm to 4.56 ± 1.67 cm; p = 0.005) and between early and mid adaptation (values for mid adaptation, 5.27 ± 2.11 cm; p = 0.013) but there was no significant difference between mid and late adaptation (p = 0.185; **Figure *8***).

4.4.2 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 (**Figure *8***). 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; **Figure *9***) 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 ±

3.04 cm and 4.35 ± 2.03 cm; p = 0.044) and between early and mid adaptation (mid values, 4.93 ± 2.04 cm; p = 0.016) but there was no significant difference between the mid and late adaptation (p = 1.00; **Figure *8***). 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).

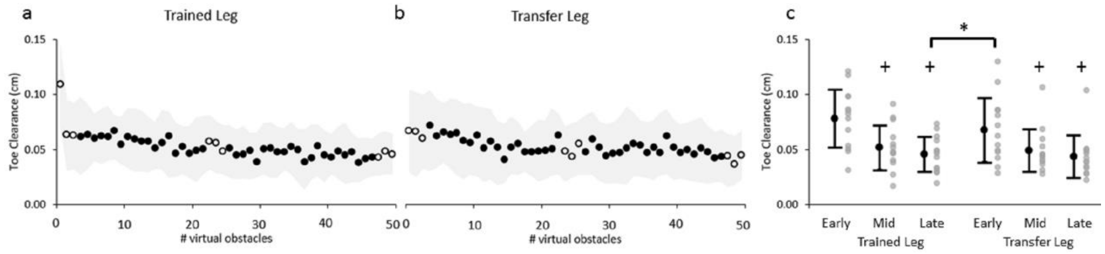

Figure 8: Adaptation of toe clearance for (a) trained leg and (b) transfer leg for obstacle crossing. Circles present mean values and grey shading presents standard deviations for all participants. Obstacles used to investigate adaptation (early, mid and late adaptation) are presented as white circles. (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).

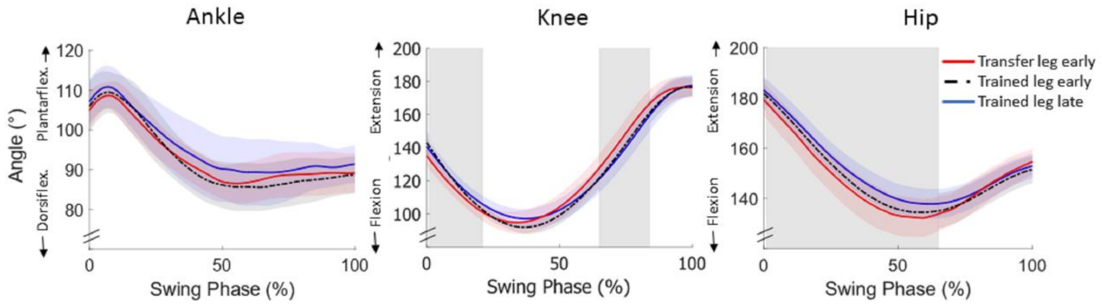

Figure 9: Sagittal plane ankle, knee and hip joint angle trajectories of the crossing leg during swing phase for early and late adaptation trained leg and early adaptation transfer leg as means and standard deviations (blue and red shadings respectively) for VR obstacle crossing. Grey areas indicate 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).

4.5 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 is 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 ± 2.01 cm vs 11.69 ± 7.20 cm, 50th: 4.55 ± 1.92 cm vs. 8.96 ± 4.18 cm) while baseline performance did not differ (1st: 12.49 ± 10.55 cm vs. 14.21 ± 5.01 cm). 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 (**Figure *8***). 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 and Dietz 2012; van Hedel et al. 2002) and others did not (e.g. Bhatt and Pai 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; Stöckel 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.

4.6 Acknowledgements

A scholarship grant from the German Social Accident Insurance (DGUV) for the first author (A.W.) is gratefully acknowledged.

5. Third study: Limited transfer and retention of locomotor adaptations from virtual reality obstacle avoidance to the physical world

Scientific Reports (2022, v. 12, p. 19655, DOI: 10.1038/s41598-022-24085-w)

5.1 Abstract

Locomotor training based in virtual reality (VR) is promising for motor skill learning, with transfer of VR skills in turn required to benefit daily life locomotion. This study aimed to assess whether VR-adapted obstacle avoidance can be transferred to a physical obstacle and whether such transfer is retained after one week. Thirty-two young adults were randomly divided between two groups. A control group (CG) merely walked on a treadmill and an intervention group (IG) trained crossing 50 suddenly-appearing virtual obstacles. Both groups crossed three physical obstacles (transfer task) immediately after training (T1) and one week later (T2, transfer retention). Repeated practice in VR led to a decrease in toe clearance along with greater ankle plantarflexion and knee extension. IG participants crossed physical obstacles with a lower toe clearance compared to CG but revealed significantly higher values compared to the VR condition. VR adaptation was fully retained over one week. For physical obstacle avoidance there were differences between toe clearance of the third obstacle at T1 and the first obstacle at T2, indicating only partial transfer retention. We suggest that perception-action coupling, and thus sensorimotor coordination, may differ between VR and the physical world, potentially limiting retained transfer between conditions.

5.2 Introduction

Given uneven ground, slippery surfaces, or obstacles blocking the way, walking in everyday life is somewhat challenging. In this context, the neuromotor system must be able to adapt its motor strategies to cope with such external variations. Falls and their physical (Burns and Kakara 2018) and economic (Florence et al. 2018) consequences may be reduced if means can be found to enhance locomotor skills through training. Perturbation-based balance training aims to reduce the number of falls and resulting severe consequences through participant experience of repeated, unexpected slip- or trip-like perturbations to gait, enhancing predominately reactive balance response (Gerards et al. 2017; Karamanidis et al. 2020). These paradigms incorporating perturbation-based balance training have been used for many years to improve postural control mechanisms (e.g. increasing base of support) and reduce the likelihood of falls (Karamanidis et al. 2020; Mansfield et al. 2015). In contrast to perturbation-based balance training which focuses on reactive locomotor adaptations during tripping, obstacle avoidance training is about avoiding tripping as such and thus addresses protective mechanism in human gait. It has been shown that humans adjust their locomotor commands with repeated practice of obstacles avoidance and use a lower toe clearance aimed at reducing active musculature in the lower extremity (Kloter and Dietz 2012; Michel et al. 2008) and hence potentially reduce muscle mechanical work at a cost of a lower safety margin. Moreover, it has been shown that these adaptive changes at the lower extremity can be partly transferred to the untrained leg (Kloter and Dietz 2012; van Hedel et al. 2002). However, the methods used for the assessment and training paradigms targeting adaptations and transfer of locomotor skills usually require complex mechanical devices that may not only be expensive but also restrict use to dedicated locations. An alternative paradigm mitigating the complexity of instrumentation mentioned above relies on perturbations induced using virtual reality (VR). Research has previously shown that VR-based training using visual perturbations can produce compensatory adaptations that prevent injuries due to slips, trips, and falls, without the need for other perturbation devices (see Delgado and Der Ananian 2021 for a review). Use of visual perturbations (e.g. tilting the virtual environment) has led to adaptations in spatiotemporal gait parameters (Martelli et al. 2019; Osaba et al. 2020; Parijat et al. 2015a), muscle activity and kinematic responses (Martelli et al. 2019). Those findings indicate a promising effect of VR-based training of adaptation of stability control.

Effective learning and adaptation is often associated with characteristics of transfer and retention. Previous studies of mechanical slip- and trip-perturbations have shown a partial retention over several weeks or even years, whereas demonstrating transfer has been more challenging (e.g. (Karamanidis et al. 2020; Liu et al. 2021; McCrum et al. 2018; Rieger et al. 2020). Skill transfer may be particularly challenging for VR-based training as learned skills have to be transferred between quite different worlds (virtual and physical). It is known that egocentric distance judgments are limited in virtual environments (see Renner et al. 2013 and Creem-Regehr et al. 2015 for reviews) potentially leading to different perception-action coupling, which would impede the transfer to the physical world. Until now, few studies have investigated transfer and retention of VR skills for gait and balance training. Parijat et al. 2015a demonstrated that slip-like compensatory movements (both proactive and reactive) learned by tilting virtual environments can be applied to physical world conditions. Similarly, VR-based obstacle avoidance training studies found that improved skills can, at least partially, be transferred from virtual to physical obstacles (Kim et al. 2019; LoJacono et al. 2018). However, no transfer was found from one leg to the other (Weber et al. 2021). To our knowledge, only one study investigated retained transfer of learned skills from virtual- to physical world contexts (Kim et al. 2019), and this over a short 24h period. In this study participants performed 40 VR-based obstacle avoidance trials before retention to physical obstacles was assessed. As retained transfer was tested after VR retention it cannot be excluded that the additional practice trials affected outcome measures for the physical obstacles.

The purpose of our study was to examine whether and to what extent a learned locomotor skill can be transferred from virtual to physical environments and whether such skills are retained in virtual and physical environments over one week. We used the paradigm of training obstacle crossing during treadmill walking in order to assess locomotor adaptation, transfer and retention phenomena in highly controlled and reproducible tasks. We hypothesized that a single session of VR-based obstacle avoidance training would lead to adaptation in locomotor behavior (i.e. lower obstacle toe clearance and changes in joint kinematics), that these refinements would be transferred to a physical obstacle condition and at least partially retained for VR and physical obstacle conditions.

5.3 Methods

5.3.1 Participants and experimental design

Thirty-two healthy young adults (sixteen males, sixteen females; age 22.7 ± 1.8 yr; height 177 ± 10 cm; mass 73.5 ± 11.5 kg) voluntarily participated in the present study after providing their written informed consent. To address the current investigation of adaptation, retention and transfer in physiologically and neurologically healthy young participants, they were screened for inclusion criteria via a questionnaire, i.e. normal or corrected-to-normal vision (glasses or contact lenses) and absence of known or diagnosed neurological and musculoskeletal impairments. Only young healthy participants were included to mitigate at best any bias caused via sensorimotor disfunctions or diseases on the outcome of our study. 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).

Our participants were balanced in gender and pseudo-randomly assigned by study personnel using MS Excel (RAND function) into two groups: a control group, CG (eight males, eight females; 22.9 ± 1.7 yr; 177 ± 9 cm; 74.4 ± 10.4 kg) and an intervention group, IG (eight males, eight females; 22.4 ± 1.9 yr; 177 ± 10 cm; 73.5 ± 11.5 kg). All training and testing involved participants walking on a treadmill (pulsar, h/p/cosmos, Nussdorf-Traunstein, Germany) and having to avoid virtual and/or physical obstacles. The protocol consisted of two laboratory visits 7 to 10 days apart (see Figure 10). For safety reasons, all participants wore a harness attached to the arch of the treadmill for the entirety of training and testing. Participants experienced no other exposure to virtual or physical obstacles between the first and second training but were allowed to continue with their normal physical activities.

5.3.2 Experimental procedure and data acquisition

Kinematics of the two obstacle avoidance tasks were recorded using an eight-camera optical motion capture system (120 Hz; Oqus 7/Oqus 5, Qualisys, Gothenburg, Sweden). A 50-marker full-body model was used to determine each subject's locomotor responses to obstacle avoidance. Markers were placed additionally on the head-mounted display (HMD, four markers, VIVE Pro, HTC Corporation, Taoyuan, Taiwan), on the physical obstacle made of polyurethane foam (five markers) and on the treadmill (four markers) and were used for data acquisition and analysis. Unity software (Version 2019.2.7f2, Unity Technologies, San Francisco, CA, USA) was used to create the virtual environment, in which participants saw an endless corridor, a geometrically accurate model of the treadmill and its handrails, the virtual obstacles, a feedback scale (only for IG), and their own body in outline form (Weber et al., 2021). The body avatar was updated dynamically using live marker position data.

To control the suddenly-appearing physical obstacles, a custom-built wireless controlled electromagnetic device was fixed to an aluminium profile in front of the treadmill. A polyurethane foam obstacle (height 10 cm x depth 10 cm x width 30 cm) was held and released electromagnetically by means of a flat piece of ferromagnetic metal attached to the top of the obstacle. Another flat piece of metal (15 cm x 15 cm x 0.1 cm) attached to the bottom of the obstacle prevented it from rolling over. The foam obstacle was reattached manually to the reactivated electromagnet to repeat the obstacle avoidance task.

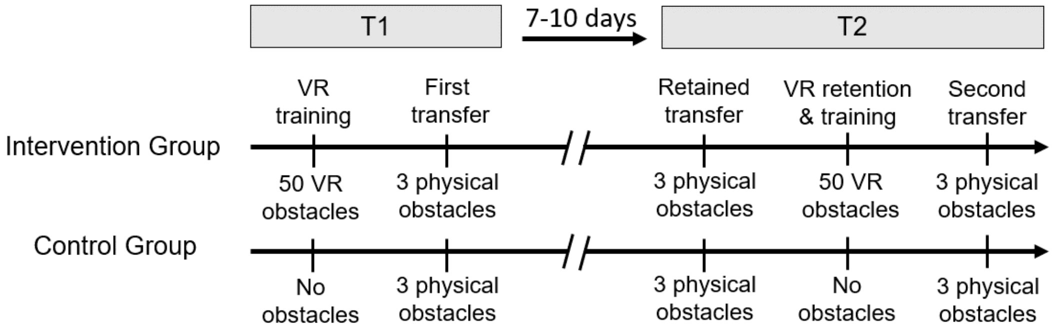

Figure 10: Experimental protocol illustrating the days of measurement (T1 session 1; T2 session 2), tasks within sessions and type and number of obstacles for the two groups.

For the first training session (T1), all participants (IG and CG) were familiarized with the set-up for about 12 minutes in a three-part procedure. They walked on the treadmill (1) without wearing the HMD, (2) whilst wearing the HMD and holding the treadmill handrails, and (3) whilst wearing the HMD having let go of the handrails. For all tasks, treadmill walking velocity was set to 1.3 m/s. The participants of the IG had to avoid 50 unilateral virtual obstacles (height 10 cm x depth 10 cm x width 50 cm) appearing 80 cm in front of their right leg at touch-down of that leg (detected via synchronized motion capture). This distance was chosen so that it did not affect rhythmic walking cadence. The obstacles appeared at random times which were fixed in the same sequence for all participants and for both trainings. Participants received visual feedback about their toe clearance height directly after each avoidance. As they were instructed to cross the obstacle within a given target range, feedback was provided in the form of a gradient color scale located at a fixed position in the virtual environment (Figure 11a). An open black circle indicated the clearance height of the participant’s toe above the front edge of the virtual obstacle and remained in that position until the next obstacle was crossed. Participants were given two instructions. Firstly, they were asked to adapt their toe clearance to a target height in the lower yellow range (position of the black open circle in Figure 11a), which corresponded to 3 to 5 cm above the leading edge of the virtual obstacle. Secondly, they were asked to avoid toe clearance below the target height, i.e. clearance in the lower red range, which corresponded to less than the safety margin of 3 cm. The participants received a detailed explanation of the target area before the training, using a picture of the scale. However, they were not informed about the meaning of the color scale. They only knew that they should cross the obstacle in the lower yellow range and not below it, and that the lower end of the scale meant that they would hit the obstacle. CG participants walked through the obstacle-free virtual corridor for the same duration as the IG.

After the VR-based training in T1 all participants had to cross three physical obstacles with the same leg as in the virtual reality training to test for transfer from virtual to physical obstacle conditions (first transfer). Prior to the transfer test all participants walked obstacle-free for four minutes on the treadmill without HMD to allow re-acclimation to the physical environment. The physical foam obstacles were of the same height and depth as those in VR (Figure 11b) and of width 30 cm (Figure 11c). They were triggered, unpredictably for participants, by their right heel touchdown. The physical obstacle was located at the same distance (± 2.5 cm) as in the virtual condition. Participants were instructed to cross each physical obstacle as low as possible. No feedback was given about the distance between toe and obstacle in order to test the transfer of the skills acquired in the virtual environment. They were informed beforehand that the obstacles were made of foam and therefore collisions at any time would not pose risk of injury.

All participants in training session 2 (T2; 7-10 days after T1; Figure 10) had to cross three physical obstacles followed by a repetition of their protocol from T1 in order to assess retention effects and to determine whether obstacle avoidance adaptations in the virtual environment led to retained transfer to the physical obstacle. The repetition involved a VR-based familiarization prior to IG and CG training in VR (second training; retention), followed by another three trials with physical obstacles (second transfer).

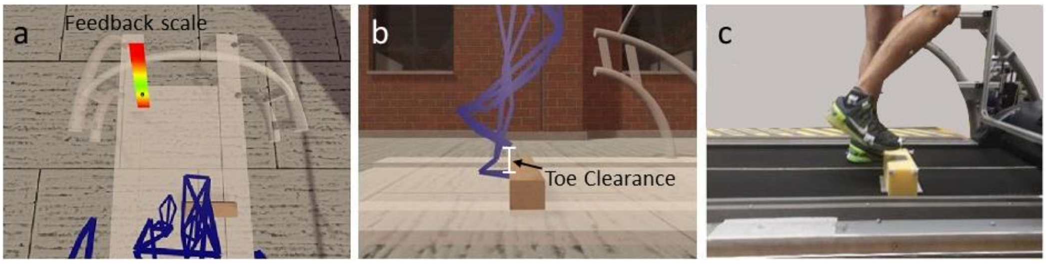

Figure 11: (A) Virtual environment containing a corridor, a model of the treadmill, avatar of participant, virtual obstacle and visual feedback about avoidance height. (B) Participant avoiding the virtual obstacle. (C) Participant avoiding the physical obstacle.

5.3.3 Data processing

The three-dimensional coordinates of markers from motion capture 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 and the height of the obstacle when that marker was above the leading edge of the obstacle (Weber et al. 2021; Figure 11b). Sagittal plane hip, knee and ankle angles of the right leg were calculated for the swing phase which was defined as the time between take-off and touchdown of the right foot. Lower extremity joint kinematics were analyzed over the entire swing phase of the crossing leg in order to identify the time course of any joint-related adaptive phenomena including changes in coordination. Foot take-off and touchdown were determined using the foot contact algorithms of (Maiwald et al. 2009).Take-off is specified as either the local maximum of the vertical acceleration or the minimum vertical position of the toe marker. Touchdown is defined as the local maximum in the vertical acceleration curve of the heel or fifth metatarsal marker within an approximation interval based on the earlier of the two events. Hip angle was calculated from the hip center, hip joint center (calculated according to Hara et al. 2016) and knee joint center. Knee angle was calculated from the hip joint center, knee joint center and ankle joint center. Ankle angle was calculated from the knee joint center, ankle joint center and mid foot. All calculations were performed using customized routines written in MATLAB (version 9.3.0, The Mathworks Inc, Natick, MA, USA).

5.3.4 Statistics

Four participants (two IG and two CG) were excluded from the analysis due to technical issues during the measurements (connection losses to the computer from both the wireless VR device and the wireless physical obstacle release system). Participant response adaptations to repeated practice while avoiding virtual obstacles were examined by pooling trials. Accordingly, trial data for hip, knee and ankle joint angles as well as for toe clearance were combined for obstacles 1-3 and 48-50, named early and late adaptation respectively. Statistical Parametric Mapping t-tests (SPM; Pataky 2010 were used to detect potential VR-based effects of obstacle avoidance training on sagittal plane hip, knee and ankle joint angles of the obstacle avoiding leg during swing phase. For this purpose, all analyzed kinematic trajectories were time-normalized to the swing phase (from take-off to touchdown of the right leg). All data were tested for normal distribution using the Shapiro-Wilk test ($p > 0.05$). Paired t-tests were used to compare early and late adaptation of the IG for both T1 and T2. Possible retention effects for the VR condition were examined by comparing toe clearance and joint angle kinematics of the IG between late T1 and early T2 using a paired t-test and its SPM equivalent. Furthermore, an equivalence test (two one-sided t-test, 90% confidence interval with $\delta = 0.1$; (Lakens et al. 2018) was performed on toe clearance data from late T1 and early T2. Concerning avoiding physical obstacles for the IG and CG, the three trials for each time point (T1 and T2) were considered separately by two-sample t-tests for toe clearance and SPM for joint angle kinematics to analyze potential transfer and transfer retention effects for the physical obstacle condition. Possible physical obstacle transfer effects were further examined by comparing the data of toe clearance late adaptation VR with first physical obstacle at T1 of the IG using a paired sample t-test. Potential adaptations due to repeated crossing of physical obstacles were analyzed using separate paired sample t-tests for both groups, comparing the first and third obstacles at T1. Retention of transfer in the IG was further analyzed by comparing the first and third physical obstacle at T1 with the first obstacle at T2 using a paired sample t-test. Statistical analyses were performed either using SPSS Statistics (version 27, IBM, Armonk, NY, USA) or open-source code SPM1d (version M.0.4.8, www.spm1d.org) in MATLAB (version 9.3.0, The Mathworks Inc, Natick, MA, USA), with α set at 0.05. The one-sample equivalence test was performed using MS Excel (Microsoft, Redmond, WA, USA). All results in text are presented as mean ± SD.

5.4 Results

5.4.1 Locomotor adaptation and retention for VR-based obstacle avoidance

There were no collisions between the participants' feet and virtual obstacles during the statistically analyzed trials, but some collisions during other trials in VR training (3 participants, 7 hits in trials 10-37 at T1). The participants crossed the leading edge of obstacles (both virtual and physical) at 39 ± 5% of swing phase. Please note that similar percentages for timing were found for early and late adaptation, and in retention and transfer tasks. A significant difference ($t(13) = 3.754$, $p = 0.002$) was observed in the first training session (T1) in toe clearance between early (9.4 ± 5.0 cm) and late adaptation (4.7 ± 2.1 cm; Figure 12a, Figure 12c). Concerning the joint angle analysis using SPM for the swing phase of the avoiding right leg, the ankle joint demonstrated a significantly greater plantarflexion from 48-75% of swing phase ($p < 0.001$) and the knee joint a greater extension from 19-43% of swing phase ($p = 0.001$) for late compared to early adaptation (Figure 13). Toe clearance decreased significantly ($t(13) = 2.846$, $p = 0.014$) from early to late phases during the second VR-based training at T2 (early 5.8 ± 1.6 cm; late 4.5 ± 1.9 cm; *Figure 12*B, *Figure 12*c). Joint angle comparison revealed a more plantarflexed ankle joint at 23-33% of swing phase for late in comparison to early adaptation for T2 ($p = 0.020$; Figure *13*).

Comparison of participants performing the task in the virtual environment at T1 and T2 showed equivalence in toe clearance ($p < 0.001$) between late adaptation at T1 (4.5 ± 1.9 cm) and early adaptation at T2 (5.8 ± 1.6 cm), though there was a trend to significant difference ($t(13) = 2.011$, $p = 0.066$). Joint angle comparisons for the swing phase of the avoiding leg between late adaptation T1 and early adaptation T2 revealed no statistically significant differences for all three joints.

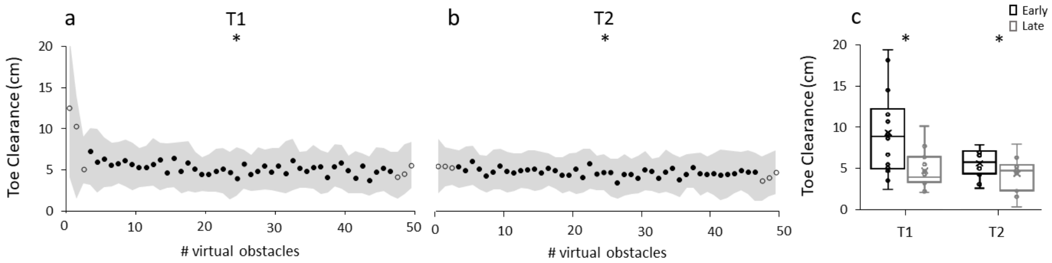

Figure 12: Adaptation of toe clearance for (A) first VR-based training (T1) and (B) second VR-based training (T2) for avoiding obstacles with the right leg (1-50) presented as means (circles) with standard deviations (grey shading) for all IG participants. Obstacles used to investigate adaptation (early and late) are presented as open circles. *: significant difference between early and late adaptation ($p < 0.05$). No differences were detected between late T1 and early T2.

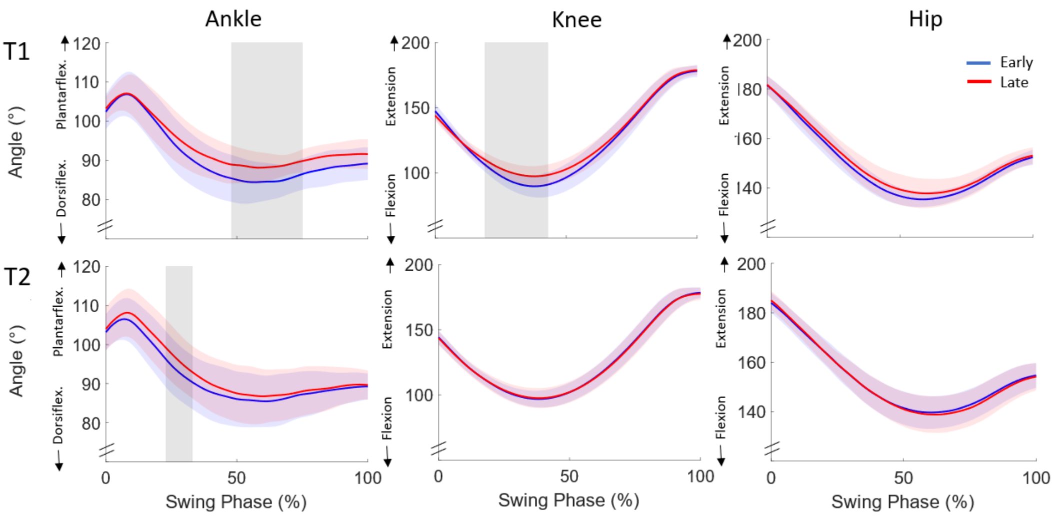

Figure 13: Sagittal plane ankle, knee and hip joint angle trajectories of the avoiding leg during swing phase for T1 (day 1) and T2 (post 7-10 days) for early and late adaptation as mean and standard deviation (blue and red shading) during VR obstacle avoidance. Vertical grey areas indicate significant differences between early and late adaptation.

5.4.2 First transfer at T1, retained transfer and second transfer at T2

Toe clearance was significantly lower in the IG compared to the CG for all three physical trials at T1 (first trial t(26) = 2.854, p = 0.008, second trial t(26) = 2.105, p = 0.047, third trial t(26) = 2.904, p = 0.007; Figure 15:). Furthermore, the IG showed a significantly more extended knee joint (for 39-78% of swing phase; p = 0.001; Figure 14) while avoiding the first physical obstacle, as compared to the CG. However, when comparing late adaptation in VR at T1 with the first physical obstacle at T1 for the IG, there was a significant difference (t(13) = 4.014, p < 0.01) with higher values in toe clearance for the physical obstacle in relation to the VR condition. Within the physical trials in T1 there was no statistically significant change in toe clearance when comparing the first and third obstacle in the IG but approaching significance (t(13) = 1.873, p = 0.084). The CG significantly adapted their toe clearance from physical obstacle one to obstacle three (t(13) = 3.360, p < 0.01). Regarding the retained transfer and second transfer, no significant differences in toe clearance or joint kinematics between IG and CG were found for any of the three trials of physical obstacles. Although there were no differences between the first physical obstacle at T1 and at T2 in the IG (t(13) = 0.157, p = 0.878) we detected significant differences between the third obstacle at T1 and the first obstacle at T2 (t(13) = 2.429, p = 0.030).

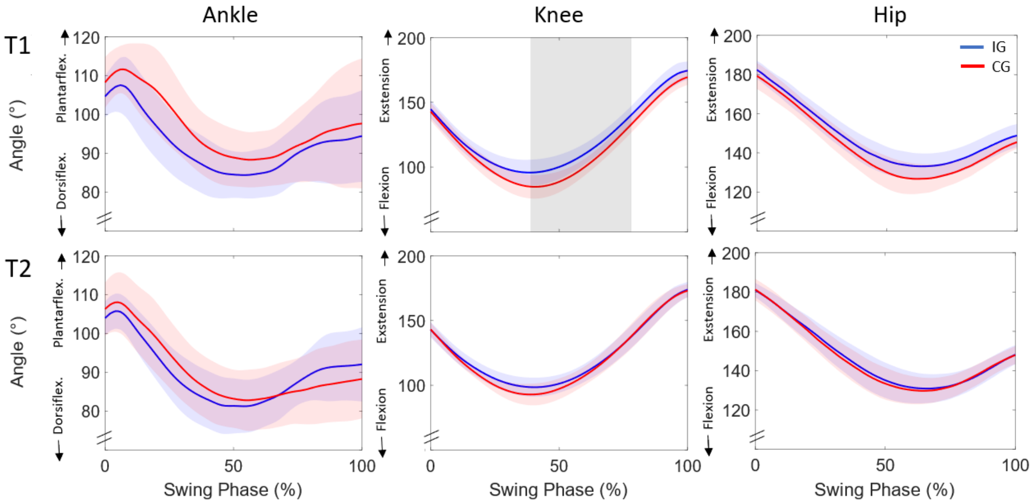

Figure 14: Sagittal plane ankle, knee and hip joint angle trajectories of the avoiding leg during swing phase for T1 (day 1) and T2 (post 7–10 days) for intervention group (IG) and control group (CG) as mean and standard deviation (blue and red shading) during the first physical obstacle avoidance (trial 1). The vertical gray area indicates a significant difference between groups.

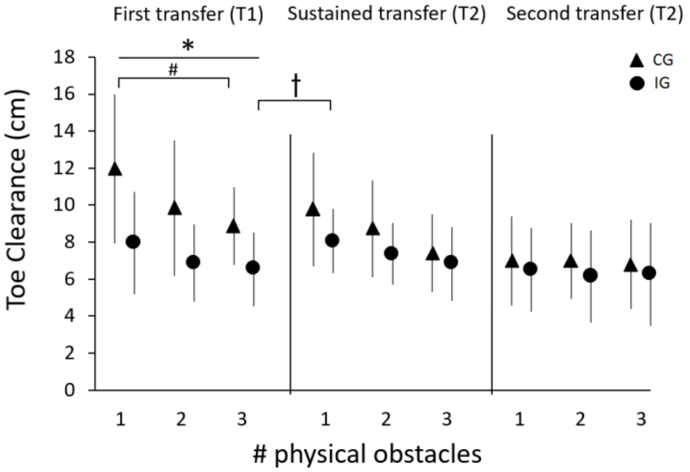

Figure 15: Mean and standard deviation of toe clearance for all participants of the intervention group (IG, circles; n = 14) and control group (CG, triangles; n = 14) for avoiding the three physical obstacles of each transfer task on T1 (first transfer), and T2 (retained transfer and second transfer). * Significant difference between IG and CG for obstacles 1–3 in T1 ($p < 0.05$), † significant difference between third obstacle T1 and first obstacle T2 IG ($p < 0.05$), # significant difference between first and third obstacle T1 CG.

5.5 Discussion

This study investigated whether obstacle avoidance skills learned during VR-based training of young adults can be transferred to physical obstacles, and be retained over one week in both virtual and physical environments. We could partially confirm our hypothesis and observed limited transfer of obstacle avoidance skills from a virtual to a physical obstacle. The IG replicated similar joint angle patterns as learned in VR to cross the physical obstacle at a lower height than the CG. Furthermore, we were able to show that these adaptive refinements are partially retained over a period of one week for the physical obstacles since IG could retain their physical crossing performance of their first crossing at T1 but not for the third obstacle at T1 compared to T2. Altogether the outcomes give reason to question the effectiveness of VR-based training for enhancing locomotor function in physical settings over a long time period.

Results of the present study showed that participants were able to adapt their toe clearance to the target height (i.e. 3-5 cm above the virtual obstacle) and maintain that clearance (mean toe clearance in late adaptation of 4.7 cm). Our findings are thus in accordance with those of Kim and colleagues (2019) revealing similar toe clearance for the initial and final VR obstacles (initial 13 cm vs. 13 cm; final 4 cm vs. 5 cm; Kim et al. 2019 vs. our results respectively). In the current study, toe clearance significantly reduced between early and late adaptation when participants received visual feedback about their avoidance performance. It is noteworthy that participants were able to reduce their toe clearance to 5 cm when receiving feedback compared to the no-feedback value of 9 cm for our previous investigation using a similar experimental design (Weber et al. 2021). The reduction of toe clearance is a result of combined lower knee flexion and ankle dorsiflexion for obstacle crossing. The knee joint is used to adapt the toe clearance in the first phase of obstacle crossing until the toe is above the front edge; the ankle joint is used more in the late phase of obstacle crossing (after crossing the front edge of the obstacle). Accordingly different joints may play roles in different aspects of locomotor learning during repeated obstacle crossing. Our results therefore suggest that adaptive refinements in toe clearance over repeated virtual obstacle trials are achieved by recalibrating motor task execution predominately at the ankle and knee joints and less at the hip.

The acquired avoidance patterns were partially transferred to a physical obstacle. Comparing joint kinematics between groups, significantly lower knee flexion was found for the IG compared to CG in avoiding the physical obstacle. Although descriptive differences in ankle dorsiflexion were observed between the two groups, no significant differences were found on account of the high variation amongst participants (see SD values in Figure 14), which may be caused by a forefoot instead of heel-strike pattern for some group members. Nevertheless, the differences in knee flexion led to significantly lower toe clearance when avoiding the first physical obstacle in the IG. Despite robust adaptations in the virtual environment, transfer of VR skills to physical obstacles seems to be only partial. Participants crossed the first physical obstacle with a toe clearance of 8 cm instead of the 5 cm learned in the virtual environment. As the obstacle avoidance task was practiced in a safe virtual environment, colliding with an obstacle could not have severe consequences, i.e. participants could not trip over VR obstacles. Due to the safer environment, the participants may therefore have taken a greater risk when avoiding virtual obstacles than they did with physical obstacles (Rohde et al. 2019). IG participants, however, adapted their toe clearance within the first three performed physical obstacle trials from 7.9 cm to 6.5 cm on average (approaching significance with $p = 0.084$). Consequently, our results suggest that VR obstacle avoidance training leads to partial acute transfer of skills to the physical obstacle.

After one week without training, participants returned to the laboratory to be tested for retention of transfer (physical obstacle avoidance) and VR-based adaptation. Participants were partially able to retain their learned physical obstacle skills over one week. As stated above, the IG adapted their toe clearance within the first three physical trials at T1 and were able to retain this performance partially at T2 (similar performance to the first physical trial but not to the third trial at T1). As participants of the CG also adapted their toe clearance according to the absolute values (trial 1, 11.9 cm vs. trial 3, 8.8 cm on average) during the physical trials at T1 and retained this performance at

T2 (trial 1 T2, 9.7 cm on average), there were no differences between groups over all three trials. The participants of the IG retained their toe clearance for physical obstacle avoidance from the first obstacle but not from the third obstacle at T1 to the first physical obstacle at T2. Since the CG was able to retain its performance from the third obstacle for one week, but the IG returned to a level similar to the first obstacle, we can only conclude that there was partial retained transfer. Despite limited retained transfer for physical obstacles in the IG, the participants were able to fully retain their performance in the virtual environment. Their toe clearance was not statistically significantly higher in the first three VR-based obstacle avoiding trials at T2 compared with the last three trials at T1. These differences between physical and virtual performance may be due to different perception of dimensions between virtual and real-world conditions. Regarding this, several previous studies mentioned that discrepancies between perception in real and virtual environments are contributing to distances in virtual environments being underestimated by 50-80% (Renner et al. 2013) and heights overestimated (Asjad et al. 2018). Since the reasons for the differences in distance estimates are multifactorial (e.g. technical factors, compositional factors, and human factors; (Renner et al. 2013), it is difficult to counteract the different perceptions by changing software parameters. Further research is needed here. Our findings indicate that perception-action coupling and hence sensorimotor coordination in virtual environments may differ from those in the physical world, potentially limiting transfer and retention and hence the effectiveness of VR-based training.

Within the second VR-based obstacle avoidance training a small but significant improvement in toe clearance was found when comparing early T2 with late T2. This improvement resulted from lower ankle dorsiflexion in early swing phase for late adaptation. However, the adaptation in toe clearance was relatively small (on average 1 cm) indicating that a steady state and ceiling effect had already occurred at T1. When testing for a second transfer to physical obstacle avoidance no further improvements were found relative to the three trials (retained transfer) performed prior to the second VR-based training. We may argue that there was no further, practically-relevant skill improvement to be transferred. On a different note, there seemed to be a threshold of approximately 6 cm toe clearance beyond which no participant progressed in the physical obstacle condition, despite adjustments between trials. There was clear skill retention for the virtual environment but only partial retained transfer and second transfer for physical obstacles. We can thus infer relatively long-lasting adaptive refinements in motor task execution strategy, though these are condition specific.

We must acknowledge that our current protocol has some limitations. In the current investigation we did not perform a pre-training baseline test in the physical obstacle condition. We chose to avoid this due to concerns about rapid learning effects potentially affecting our conclusions for transfer. Although all participants in both groups (IG and CG) were young and healthy and showed no between-group differences in age, gender, or anthropometric characteristics, we cannot rule out the possibility that obstacle avoidance at baseline differed between groups. However, since the IG showed performance differences between late adaptation in VR and the first physical obstacle, we have no reason to suggest that this limitation affects our main conclusion. Furthermore, the physical obstacle avoidance led to rapid adjustments in toe clearance within a few trials for both groups. Therefore it is not possible to distinguish clearly between the physical avoidance performance at T2 of the IG being due to partially retained transfer of the VR-based training or a partial retention of the physical avoidance skills learned at T1. In addition, it is to be noted that there were differences in instructions and setup between virtual and physical obstacle avoidance tasks. Participants were able to focus on the physical obstacle because it was constantly visible before release, whereas virtual obstacles appeared suddenly in the virtual environment. Also, participants were instructed to cross virtual obstacles in the target range whereas they were instructed to cross the physical obstacles “as low as possible.” These differences may have contributed to the diminished transfer. In this study, the participants were trained on a treadmill with obstacles of the same height to use a lower toe clearance when crossing the obstacles. In everyday life, crossing with a lower as opposed to a higher toe clearance poses a higher risk of tripping. Our goal, however, was not to reduce the risk of tripping or to replicate real-world conditions, but to use the paradigm of obstacle avoidance and reduced toe clearance as a general means of testing adaptation, transfer, and retention of VR training.

In conclusion, our findings revealed that participants in VR-based obstacle avoidance training were able to adapt their toe clearance to a target height through changes in ankle and knee joint angles in a situation in which they received visual feedback about their performance. They were able to retain those skills fully in the virtual environment over one week, but showed only limited transfer and retention of those skills over one week to avoidance of physical obstacles. Additional VR-based training did not further improve virtual-to-physical-environment transfer. It may be concluded that perception-action coupling, and thus sensorimotor coordination, in the virtual environment differs from that in the physical world, potentially inhibiting retained transfer between conditions. Accordingly, VR-based locomotor skill training paradigms need to be considered carefully if they are to replace training in the physical world.

5.6 Acknowledgements

A scholarship grant from the German Social Accident Insurance (DGUV) for the first author (A.W.) is gratefully acknowledged.

6. Main findings and discussion

In the context of utilizing VR for locomotor skill training, it is crucial to understand the factors that enable the neuromotor system to adapt, retain, and transfer locomotor skills between legs and between different environments. This thesis examined the implementation of VR for obstacle crossing training, related transfer phenomena and retention over one week. The insights gained could improve understanding of learning and transfer for tasks performed in virtual reality more generally. Summarizing the results of the individual studies, several conclusions related to the overall project aim will be drawn in this chapter. Subsequently, the limitations, practical relevance and perspectives for future research will be discussed.

6.1 Adaptations and interlimb transfer

The first and second study of this thesis aimed to examine adaptation and interlimb transfer resulting from virtual reality obstacle avoidance training, with and without feedback about crossing performance and awareness of limb change. Previous studies on physical obstacle crossing have already shown that humans are able to adapt their locomotion to multiple obstacle crossings through reducing their toe clearance and lower extremity muscle activation (Kloter and Dietz 2012; Michel et al. 2008). The combined results of the first and second studies suggest that obstacle avoidance skills can be adapted through virtual reality-based training. In the absence of instructions, participants adjusted their obstacle crossing to be more efficient (lower toe clearance) and more stable (higher MoS). The increase in dynamic stability was likely due to a longer step taken after crossing the obstacle, as evidenced by the adaptation of the base of support rather than the extrapolated center of mass. The adaptation of MoS appeared to plateau at approximately the 25th obstacle, which may represent a dose threshold in the nonlinear practice dose-response relationship, as proposed in previous studies (Karamanidis et al. 2020). However, toe clearance adapted more slowly to repeated obstacle crossing than MoS. It is possible that humans may initially modify their gait to achieve greater stability and then improve efficiency by reducing energy consumption, which can be achieved through reducing toe clearance. We found similar initial crossing values for clearance to another VR obstacle crossing study (Kim et al. 2019). However, in our study without feedback about crossing performance, there was higher final toe clearance. This may be the outcome of differences in instructions, the absence of performance feedback, or the unexpected appearance of obstacles in our study. Additionally, a high variability within and between participants due to the missing feedback may have influenced the results.

Despite the absence of instruction to reduce toe clearance, participants in this study combined lower toe clearance with an increase in BoS when adapting their crossing strategy with repeated practice. This suggests a change to a more effective and stable movement. While it is known that humans reduce their toe clearance with repeated obstacle avoidance training (e.g. Michel et al. 2008), joint-related changes and time course with repeated practice are not well established. In order to address this we further investigated joint kinematics to identify joint-related adaptive phenomena. Our study identified that the decrease in toe clearance during obstacle crossing can be attributed to coordinated change in movements of lower knee flexion and ankle dorsiflexion. We noted that participants typically reached the front edge of the simulated obstacle approximately 37% into swing phase. During the initial phase of obstacle crossing, participants utilized knee movements to adjust toe clearance until it projected beyond the front edge, whereas ankle movements became more prominent in the later phase of crossing, after the front edge of the obstacle had been crossed (see

Figure ***16***). Based on these observations, we think that distinct joints may contribute to different aspects of locomotor adaptation in the context of repeated virtual obstacle crossing.

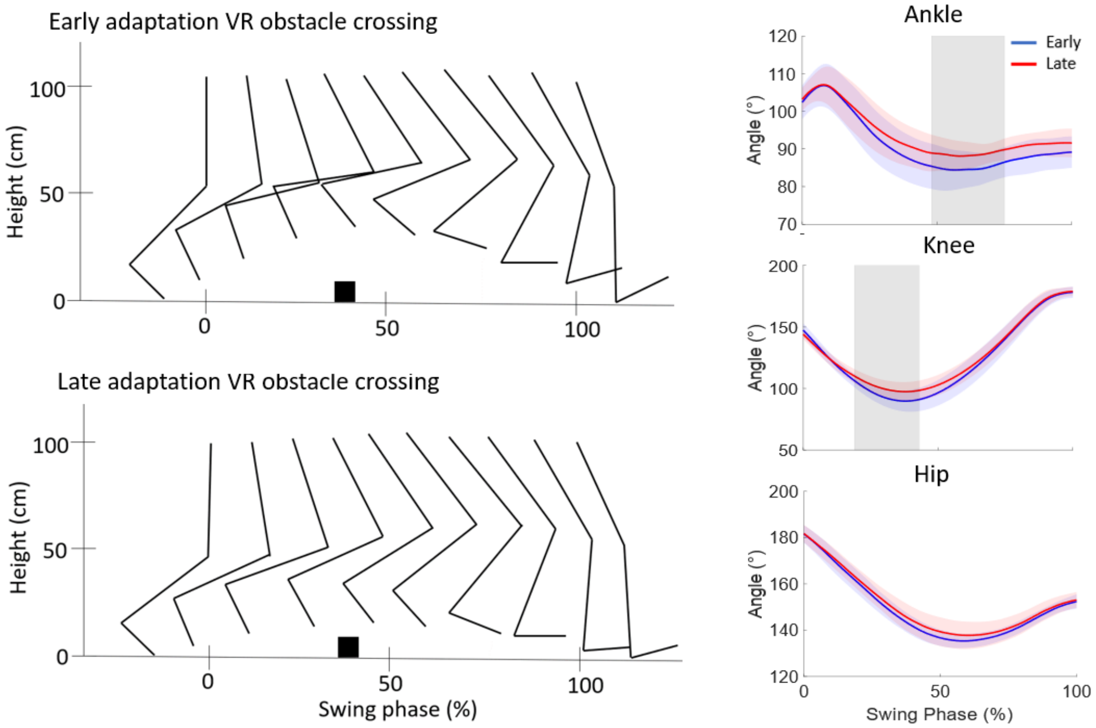

Figure 16: Left: Schematic illustration of the trained leg while crossing a virtual obstacle during swing phase in early and late adaptation. Right: ankle, knee and hip sagittal plane angle for early and late adaptation as mean and standard deviation (blue and red shading) for VR obstacle avoidance. Vertical grey areas indicate significant differences between early and late adaptation ($p < 0.05$).

When feedback was available and an explicit performance target for toe clearance was set, toe clearance over the 25th and 50th obstacle was significantly smaller compared to without feedback, indicating that both rate and magnitude of refinements in locomotor skill using VR can be enhanced via feedback on one’s performance (see Figure 17). The provision of feedback resulted in a substantial reduction of toe clearance to 5 cm among participants, representing a significant improvement from the no-feedback condition where toe clearance averaged at 9 cm. This final toe clearance is comparable with the toe clearance from the study of Kim and colleagues (2019). Therefore, it can be inferred that the differences in final toe clearance between our first and second studies were a consequence of missing feedback.

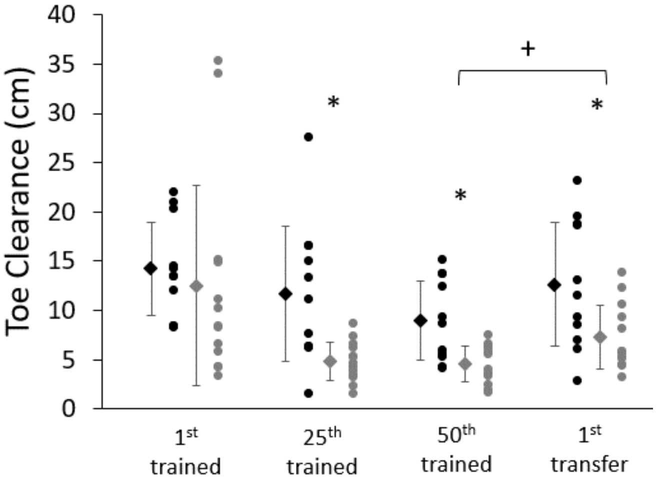

Figure 17: Toe clearance of the 1st, 25th and 50th obstacle of the trained leg and 1st obstacle of the transfer leg for participants without feedback (black) and with feedback (grey), individual data, mean and standard deviation. *: significant differences between with and without feedback groups ($p < 0.05$). +: significant differences between 50th obstacle right and 1st obstacle left for both groups ($p < 0.05$).

Although locomotor skill adaptation was improved by feedback and participants were informed about limb change before starting the transfer task, there was no 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). This finding was consistent in both studies (with and without feedback), indicating that the acquisition of locomotor skills in a VR obstacle crossing task is limb-specific. Krishnan et al. (2018) and Swinnen et al. (1997) propose that optimizing performance through feedback improves transfer performance. In addition, Malfait and Ostry (2004) suggested that awareness of perturbation and explicit goals are essential for interlimb transfer to take place. Bhatt and Pai (2010) have also argued that their only partial interlimb transfer is due to limited awareness and feedback. However, our study failed to support these claims as we did not observe any interlimb transfer regardless of whether feedback and enhanced awareness were used or not.

Extensive research has been conducted on interlimb transfer for the upper-limb, with various factors affecting the transfer such as the task type, concept, spatial reference frame, training duration, motor variability during training, ageing, and sleep. However, there are only a few studies investigating interlimb transfer of skills in the lower extremities. Most of these studies only investigated whether interlimb transfer occurs in general and not which factors might influence this transfer. Houldin et al. (2012) found only limited transfer in an unipedal walking task and suggested that explicit feedback about locomotor performance, specific task requirements, as well as the possible role of leg dominance, may play a role in interlimb transfer of adaptations. There was a significant transfer of skills but no asymmetry in transfer between limbs in an obstacle avoidance task (van Hedel et al. 2002) and in a foot-trajectory tracking task (Krishnan et al. 2018). However, another study found asymmetric interlimb transfer and suggested that this is task context-dependent, with feedback type (kinematic or dynamic) playing a role (Stöckel and Wang 2011). Age might be another factor influencing interlimb transfer. McCrum et al. did not observe interlimb transfer in a PBT task in young adults (McCrum et al. 2018) but older adults were able to transfer skills across legs in the same task (McCrum et al. 2020). Note, there was a reduction of interlimb transfer in older adults compared to young adults in a foot-trajectory tracking task (Krishnan et al. 2018). Our results indicate that VR training with feedback enhances the effectiveness of adapting locomotor skills which are, however, limb-specific. It remains unclear which factors may influence interlimb transfer during VR obstacle avoidance, hence further investigations are needed.

6.2 Retention and physical world transfer

The third study of this thesis aimed to examine the retention of virtual reality obstacle avoidance training over one week and its transfer to physical obstacles. As mentioned in section 6.1, participants are able to adapt their toe clearance and joint angles to crossing multiple virtual obstacles. To investigate transfer to physical obstacles we chose to use a between-subjects comparison of an IG and CG. We found that acquired avoidance patterns were partially transferred to a physical obstacle. The intervention group exhibited markedly lower levels of knee flexion compared to the control group when avoiding physical obstacles. While there were only descriptive differences in ankle dorsiflexion between the two groups the differences in knee flexion led to significantly lower toe clearance when crossing the initial physical obstacle in the trained group. Our findings suggest that although participants demonstrated significant improvements in the VE, their ability to transfer these acquired skills to physical obstacles was limited. There was a significant difference ($p < 0.01$) between late adaptation in VR and the first physical obstacle in toe clearance. We observed that participants crossed the initial physical obstacle with a toe clearance of 8 cm, which contrasts with the 5 cm toe clearance achieved during virtual environment training. The relatively safer environment of the virtual setting may have prompted participants to take more risks when avoiding obstacles in the virtual environment, which could explain higher toe clearance for the physical obstacle. It must be noted that VR and physical obstacles had the same dimensions and appeared at the same time point of the gait cycle.

The statement of partial transfer is further supported by the observation that within the three physical trials in T1 for the intervention group there was a tendency towards an adaptation in toe clearance from 7.9 cm to 6.5 cm on average (which approached significance, $p = 0.084$). There was, however, a ceiling effect in the VR training condition over 50 trials, i.e. additional analyses revealed no differences ($p = 0.733$) between trials 24-26 (mid: 4.8 ± 2.2 cm) and trials 48-50 (late: 4.7 ± 2.1 cm). Even though both subject groups revealed adaptation in toe clearance within the three physical trials at T1 (IG, $p = 0.084$ and CG, $p < 0.01$), the third physical obstacle for the intervention group did show significant difference to late VR in T1 ($p = 0.023$). Given that the 50 trials in VR led to a ceiling effect in locomotion adaptation and considering the findings mentioned above, we have a strong argument that transfer was only partial.

Retention of physical and virtual obstacle crossing skills was tested after one week without further training. The results showed partial retention of learned physical obstacle skills for both the IG and CG. The IG participants partially retained their performance after one week since they were able to retain their toe clearance from the first physical obstacle at T1 to the first physical obstacle at T2, but not from the third obstacle at T1 to the first obstacle at T2. The CG sustained their performance. Therefore, there were no significant differences between the groups in all three trials. Our findings suggest that although participants were able to fully retain their acquired skills within the virtual environment, their ability to transfer these skills to physical obstacles was limited. The fact that we found full retention in VR but not for physical obstacles supports our assumption that retention was less beneficial for physical as opposed to VR obstacles.

The differences in performance between physical and virtual environments may be attributed to differences in perception of dimensions. Studies have demonstrated that judgments of egocentric distances in the physical environment are highly accurate, with an accuracy rate of nearly 100% (see Loomis and Philbeck 2008 for a review). However, in VEs egocentric distances are only judged to be 50 – 85 % of the environment developers intended anterior-posterior distance (see Renner et al. 2013 and Creem-Regehr et al. 2015 for reviews). Furthermore, heights are overestimated in VEs (Asjad et al. 2018). If distances are underestimated and heights overestimated in VR, differences in perceptions, and therefore also in actions, will occur between virtual and physical environments. We think that the partial transfer may be caused to some extent by different perceptions of heights and distances in VR which potentially may impede the effectiveness of VR-based training. As already explained in the Introduction there are many factors that influence distance and size perception in VEs. Further research is needed to address such issues and will be explained below in the section on future perspectives.

During the second VR-based obstacle avoidance training participants slightly adapted their movements and further reduced their toe clearance by 1 cm. This indicates that a steady state and ceiling effect had already occurred at the first training session. In terms of transfer to physical obstacle avoidance, no further improvement was found beyond the three trials performed before the second VR-based training. Our study revealed that despite adjusting between these trials, participants failed to make any progress in the physical obstacle condition beyond a certain toe clearance threshold of approximately 6 cm. We were able to show a steady state after around 25 VR obstacles, i.e. no significant differences in toe clearance between mid (trials 24-26) and late (trials 48-50) adaptation. 50 obstacles were sufficient to elicit an adaptation that was retained in VR. We do not have any evidence from our data to conclude that a higher exercise dose in the VR would have led to a more effective retained transfer to the physical environment. Although the participants were able to retain their skills in the VE, the retention and transfer of those skills to physical obstacles were only partial. These findings suggest that adaptive refinements in motor task execution strategy are long-lasting and specific to the training conditions.

Upon being instructed to cross obstacles within a specific range, participants exhibited the ability to adapt their movements (toe clearance and ankle joint kinematics) and partially transfer these adaptations to physical-world obstacle avoidance. However, retention and transferability of skills from VR-based training to physical-world scenarios were limited. This implies that the use of VR-based training as a replacement for physical-world training must be carefully considered.

6.3 Limitations

Acknowledging the limitations of our current protocols is crucial. In our initial study, we only used one obstacle to test interlimb transfer, potentially causing participants to be surprised by the appearance of an obstacle for the transfer leg. This may have led to an insufficient motor response. Additionally, we could not test the possibility of interlimb transfer as faster learning with the transfer leg since we only used a single obstacle. Therefore, in our second study we used 50 obstacles to test interlimb transfer, and participants were informed about the limb change. Despite this, we could not detect any interlimb transfer. Furthermore, we did not conduct a direct feedback vs. no feedback comparison in this study using two groups with the same protocol except for feedback. We compared data from our first study to data from our second study. Since study protocols differed slightly, and we changed more than one variable of our training/testing, it is difficult to determine the effects of these changes separately from each other. However, as we did not find any interlimb transfer though we changed two variables, we assume that neither of these variables had an effect on interlimb transfer.

In our third study, we did not perform baseline physical obstacle trials. We know from previous studies that rapid learning occurs with physical obstacles (see for example Michel et al. 2008) and this might have had an impact on the transfer analysis post VR training. Therefore, we decided not to do baseline measurements and conduct a within-subject comparison, but rather to compare the transfer trials with an untrained control group. As both the IG and CG were composed of young, healthy participants who did not differ significantly in terms of age, gender, or anthropometric characteristics, our assumption was that they had an equal baseline toe clearance when crossing physical obstacles. It is unlikely that this limitation impacts our primary conclusion as the intervention group showed performance differences between late virtual reality adaptation and the initial physical obstacle. Our data clearly confirms our conclusion that transfer of VR adaptations to the physical world is limited (physical obstacles showed significantly higher toe clearance values in comparison to late VR).

The limited transfer to the physical world may be due to a difference in perception as opposed to the virtual environment itself. Such differences account for distance as well as motion due to latencies in VR. Previous findings indicate that latencies exceeding 75 ms have an impact on motor performance and the perception of simultaneity (Waltermate et al. 2015). However, latencies occurring with the HTC Vive Pro used for the current studies (33 ms; Le Chénéchal and Chatel-Goldman 2018) and Qualisys real-time streaming (6-7 ms) add up to approximately 39-40 ms, which is below 75 ms Therefore, we think that the relatively short latency does not significantly affect our main findings.

It is challenging to determine whether the partially retained transfer of the IG was due to the retention of VR training or crossing the physical obstacles since both groups rapidly adjusted their toe clearance whilst avoiding physical obstacles. It is important to consider the distinctions in instructions and setups between the virtual and physical obstacle avoidance tasks. Participants had continuous visibility of physical obstacles before release, while virtual obstacles appeared abruptly. Additionally, participants were directed to cross virtual obstacles within a specific range, whereas for physical obstacles, they were instructed to cross them "as low as possible". Although there were some differences in the setup and instructions, virtual and physical obstacles were always released at touchdown of the crossing leg 0.8 m in front of the participants (automatically detection and release via gait kinematics). In addition to the modification of joint angles, toe clearance adaptation may also be influenced by other components of whole-body movement, such as adjustments in the positioning and kinematics of the contralateral stance limb, as well as medio-lateral whole-body components. The reduction in toe clearance could be attributed, in part, to a decrease in elevation of the ipsilateral pelvis (Patla et al. 1991). This aspect warrants further analysis to gain deeper insight. One might argue that the current participants were partly fatigued or less motivated when performing the virtual and mechanical obstacle crossing task resulting in toe clearance decrease. However, it must be emphasised that we investigated healthy young and active participants, and the entire protocol with 50 virtual and a maximum of 6 mechanical obstacles lasted no more than 35 minutes including baseline walking. Moreover, the chosen gait velocity and obstacle dimensions were relatively low (gait velocity 1.3 m/s; obstacle dimensions 10 cm height and 10 cm depth). Thus we do not think that any functionally relevant fatigue or motivational effects affected the current findings.

In contrast to most real-world obstacle crossing scenarios where gait adjustments can be made in anticipation of the obstacle (Chen et al. 1994; Patla et al. 2004), the timing of obstacle appearance in our studies did not allow for predictive gait adjustments with the crossing leg. Nonetheless, we deliberately set the obstacle distance at 0.8 m to introduce a higher level of difficulty for our young and healthy participants. During level walking, the intended landing location is strategically chosen to optimize maintenance of balance (Bancroft and Day 2016). Consequently, being faced with a suddenly-appearing obstacle, which requires deviation from this optimal landing position, poses a greater challenge to the maintenance of dynamic stability.

The meaning of the color scale was not explicitly communicated to our study participants. They were instructed to cross the obstacles within a specific target range by its color assignment and were prior informed that the lower end of the color scale meant hitting the virtual obstacle. We decided against informing the participants about the heights assigned to each color and against provided a scaling with numbers, as this was not necessary for performance of the task as required. Such arrangements would have further increased the motor task complexity, for example by potentially introducing dual tasking. Our aim was for participants to naturally encounter the first obstacle and use the feedback to help them adjust to the target area without thinking about crossing obstacles at a specific height in cm.

Perturbing gait while walking on a treadmill is somewhat different to walking overground using perturbations. The main difference when experiencing gait perturbations is that humans need to keep walking during treadmill perturbations whilst they can stop walking during overground perturbations. Additionally, disparities in gait kinematics and kinetics can be observed when comparing treadmill walking to overground walking, possibly attributed to variations in optic flow (Hollmann et al. 2015). Consequently, the outcomes of the study may not be directly applicable to overground walking. In addition, it should be noted that the training environment for participants included obstacles of a consistent height (no variability). This does not accurately simulate physical-world conditions. However, our intention was not to simulate a physical-world condition but rather to analyse adaptation phenomena, transfer, and retention. For such aims the treadmill paradigm is valuable as the settings and interventions can be well controlled and a large number of gait perturbations can be applied within a short time, reducing the potential effect of fatigue. For example, the gait speed can be kept constant and the manipulation of gait can be controlled without any bias caused by predictive gait adjustments due to knowledge of where and when an obstacle occurs on transition to the physical obstacle condition. Regarding our decision to use only a single obstacle height, we aimed to test general adaptation, transfer, and retention. Therefore, it is necessary for the participants to learn a specific movement sequence without much variation in the condition, which in this case was realized by the constant height of the obstacle and, in addition, obstacle appearance occurred at a controlled time point in the gait cycle. Nevertheless, to provoke generalization and closer applicability to physical world situations, obstacles of different heights and various time points within gait cycle would be necessary.

On a further note, a lower obstacle toe clearance is not be desirable in relation to the reduction of fall risk when crossing obstacles. Our aim, however, was not to replicate physical-world conditions or minimize the risk of tripping. Instead, we used the obstacle avoidance and reduced toe clearance paradigm as a broad means of examining the adaptation, transfer, and retention of VR training. In this regard, several previous studies addressing mechanical obstacle training have also used this paradigm to assess human potential to adapt the neuromechanics of locomotion and for which the participants were instructed to cross the obstacle “as low as possible” (e.g. Kloter and Dietz 2012; Michel et al. 2008; van Hedel et al. 2002). When repeatedly stepping over “small” obstacles during walking (as used in the studies of the current thesis), humans try to adapt their locomotor patterns and reduce toe clearance (e.g. van Hedel et al. 2002; Weber et al. 2021), with the aim of walking more like unperturbed gait and reducing active muscle volume. As we wanted to make this study comparable to others (e.g. van Hedel et al. 2002), we think that the paradigm of obstacle avoidance as a controlled locomotion task and toe clearance as an outcome variable is appropriate to address adaptation, transfer, and retention effects trained in a VR environment.

A further limitation of our studies is use of a homogeneous sample of healthy young adults. While this was a deliberate choice to control for potential confounding factors, such as sensorimotor dysfunction or disease, it is likely to limit the generalizability of our findings to other populations, such as the elderly or individuals with pathologies. Nevertheless, our primary aim was to investigate the mechanisms of adaptation, retention, and transfer in a sample of healthy young participants, as a first step towards better understanding of these processes in different populations. As it has been shown, however, that obstacle crossing differs between young and older adults (Kovacs 2005; Weerdesteyn et al. 2007), future studies should also investigate these aspects in VR training of older populations.

6.4 Practical relevance and future perspectives

Trained motor adaptations for crossing obstacles, which require precise inter-leg coordination, could potentially prevent accidents in challenging daily life situations. VR training appears to be an effective tool for training these locomotor adaptations. However, the transfer of these adaptations to the untrained leg and to real-life situations is currently limited, which reduces the usefulness of VR training for everyday life (Figure 18). Factors influencing interlimb transfer have already been explored for the upper extremities. However, further research is needed to understand factors influencing interlimb transfer in the lower extremities.

We think that the limited transferability of our virtual reality obstacle avoidance training to the physical world is caused by differences in distance and size perception. Optimizing distance perception in VEs requires attention to quite a number of important factors such as incorporating binocular disparity, utilizing high-quality graphics, fine-tuning virtual camera settings, featuring a regularly structured ground texture and enhancing the user's sense of presence. Importantly however, despite extensive research, the concept of presence remains elusive, making it a valuable area for further study in the context of distance perception. Additionally, advances in rendering technology and hardware may address the issue of graphics quality and its relationship to underestimation of distance in VEs. Another avenue for exploration in both virtual and real environments is the influence of contextual factors (e.g. hallway or open field environment) on distance perception. Additionally, there is a necessity to further explore how sensory information in VR conditions are perceived and cause a recalibration in motor tasks execution and thereby potentially impact the transfer of learned skills to physical world (Figure 18).

Due to the lack of transfer to real situations, probably caused by different estimations of distances and sizes in VEs, VR applications that train specific spatial actions should be considered with caution. It will be worthwhile to examine the conditions under which underestimation of distance can impact the application of VR technology. This applies, among other things, to applications in rehabilitation but also to simulations of, for example, dangerous workplace situations in which spatial parameters play a role. In rehabilitation applications, both arms or legs should be trained for as long as the factors that cause interlimb transfer have not been established. Tilting of VEs can be used in slip and trip fall prevention training as they do not depend on distance-based spatial components and have been shown to transfer to the physical world.

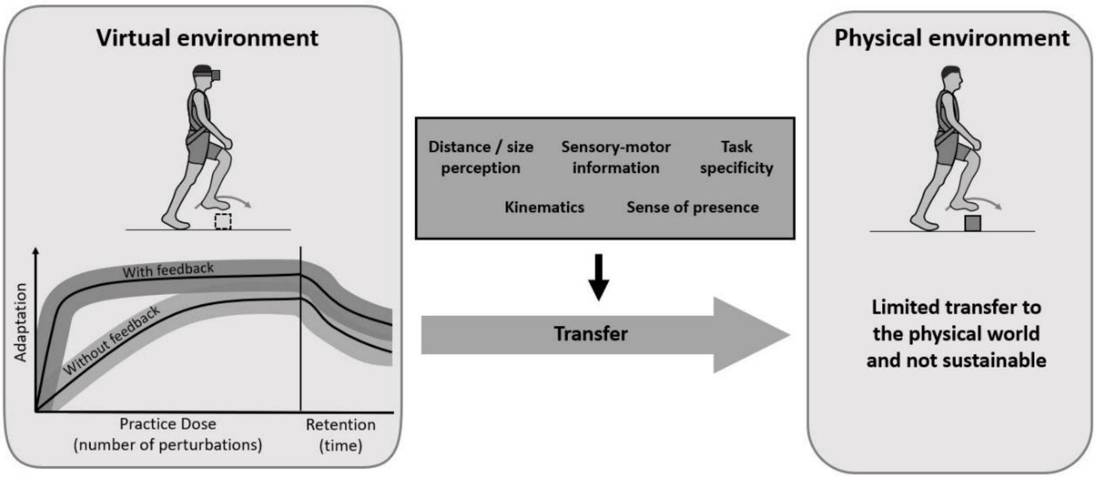

Figure 18*:* Schematic illustration of the findings: virtual reality obstacle avoidance training, can stimulate adaptive changes within the locomotor system that are enhanced with visual feedback. These changes can be retained in the virtual environment. Transfer and retention to the physical environment are, however, limited. Transfer from the virtual to the physical environment may be influenced by distance/size perception, sensory-motor information, task specificity, kinematics and sense of presence.

6.5 Conclusions

In conclusion, the findings of the current thesis revealed that VR-based obstacle avoidance training can stimulate adaptive changes in dynamic stability and toe clearance which are primarily modulated via changes in ankle and knee joint motion during the swing phase of the crossing leg. Moreover, the data from the current work clearly emphasise that providing additional feedback of crossing performance is an effective stimulus to further enhance the rate and magnitude of locomotor adaptations. Feedback may be of importance in increasing the effectiveness of VR training paradigms in healthy and pathological conditions. However, despite significant adaptive changes in locomotion kinematics with repeated practice of VR obstacle crossing, transfer to the untrained leg and to the physical world seems to be limited and can only partially be retained. It may be concluded that perception-action coupling, and thus sensorimotor coordination, in the virtual environment differs from that in the physical world, potentially inhibiting retained transfer between conditions. Accordingly, VR-based locomotor skill training paradigms need to be considered carefully if they are to replace training in the physical world.

7. Appendix: General methods and analysis

7.1 Materials and experimental setup

The virtual environment was created using the game engine Unity (Version 2019.2.7f2, Unity Technologies, San Francisco, CA, USA). It consisted of an endless corridor that moved with the same speed as the treadmill (1.3 m/s). The virtual environment also included a realistic model of the treadmill (pulsar, h/p/cosmos, Nussdorf-Traunstein, Germany), an avatar generated in real-time using motion capture data (13 segment model, 120 Hz, Oqus 7/Oqus 5, Qualisys, Gothenburg, Sweden), and virtual obstacles (Figure 19). The HMD Vive Pro (HTC Corporation, Taoyuan, Taiwan) was used to display the virtual environment. It has a latency of 31.33ms (Le Chénéchal and Chatel-Goldman 2018).

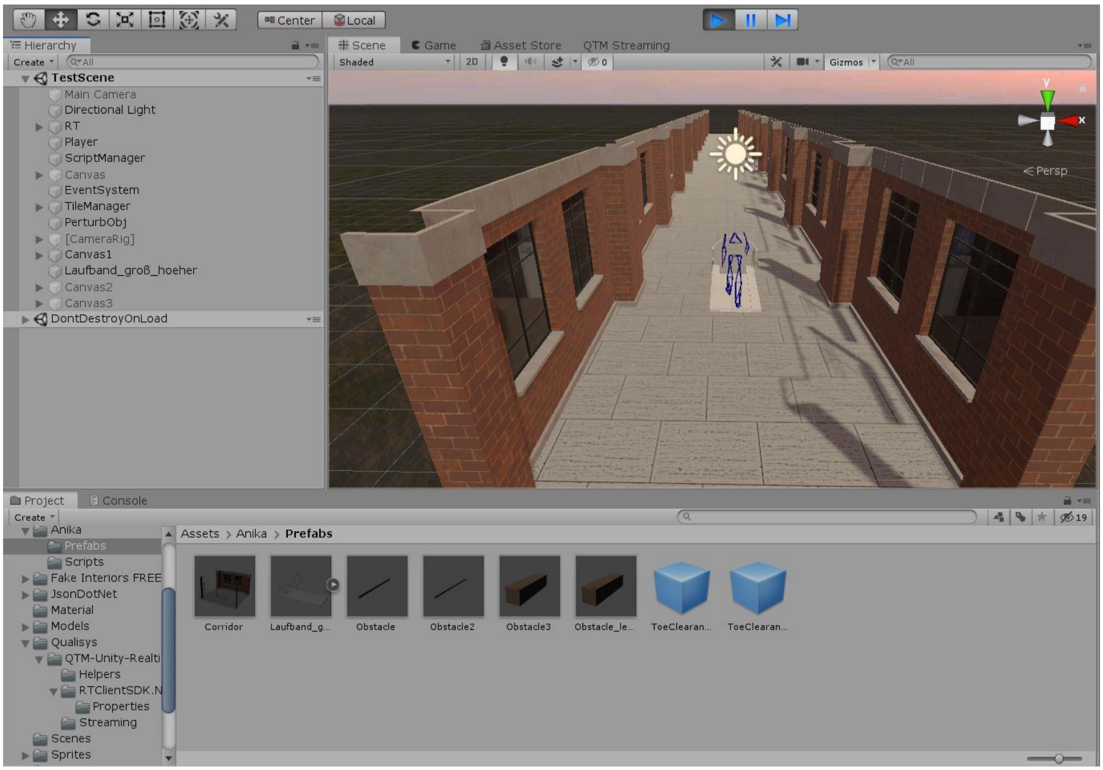

Figure 19: Virtual environment displayed in the game engine Unity containing the endless corridor, the model of the treadmill and the avatar streamed by Qualisys.

The Qualisys real-time streaming package (latency 6-7 ms) enabled the integration of the treadmill position and the participant's avatar within the virtual environment (Figure 20). In this setup, Unity units directly corresponded to real-world meters, ensuring a consistent spatial representation. To ensure the accuracy of the treadmill model, we conducted thorough validations of its essential features. This verification was accomplished by employing a Qualisys marker with a high level of precision (< 1 mm). The avatar's representation was achieved by utilizing the bone segments obtained from the connections of the Qualisys markers. Automatic identification of markers (AIM) was employed to facilitate efficient and reliable marker recognition. The AIM model was tailored to each participant, enabling accurate and consistent marker identification.

To establish seamless integration between the virtual environment and the Qualisys system, a calibration process was performed. The x-axis of the Qualisys system was aligned with the z-axis of Unity by calibrating both facing in treadmill walking direction. Moreover, the origins of both systems needed to coincide. This was achieved by shifting the virtual origin in such a way that the position of the HMD coincided with a virtual Qualisys marker positioned "inside" the HMD. The position of the treadmill was also calibrated by attaching a Qualisys marker to it and coinciding the marker's position with the origin of the treadmill model. Real-time foot touchdown detection was implemented by utilizing a “plane” game object set to the height of the heel marker when the foot was in a flat position on the ground. During normal gait, the trajectory of the heel marker exhibited a local minimum just below this plane at the moment of touch-down. This minimum was used as a trigger to activate both the virtual and mechanical obstacles within the system.

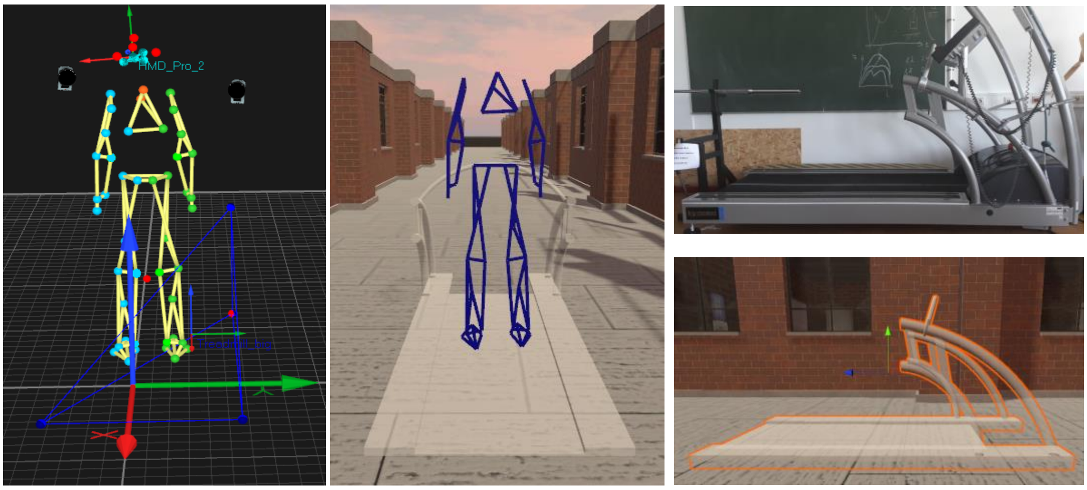

Figure 20: Left: view of markers and bones (yellow) used for avatar streaming and treadmill markers (blue). Middle: view of the virtual environment with the streamed avatar and treadmill position. Right: real treadmill and its virtual model.

To introduce mechanical obstacles, a custom-built obstacle machine was employed. This machine comprised an aluminium bridge positioned at the front end of the treadmill belt, housing an electromagnet. A soft foam obstacle, mirroring the dimensions of the virtual obstacle, was affixed to the electromagnet using a small aluminium plate (Figure 21). The release of the obstacle was controlled via a microcontroller (ESP8266, Espressif Systems, Shanghai, China), which wirelessly communicated with the computer. Unity software was utilized by the study personnel to assist the participants during the familiarization phase, guiding them to maintain the appropriate distance from the obstacle. Additionally, Unity automatically triggered the obstacle release when the participant's heel, upon touchdown, fell within the desired horizontal distance to the obstacle (0.800 ± 0.025 m). Once released, the obstacle descended onto the treadmill, thereby allowing the participant to cross it, after which it landed on a platform located behind the treadmill. To prepare for subsequent crossings, the obstacle was manually reattached to the reactivated electromagnet.

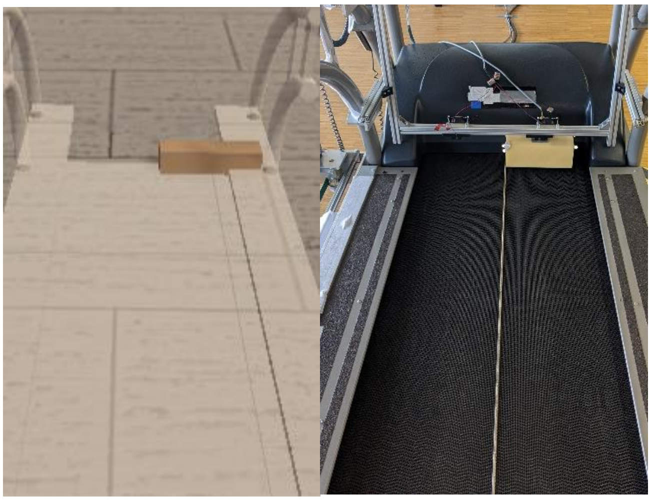

Figure 21: Obstacle setup for virtual and physical environments. In the physical environment, a foam obstacle with the same dimensions as those in the virtual environment was attached to an electromagnet which released the obstacle at foot touchdown of the crossing leg.

7.2 Data analysis / parameters

In order to assess adaptation, retention and transfer we used toe clearance as an indicator of gait efficiency and margin of stability (*MoS*) as indicator of gait stability. In addition, angular kinematics of hip, knee and ankle joints were analysed for joint angle configuration. Toe clearance was defined as the vertical distance between the toe marker and the leading edge of the obstacle when the toe was above the obstacle. The anteroposterior margin of stability at foot touchdown of the crossing leg was calculated as the anteroposterior distance between the base of support (*BoS*) and the extrapolated centre of mass ($XCoM$). BoS was defined as the anteroposterior component of the toe projection to the ground. $XCoM$ was calculated as follows:

$$XCoM = P_{CoM} + \frac{0.5 \times (V_{CoM} + V_{C7}) + V_{Treadmill}}{\sqrt{\frac{g}{L}}}$$

With P_{CoM} calculated as the average position of the four pelvis markers (left and right anterior and posterior superior iliac spines). V_{CoM} and V_{C7} are the first derivatives of P_{CoM} and P_{C7} respectively. $V_{Treadmill}$ corresponds to the treadmill speed which was set to 1.3 m/s. L represents the leg length which was calculated as the distance between the lateral ankle marker and P_{CoM}. g represents the gravitational constant (9.81 m/s²).

In order to examine any joint-related adaptations and analyse changes in coordination, the ankle, knee, and hip joint angles during the swing phase of the crossing leg were computed. The events of foot take off and touchdown were determined using the foot contact algorithm developed by Maiwald et al. (2009). The hip joint angle was derived from the hip and knee joint centres with hip joint centre calculated following the method of Hara et al. (2016). The knee joint angle was calculated based on the hip, knee and ankle joint centres. Lastly, the ankle joint angle was computed using the knee, ankle and midfoot centres.

To identify differences between conditions, Statistical Parametric Mapping (SPM) of the joint angles was utilized. SPM applies Random Field Theory to make statistical inferences about the characteristics of spatially or temporally continuous processes. While commonly employed to detect regionally specific effects in neuroimaging data, such as brain activations, SPM is also frequently used in biomechanics for analysing one-dimensional (1D) data (Pataky 2010). An advantageous feature of SPM is that it eliminates the need for abstracting the originally sampled time series prior to statistical analysis. This allows for a comprehensive examination of the entire 1D field without the requirement of data transformation and without multiple testing. In order to use the MATLAB SPM package (www.spm1d.org) data was time normalised to 101 values (0% to 100% of the swing phase).

8. References

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