



Capture of Stability and Coordination Indicators in Virtual Training Scenarios for the Prevention of Slip, Trip, and Fall (STF) Accidents

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Abstract. The aim of the project is to develop and evaluate a training environment for the prevention of falls with the help of an application in virtual reality (VR). The participants of our study walk on a treadmill with fall protection while immersing into a virtual scenario where they should cross virtual obstacles. Potential parameters reflecting the plasticity of the neuromotor system are investigated in order to search for possible learning effects and their stabilization. In addition, it will be determined how many perturbations (i.e. obstacles) are necessary to establish a learning process. The results will be used to check the experimental setup and to prepare a main study for the development of a training program that helps preventing slip, trip, and fall (STF) accidents using a VR environment. So far two pilot measurements have been completed and parameters that may indicate learning effects were calculated. Initial results do not reveal clear learning effects, however, they inform about relevant adjustments for setting up systematic investigations and provide important details about strategies for data acquisition and analysis.

Keywords: Accident prevention · STF hazards · Virtual reality · Transfer effects · Gait perturbation · Behavioral training

1 Introduction

In Germany, about 20% of all accidents at work are associated with slipping, tripping and falling (STF). A significant percentage of the 176,000 STF accidents in 2015, i.e. almost 3,500 led to such serious injuries that those affected received an accident pension [1]. In addition to painful injuries and even permanent damage to those affected, the accident insured companies incur additional expenses because of lost working days of their employees. Therefore, the prevention of STF accidents has high

relevance not only for occupational health and safety (OSH) but also for economic and social reasons.

Statistics show that a majority (about 60%) of falls take place on ground level resulting from slips and trips [1]. Causes of accidents in this group are manifold and diverse. They may refer to damages of the ground floor, slippery walking ways or left over working and operating equipment on the ground floor. Sometimes, accidents seemingly occur for no reason on stairs or paths. Preventive measures should be based to the hierarchy of controls (STOP model) and take into account a structural redesign that prevents STF hazards as far as possible (e.g. work areas without steps, anti-slip floors). Furthermore, organizational and personal measures (e.g. tidying up work areas and work shoes as personal protective equipment) must not be neglected [2, 3].

In addition to the above-mentioned prevention measures, behavioral prevention measures are particularly suitable for actively involving a large number of potentially affected employees in prevention activities. There are fall prevention programs aiming at training of balance, orientation and reactivity. Investigations carried out in these trainings point to slight improvements in dynamic balance and responsiveness [4]. Recent findings in the development of training concepts to reduce STF hazards indicate that some of the disadvantages of training (e.g. decreasing motivation and endurance of participation, high and long-lasting expenditure of time, availability of training equipment) must be overcome to improve the outcome.

Mechanical training with older people (65 ± 7 yr) has already shown that the neuromotor system has a high plasticity for repeated unexpected perturbations and has the ability to maintain adaptations over longer periods of time (about 1.5 years) [5]. Effects of the use of mechanical perturbation were found to be long-term effects with low training effort and they were rated to reduce the risk of fall injuries [5]. Training studies with perturbations show that the neuromotor system adapts and learns to deal with situations by continuous repetition [6]. Acquired behavioral strategies in trainings are probable to provide long-term fall prevention.

Simulation techniques such as virtual reality (VR) have increasingly being used in training research and for the development of training programs. This is due to easy access to physical training devices in VR, more flexibility for training programs in terms of location and time, and, in addition to modeling options for realistic contexts of training scenarios that may also result in options for the implementation of training content [7].

With the help of VR, several training programs have already been developed that appear relevant and effective in the context of STF accident prevention. Simple training with visual stimuli and postural standing training in a virtual environment resulted in improved static equilibrium parameters (e.g. in terms of limits of stability and confidence ellipse) [8]. Over time, however, these effects are gradually diminishing. In VR-supported training for people with Parkinson's disease, gait parameters improve. In addition, characteristics of cognitive performance improve in terms of better planning capabilities when dodging objects [9]. Treadmill training, in which perturbation is triggered by a sudden inclination of the virtual image, lead to a better interception strategy during transfer into real slipping situations. This can reduce the occurrence of falls. However, long-term effects were not investigated [10]. In another study, visual perturbations were used and compared to visual combined with physical perturbations.

The adjustment and variability in gait induced by purely visual perturbations caused compensatory changes in gait parameters like those obtained in response to physical perturbations [11].

Stimulated by these positive findings, the present study is investigating whether and to what extent criteria from real training settings can depict and reflect aspects of learning success from virtual settings.

2 Methods

2.1 Participant Preparation and Training Procedure

Two healthy young adults participated in the pilot study (Table 1). Participants provided informed consent to take part in the pilot study. They reported adequate or corrected visual acuity, color and stereo vision. Participants did not report orthopedic or neurological impairments.

Table 1. Participant characteristics

	Participant 1	Participant 2
Age (years)	22	26
Sex	Female	Male
Height (m)	1.72	1.79
Body mass (kg)	70	91

Investigations were conducted in the biomechanical laboratory of the University of Applied Sciences Koblenz, RAC, Department of Technology and Mathematics. The participants walked through a virtual course of obstacles on a real treadmill (pluto med, h/p/cosmos, Germany) as an endless walking distance and they stepped over virtual obstacles in recurring sections while walking. For the participant's safety they wore a safety belt on the upper body and the virtual environment included hand rails mapped to the physical handrails of the treadmill. The virtual scene is shown in Fig. 1. A motion capturing system (Qualisys, Sweden) in combination with the VR software system Unity (Version 2018.2.18f1, Unity Technologies, USA) supported acquisition and logging of measurement data. Unity also served for modeling and simulating the virtual environment, which also presented perturbations to the participant on a virtual tour wearing the head mounted display (HMD) HTC Vive Pro (HTC Corporation, Taiwan) with a wireless adapter. In addition, data from the motion capturing system was used to visualize the schematic human body in VR. The virtual environment was constructed using assets in Unity. The handrail was built with Solidworks (Education Edition, Dassault Systems, France) and imported in Unity. Potentially relevant movement parameters for the plasticity of neuromotor systems were recorded, especially during crossing of virtual obstacles (e.g. toe clearance, toe distance and crossing versus precrossing stride length) [12].

The treadmill speed was set to 1.3 m/s according to the speed of the virtual environment. In intervals of about 15 s to 25 s chosen at random, after initially hitting the ground with the foot, a perturbation obstacle was generated 1.5 m in front of the participant. The dimensions of the obstacle were 100 mm by 100 mm by 4000 mm. Stepping over the obstacle triggered an event in the motion capturing software Qualisys Track Manager (QTM). Participants were required to always step over the obstacle with the right foot. Before the measurement was started, the participants were asked to move randomly for about 15 s. This information was used to create an AIM (automatic identification of markers) model that is needed for the visualization of the participants' body in VR. At the beginning, participants walked for about 3 min on the treadmill using VR without perturbations to get used to walking on the treadmill with HMD and VR. Afterwards, the perturbation session started. The participant walked on the treadmill for 50 perturbations.

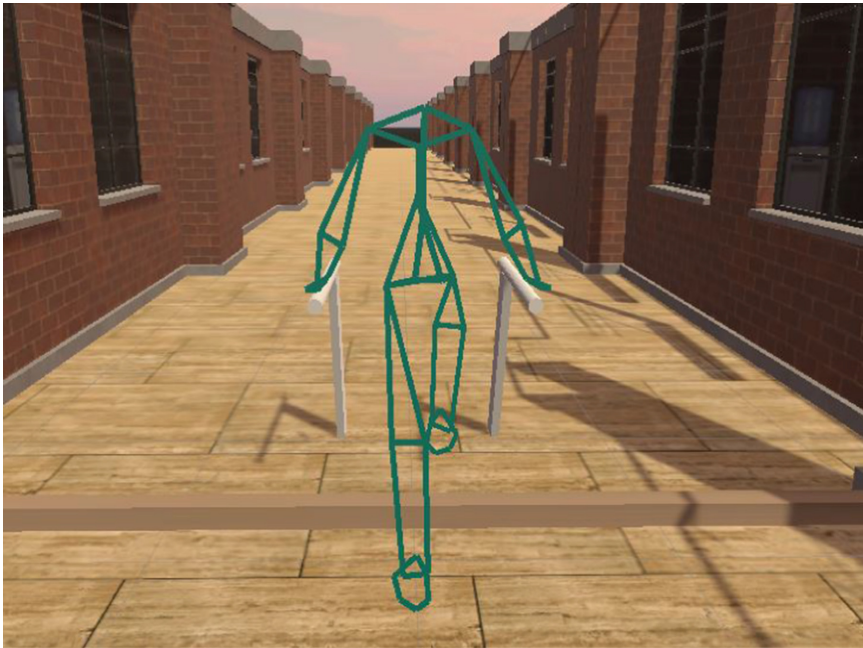


Fig. 1. Reproduction of participant stepping over an obstacle in VR.

As participants walked on the treadmill, gait kinematics were measured using an 8-camera Qualisys motion capture system. Kinematic data was recorded at 120 Hz using a 42-marker modified dynamicus alaska model. Four infrared markers were placed on the HMD and six markers were placed on the trunk (right and left acromioclavicular, C7, T10, clavicle and sternum). Four markers were placed on the pelvis (right and left anterior and posterior superior iliac spine). 10 markers were placed at the left and right arms (elbow lateral, elbow medial, wrist lateral, wrist medial, third meta head).

22 markers were placed at the left and right legs (medial knee, lateral knee, tibia, medial ankle, lateral ankle, heel, back foot medial, back foot lateral, second meta head, fifth meta head and toe). A fully equipped participant is shown in Fig. 2.



Fig. 2. Measurement setup on the treadmill with a participant wearing markers. The participant is safeguarded against fall by a safety belt on the upper body attached to the beam of the treadmill.

2.2 Data Analysis

Human gait is characterized by a cyclic pattern of toe offs (TO), and touch downs (TD) on alternating sides of the body. The time at which the toe leaves the ground is called TO. TD is the time frame at which the foot initially hits ground. TO and TD can be identified by analyzing the changes in position of kinematic markers placed on the participant. From these events, temporal parameters such as step length (SL: distance from TD to TO of the opposing feet) and step width (SW: distance from medial to lateral distance between the feet) can be determined. The quantification of gait characteristics can be used to investigate the participant's ability to control balance during exercise and to study balance compensation in response to external disturbances.

Anatomical markers from the motion capture system were labeled and processed in QTM. All calculations were performed using a customized routine written in MATLAB (Version 9.3.0, The Mathworks Inc., Natick, USA).

The calculated parameters are shown in Fig. 3. Toe clearance is calculated as the height of the toe marker when the marker is above the leading edge of the perturbation obstacle minus the height of the obstacle. Critical toe clearance is calculated as the minimum distance between toe and heel marker and front and rear edge of the perturbation obstacle. Lead and trail foot distance are calculated as the horizontal distance between the toe markers and the leading edge of the obstacle at toe off. TD and TO are determined using the foot contact algorithm (FCA) [13]. Therefore, data is filtered with a low-pass filter set at 50 Hz. To identify different types of foot strikers, time frames of the vertical position of the heel and the fifth meta head markers are compared. A time interval around this minimal position is defined. To estimate touch down, FCA uses a characteristic maximum in the vertical acceleration curve of the target marker in the given approximation interval. For toe off, a local maximum in the vertical acceleration of the toe marker is detected and compared to the minimal vertical position of the toe marker. A logical operation selects the event that occurs earlier in time, which is then used to estimate the time of toe off.

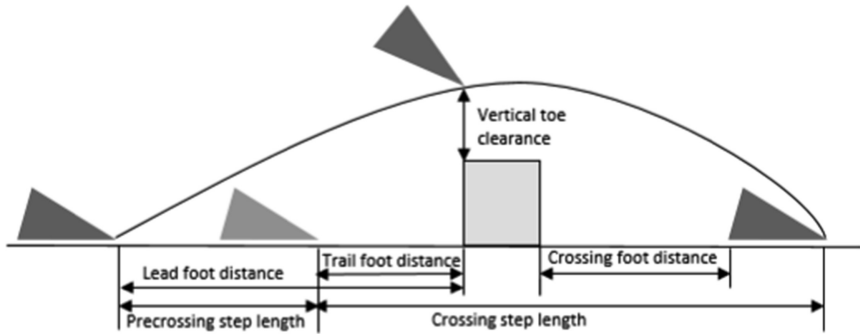


Fig. 3. Recorded gait parameters for both feet when crossing obstacles.

2.3 Margin of Stability (MoS)

In the static case, a body is stable when the center of mass (CoM) is located within the boundaries of support (BoS).

The dynamic balance control is characterized by the fact that the CoM is kept within the bounds of the feet during the gait cycle. A CoM outside the bounds of the feet represents a more unstable system and carries the risk of falling. To maintain balance under unstable conditions, healthy participants typically increase step width and MoS, and decrease step length [14].

To determine MoS, the movement of the CoM is represented as an inverted pendulum [15]. The CoM position can be determined as the average of the four pelvis markers at the time frame of TD. Extrapolated center of mass (XCoM) is calculated according to Eq. 1 [16]:

$$XCoM = CoM_{Position} + \frac{CoM_{Velocity}}{\omega_o} \quad (1)$$

$$\omega_o = \sqrt{\frac{g}{l}} \quad (2)$$

Equation 2 consists of the gravitational constant ‘g’ and the equivalent pendulum length ‘l’, which is taken as the distance from the lateral heel marker to the COM at heel strike. MoS is defined as the vertical distance between XCoM and the anterior boundary of support, which is visualized in Fig. 4.

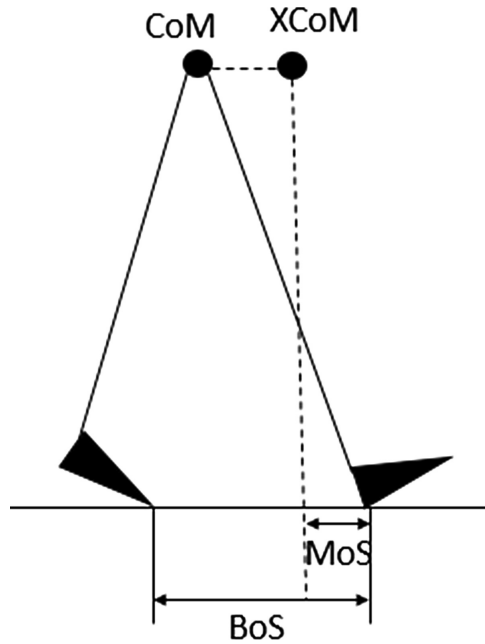


Fig. 4. Margin of stability

3 Results, Challenges and Limitations

The above-mentioned setup and data analysis could be performed without any problems. The evaluation routines are now available for further measurements in order to determine the mentioned parameters.

Future studies will also contain measuring muscular activity via EMG of the leg muscles to quantify proactive and reactive changes due to training. EMG can show co-contractions of muscles which indicate a more stiff and unstable gait.

Since the obstacles are not visible in Qualisys, they have to be calculated from given data. For this, the time at which the event was created in Qualisys is used. At this

time, the toe marker is located exactly above the front edge of the obstacle. The position, speed and dimensions of the perturbation obstacle can be used to calculate the position at any time. However, the accuracy of these calculations still needs to be validated. This allows calculation of parameters such as the critical clearance for the toe and heel marker, as well as the distance to the obstacle.

The human gait has the disadvantage that the CoM lies high above a small BoS. Small deviations from a perfect body orientation lead to significant gravitational moments that accelerate the body away from this orientation and can easily move the CoM away from the BoS, which then leads to falls. In the sagittal plane, the body moves the CoM outside the BoS during each of the single support phases of the gait cycle. Therefore, it can be assumed that when this pattern is interrupted, e.g. by a suddenly appearing object or the slipping of a foot, a fall often occurs. In addition to a good reactivity, it is necessary to have a good interception strategy should a trip occur. This also requires a good general ability to balance and control appropriate muscles. Therefore, many of the STF prevention trainings use balance and strength training but they do not prevent the actual trip. Toe and heel clearance as well as critical clearance, are important parameters because they show if a trip would have occurred. In a normal learning process, participants would first step high over the obstacles but then reduce the distance to the obstacle because the body always wants to move in an efficient way.

Initial results with two participants do not reveal specific learning effects after 50 perturbations. This could be due to different reasons. One reason that parameters chosen do not indicate a learning effect could be due to VR. The field of view is restricted by the VR goggles. When looking through the HMD the field of view is restricted to 100° horizontal and vertical. Therefore, in contrast to human behavior in reality, in VR participants were required to bend the head in order to look at their feet. With the restricted field of view in VR, participants cannot see the perturbation obstacles when looking straight forward/ahead. In reality, perturbations or obstacles would be visible because the field of view is about 150° vertical and 210° horizontal [17]. There are already VR glasses with a field of view of 130° vertical and 210° horizontal, which also have a better resolution than the HTC Vive. With the aim to develop training procedures for use at the shop floor or at home, the preferred choice for the HMD would rather be a cost effective consumer product. Another VR issue is related to the realism of the virtual environment and a potential impact on human behavior. The scenario could be improved by changing the lighting and using a humanoid avatar instead of a stick figure to create body presence. In this scenario, it would also be possible to use photorealistic models of the environment and the obstacle. In order to find out more about this issue, a usability study should inform about the quality of the virtual environment and its use as a training scenario in the present context.

Maybe the training period was too short to determine training effects. Therefore, it is possible to do three training periods of 15 min length with a break of 5 min between them.

The task may have been too difficult at given treadmill speed, so that the participants were predominantly concentrating at holding their balance while walking on the treadmill with VR. While VR only influences postures while working stationary by small margins [18], several studies have already shown gait changes while walking in

virtual reality [11], e.g. a reduced SL and increased MoS indicating an unstable gait, a reduced treadmill speed may result in improvements in training parameters.

In future measurements, it will be investigated whether participants no longer need to hold on to the handrails with reduced speed of the treadmill so that participants no longer need to hold on to the handrails. In addition, the familiarization period with VR and the treadmill should be extended. This should lead to the participants walking at the right speed themselves and therefore no longer having to hold onto the handrails. Then it is also possible to determine MoS, which is a very reliable parameter for dynamic balance.

Another effect could possibly be diminished by reducing the speed of the treadmill. Longer Treadmills have to be considered so that participants do not have to walk in the rear of the treadmill, as otherwise they would come up against the cover of the treadmill motor when crossing obstacles.

4 Conclusion

The prevention of STF accidents is not only of utmost importance from an occupational safety and health point of view, but also very relevant for economic and social reasons. The project is in the process of developing a VR training program that should enable fall prevention possibly after only a single training session. Several studies have shown VR to be a promising tool to support behavioral learning in virtually hazardous situations in a safe environment [10, 11]. When a training effect can be demonstrated, our approach should be able to serve a solid basis for conducting training courses for example as part of events to promote health and safety at the workplace. A desirable aim is to develop recommendations for further actions.

Initial results do not reveal clear learning effects, however, they inform about relevant adjustments for setting up systematic investigations and provide important details about strategies for data acquisition and analysis in the calculated parameters.

References

1. DGUV: Statistik. Arbeitsunfallgeschehen 2015. Deutsche Gesetzliche Unfallversicherung (DGUV), Berlin (2016). https://publikationen.dguv.de/dguv/pdf/10002/au_statistik_2015.pdf
2. Lehto, M.R., Cook, B.T.: Occupational health and safety management. In: Salvendy, G. (ed.) Handbook of Human Factors and Ergonomics, pp. 701–733. Wiley, Hoboken (2012). ISBN 978-0-470-52838-9
3. EU OSH Framework Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work. Official Journal of the European Union L 183, 29/06/1989, pp. 1–8 (2008)
4. Mohr, J.-O.: Fit gegen das Stolpern – Projektstudie der HFUK Nord. In: Ellegast, R. (ed.) 6. DGUV Fachgespräch Ergonomie. Zusammenfassung der Vorträge vom 2/3, November 2016, pp. 125–127. Deutsche Gesetzliche Unfallversicherung e. V. (DGUV), Berlin (2017). ISBN 978-3-86423-201-5

5. Epro, G., Mierau, A., Mccrum, C., Leyendecker, M., Bruggemann, G.-P., Karamanidis, K.: Retention of gait stability improvements over 1.5 years in older adults: effects of perturbation exposure and triceps surae neuromuscular exercise. *J. Neurophysiol.* **119**(6), 2229–2240 (2018). <https://doi.org/10.1152/jn.00513.2017>
6. Pai, Y.-C., Yang, F., Bhatt, T., Wang, E.: Learning from laboratory-induced falling: long-term motor retention among older adults. *Age* **36**(3), 1367–1376 (2014). <https://doi.org/10.1007/s11357-014-9640-5>
7. Hale, K.S., Stanney, K.M. (eds.): *Handbook of Virtual Environments: Design, Implementation, and Applications*. CRC Press, Boca Raton (2015). ISBN 9781138074637
8. Duque, G., et al.: Effects of balance training using a virtual-reality system in older fallers. *Clin. Interv. Aging* **8**, 257–263 (2013). <https://doi.org/10.2147/cia.s41453>
9. Mirelman, A., Maidan, I., Herman, T., Deutsch, J.E., Giladi, N., Hausdorff, J.M.: Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in patients with parkinson's disease? *J. Gerontol. Ser. Biol. Sci. Med. Sci.* **66A**(2), 234–240 (2010). <https://doi.org/10.1093/gerona/gdq201>
10. Parijat, P., Lockhart, T.E., Liu, J.: Effects of perturbation-based slip training using a virtual reality environment on slip-induced falls. *Ann. Biomed. Eng.* **43**(4), 958–967 (2014). <https://doi.org/10.1007/s10439-014-1128-z>
11. Riem, L., Van Dehy, J., Onushko, T., Beardsley, S.: Inducing compensatory changes in gait similar to external perturbations using an immersive head mounted display. In: *Proceedings of the 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 128–135. IEEE, New York (2018). <https://doi.org/10.1109/vr.2018.8446432>
12. Rietdyk, S., Rhea, C.K.: The effect of the visual characteristics of obstacles on risk of tripping and gait parameters during locomotion. *Ophthalmic Physiol. Opt.* **31**(3), 302–310 (2011). <https://doi.org/10.1111/j.1475-1313.2011.00837.x>
13. Maiwald, C., Sterzing, T., Mayer, T.A., Milani, T.L.: Detecting foot-to-ground contact from kinematic data in running. *Footwear Sci.* **1**(2), 111–118 (2009). <https://doi.org/10.1080/19424280903133938>
14. Hak, L., et al.: Speeding up or slowing down? Gait adaptations to preserve gait stability in response to balance perturbations. *Gait Posture* **36**(2), 260–264 (2012). <https://doi.org/10.1016/j.gaitpost.2012.03.005>
15. Winter, D.: Human balance and posture control during standing and walking. *Gait Posture* **3**(4), 193–214 (1995). [https://doi.org/10.1016/0966-6362\(96\)82849-9](https://doi.org/10.1016/0966-6362(96)82849-9)
16. Hof, A.L., Gazendam, M.G.J., Sinke, W.E.: The condition for dynamic stability. *J. Biomech.* **38**(1), 1–8 (2005). <https://doi.org/10.1016/j.jbiomech.2004.03.025>
17. Traquair, H.M.: *An Introduction to Clinical Perimetry*. Henry Kimpton, London (1938)
18. Friemert, D., Saala, F., Hartmann, U., Ellegast, R.: Similarities and differences in posture during simulated order picking in real life and virtual reality. In: Duffy, Vincent G. (ed.) *DHM 2018*. LNCS, vol. 10917, pp. 41–53. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-91397-1_4