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Performance of a visuomotor walking task in an augmented reality training setting

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ABSTRACT

Visual cues can be used to train walking patterns. Here, we studied the performance and learning capacities of healthy subjects executing a high-precision visuomotor walking task, in an augmented reality training set-up. A beamer was used to project visual stepping targets on the walking surface of an instrumented treadmill. Two speeds were used to manipulate task difficulty. All participants (n = 20) had to change their step length to hit visual stepping targets with a specific part of their foot, while walking on a treadmill over seven consecutive training blocks, each block composed of 100 stepping targets. Distance between stepping targets was varied between short, medium and long steps. Training blocks could either be composed of random stepping targets (no fixed sequence was present in the distance between the stepping targets) or sequenced stepping targets (repeating fixed sequence was present). Random training blocks were used to measure non-specific learning and sequenced training blocks were used to measure sequence-specific learning. Primary outcome measures were performance (% of correct hits), and learning effects (increase in performance over the training blocks: both sequence-specific and non-specific). Secondary outcome measures were the performance and stepping-error in relation to the step length (distance between stepping target). Subjects were able to score 76% and 54% at first try for lower speed (2.3 km/h) and higher speed (3.3 km/h) trials, respectively. Performance scores did not increase over the course of the trials, nor did the subjects show the ability to learn a sequenced walking task. Subjects were better able to hit targets while increasing their step length, compared to shortening it. In conclusion, augmented reality training by use of the current set-up was intuitive for the user. Suboptimal feedback presentation might have limited the learning effects of the subjects.

1. Introduction

Gait training on a treadmill is often not experienced as an engaging activity, since subjects (both healthy and patients) usually do not have to pay much attention during steady walking (Mazaheri et al., 2014). A popular method to increase the motivation of the user is adding explicit goals (targets/games) to the training environment, using computer-generated environments. Two types of computer-generated environments can be distinguished: virtual reality and augmented reality. The first is already widely applied in

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training situations and the second is increasing in popularity. Virtual reality creates an artificial environment, where the visual representation is separated from the physical walking environment and the user solely interacts with the computer-generated world rather than with the real world. In training situations, this is often done by the use of a motion capture system that records body movements and displays these on a screen by using an animation (Adamovich, Fluet, Tunik, & Merians, 2009). Augmented reality integrates computer-generated elements within the real world. The visual representation is incorporated into the physical walking environment and the user interacts with the real world, which is overlaid with computer-generated elements. For example, by using beamers or other projection systems that project visual objects on an instrumented treadmill. Movements of the user directly interact with the game, without interference of a motion capture system or a screen in front of the user.

Visual feedback presented by both types of computer-generated environments (virtual reality as well as augmented reality) positively contributes to learning motor tasks (Darekar, McFadyen, Lamontagne, & Fung, 2015; Lange et al., 2010). They can be used to manipulate training-context, thereby influencing context-specific learning and promoting transfer of learning to other situations (Kloter & Dietz, 2012; McVea & Pearson, 2007). van Diest, Lamoth, Stegenga, Verkerke, and Postema (2013) investigated the use of virtual reality for balance improvements in elderly and found positive training results due to an increased motivational component compared to regular training. Choi, Jensen, and Nielsen (2016) used a virtual reality training set-up to show that visual feedback can be used to improve sequence learning. In particular, the results of the study implicate that by use of this training set-up, sequence learning can be integrated with a highly automatic task such as walking, even over a relatively small period of only 300 steps. In a virtual reality set-up, proprioceptive information needs to be remapped to what is seen on a screen. The results by Choi et al. therefore also showed a non-specific learning curve, as subjects increased on task performance throughout the course of the experiment. We hypothesize that augmented reality might be more intuitive to the user on this aspect, as the real world is already integrated in the training set-up. Several studies (Fonteyn et al., 2014; van Ooijen et al., 2015) have demonstrated that augmented reality training can successfully be used for gait adaptability training in various patient groups. The results show that after a period of training in such an environment, subjects are better able to modulate their steps to the environment. However, contrary to the virtual reality environment, the effects of (sequenced) locomotor learning in an augmented reality training environment, have yet not been presented in literature. Performing such a study improves our knowledge on the performance and learning capacities (either non-specific or sequence specific) of subjects in relation to such a training set-up. This knowledge might ultimately lead to a better understanding of the different computer-generated environments, their applicability in training situations, and might thereby contribute to the improvement of training programs.

The goal of this paper is therefore to study locomotor performance and learning capacities as a result of augmented reality training. Participants performed a visuomotor walking task, where they must change their step length to hit visual targets while walking on a treadmill in an augmented reality environment. The study design was derived from Perez, Wise, Willingham, and Cohen (2007), Willingham, Wells, Farrell, and Stemwedel (2000), who have presented a method to identity training effects in motor learning tasks. Augmented reality training is expected to be intuitive to the user, therefore it was hypothesized that subjects are able to hit the visual targets at first try and that they show the ability to learn a sequenced walking task.

2. Materials and methods

Twenty participants (age 28.5 ± 7.2 years, 9M/11F) completed the training and all participants performed seven consecutive blocks of training to measure the performance and learning effects. This study was approved by the local Institutional Review Board. All methods conformed to the Declaration of Helsinki. All subjects gave written informed consent prior to participation.

2.1. Apparatus

The C-Mill (MotekForceLink, Amsterdam, The Netherlands) was used for the walking tasks. The C-Mill consists of an instrumented treadmill with an embedded force platform and a beamer that projects visual stepping targets (10 × 10 cm) on the walking surface (Fig. 1A) and therefore represents an augmented reality training environment. Position of foot placement was defined as the center of pressure (CoP) at the end of mid-stance, meaning that at that time it was underneath the (marked) 5th metatarsal (Winter, Patla, & Frank, 1990). The supplied CueFors 2.0 Software provides spatiotemporal data with respect to the presented visual targets.

2.2. Procedure

Within the training set-up, two groups of ten participants were formed based on a (randomized) imposed walking speed. Speed was set at 2.3 ± 0.2 km/h for the lower speed group and 3.3 ± 0.2 km/h for the higher speed group, to manipulate task difficulty.

We measured the change in performance across seven consecutive training blocks (performed on the same day), each block consisting of 100 stepping targets (and thus 100 steps) (Fig. 1B). Stepping targets were placed at short (80% of medium step length), medium (100%) or long (120%) stepping distances, in a random or sequenced order depending on the training block in the experiment. The medium step length was equal to 2/3 of the subject's leg length. Width between the stepping targets was set in correspondence to the step width of each subject. The first random block (*R1*) was used to familiarize the subject to the task. In this block, distance between stepping targets was presented in a random manner, with no recurring pattern in the distance between the stepping targets. The second random block (*R2*) provided a measure of final baseline performance and again, a random order was used in the distance between the stepping targets to evoke a mixture of short, medium and long steps. In the subsequent third, fourth and fifth training blocks (referred to by Fig. 1B as *S1*–*S3*), participants were presented with a repeating step length sequence. This

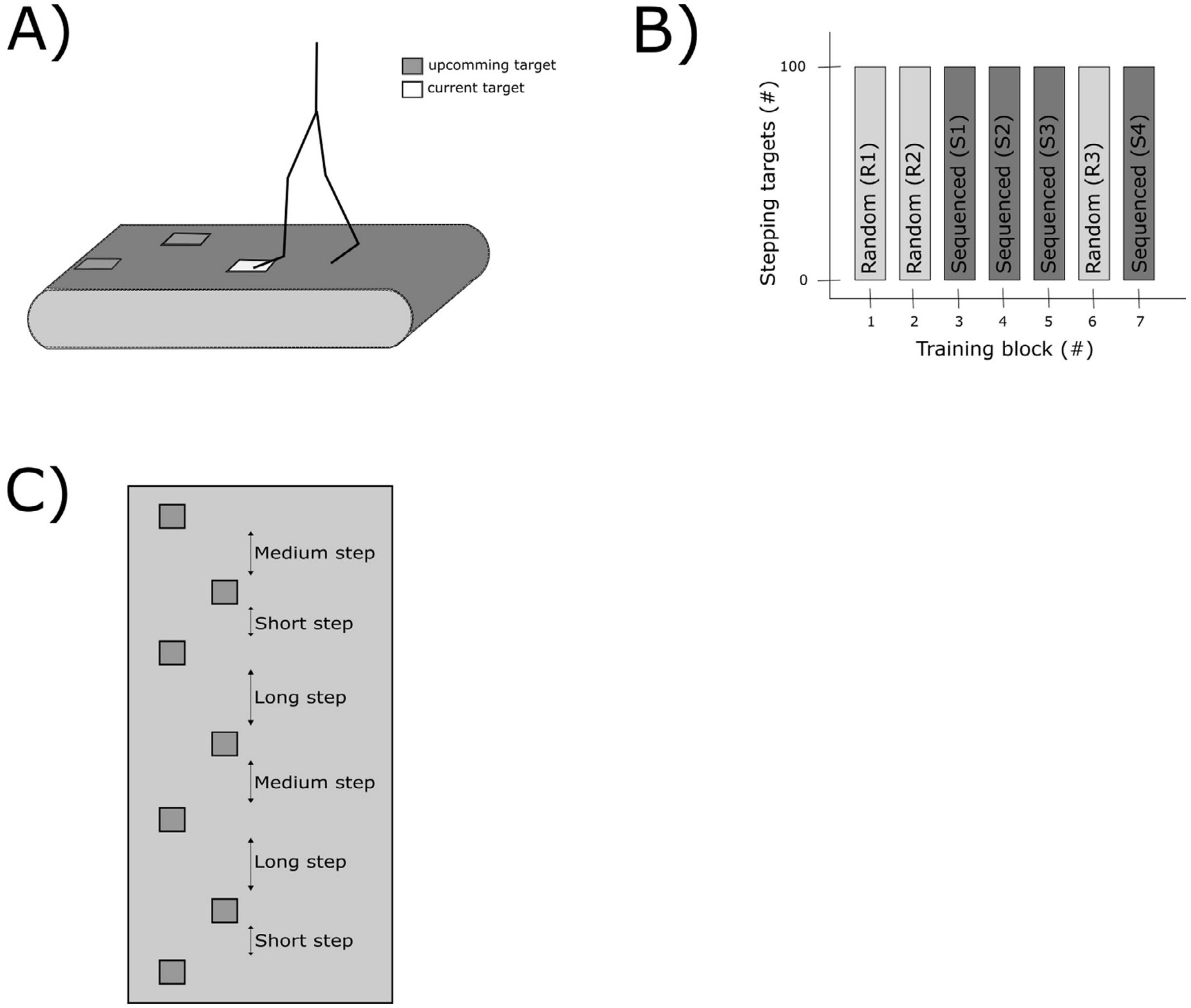

Fig. 1. Visuomotor experiment set-ups. A) Augmented Reality set-up: stepping targets projected on the treadmill. B) Stepping tasks over seven consecutive training blocks. Each stepping task is composed of 100 stepping targets. Stepping targets can either be placed in a random order or in a sequenced order. C) Representation of the fixed sequence that is continuously presented throughout the 100 stepping targets of each Sequenced Training Block (S1–S4). This fixed sequence is thus repeated 14.2× within each training block, to span a total of 100 stepping targets.

fixed sequence (short-long-medium-long-short-medium step length, see Fig. 1C) was constantly repeated within a training block and over the three training blocks (*S1–S3*), making these training blocks identical. The fixed sequence was thus repeated 14.2 times within a training block of 100 stepping targets. Participants were not explicitly informed about the structure of the sequences. The sixth training block was composed of random stepping targets (referred to as *R3*) where no fixed sequence was presented. In the last, seventh training block, participants were again presented with the fixed sequence of training block *S1–S3*. This training block measured the ability of subjects to recall the fixed sequence to which they were exposed before.

We instructed the participants to step in the middle of the visual stepping targets as accurately as possible, aiming with the marked 5th metatarsal on their feet.

Real-time visual feedback was provided to the subject during the experiment, by changing the color of target on a successful hit (green to white, indicating that white was a hit).

2.3. Data analysis

Primary outcome measures are performance (% correct hits in each block), and learning effects (amount of increase in performance over training blocks). A hit (positive score) was counted each time the distance between the center of the stepping target and foot placement was ≤5 cm in the anterior-posterior direction. Percentage of correct hits was calculated for each subject individually. Afterwards scores were averaged over all subjects within each training block separately, representing the performance.

Learning effects were divided in non-specific learning effect and sequence-specific learning effects. Non-specific learning represents the general increase in task performance throughout the course over the experiment. It was calculated as the difference between random training blocks R2 and R3 (Perez et al., 2007). Both training blocks use a random target order. The difference in performance is therefore only due to a general increase in task performance. Sequence-specific learning represents the ability to learn a specific sequence pattern while performing a highly automatic walking task. It was calculated as the difference in performance between the sequenced training block S3 and the random training block R3 (Perez et al., 2007; Willingham et al., 2000). It is presumed that the decline in performance between the two consecutive blocks is due to the lack of sequenced targets in random training block R3.

Secondary outcome measures are the performance (% correct hits) in relation to step length (short, medium, long steps) and the stepping error (distance from target) in relation to step length.

For short, medium and long steps, the distance between the foot position and the border of the stepping target (i.e., stepping error) was calculated. Stepping error was only calculated for steps in which no hit was encountered. Stepping error could either be positive (when subjects overshoot their target) or negative (when subjects undershoot their target).

Data was analyzed by using mixed models analysis (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 19.0. Armonk, NY: IBM Corp.) to investigate training effects over the seven consecutive training blocks, to investigate effects of both speeds on outcome measures and the interaction effects (training blocks*speed). If significant results were obtained, Dunn-Šidác (Šidák, 1967) was used for post hoc pairwise analysis, in order to study non-specific and sequence-specific learning effect (i.e. compare performance scores on training block R2 and R3 and training block S3 and R3 respectively).

3. Results

All 20 subjects completed the experiment. Leg length and (medium) step length were 0.89 m ± 0.029 m and 0.59 m ± 0.019 m respectively. No statistical significant differences were found between the subjects of the lower and higher speed experiments regarding these demographic characteristics ($p > .15$). Cadence was kept constant for each training set-up over the seven training blocks and were 67.1 ± 0.4 steps/min for the lower speed, and 92.9 ± 0.7 steps/min for the higher speed.

3.1. Performance

Performance (training score) over the different training blocks is presented in Fig. 2 for both speeds. Mixed model analysis indicated a significant effect of speed on performance ($F(1,18) = 16.262$, $p = .001$), where training at higher speed elicits lower performance scores.

Furthermore, interaction effects were calculated (training blocks*speed) and were found non-significant ($F(6,108) = 0.643$, $p = .695$). This demonstrates that the effect of training time (performance over the course of the different training blocks) on the change in performance was not different between the two speeds. This is also visible in the graphs: both speeds show consistent results. Specific details on this latter aspect are presented in the section below about learning effects.

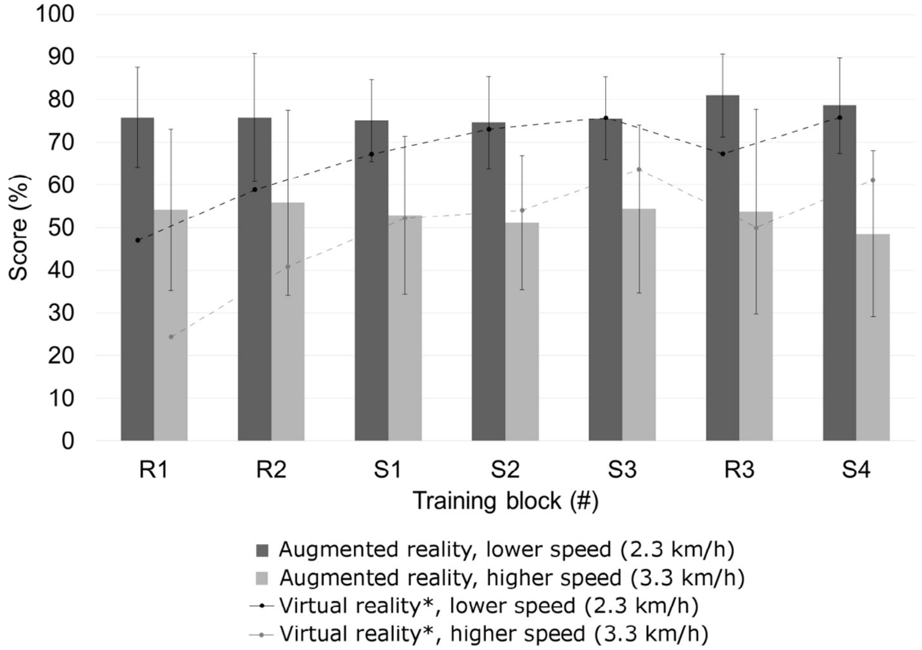

Fig. 2. Performance over training blocks. Performance (% of correct hits) over the seven consecutive training blocks after training at low (dark grey) and higher (soft grey) speed. *Virtual reality results have been retrieved from Choi et al. (2016).

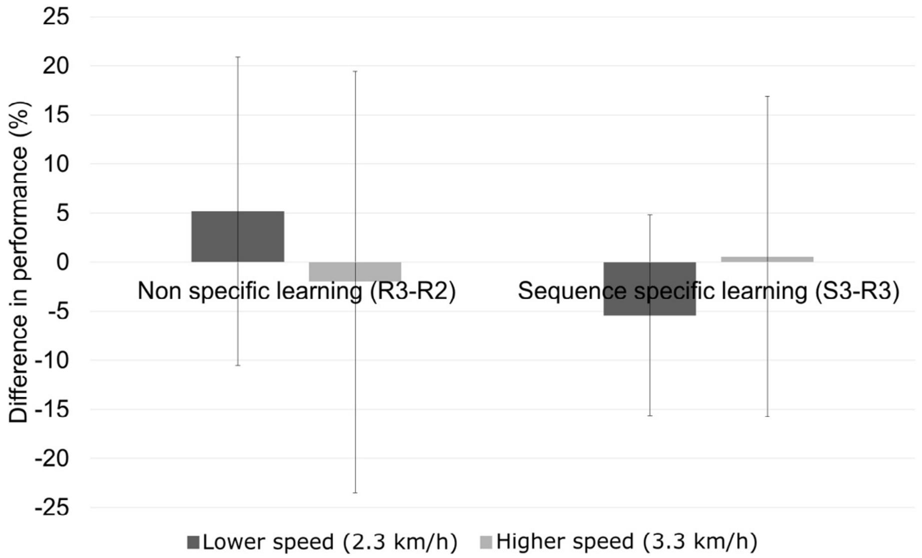

Fig. 3. Learning effects. Learning effects presented at both speeds. Non-specific learning is calculated as R3-R2, sequence-specific learning as S3-R3. A positive value in the graph indicates a (although non-significant) learning effect.

Compared to performance in the virtual reality task used in Choi et al. (2016), subjects performed better in the augmented reality task, especially in the first two blocks (Fig. 2, bars vs. dashed lines). The results suggest that the nature of the visual feedback plays an important role in guiding step length adjustments (see Discussion).

3.2. Learning effects

No deviations in performance were observed by the mixed model analysis over the different training blocks of the experiment, either at higher speed (F(6,54) = 0.440, p = .849) or at lower speed (F(6,54) = 0.736, p = .623). Therefore, neither non-specific learning effects, nor sequence specific learning effects were present after training in this current augmented reality training set-up, at both speeds.

Fig. 3 presents the difference between training block R3 and R2, and between training block S3 and R3, thereby showing the lack in non-specific and sequence specific learning effects respectively at both speeds.

3.3. Stepping error in response to step length variation

Mixed model analysis showed (at both speeds) significant different performance scores as a result of step length variation (F(2,18) = 7.636, p = .004 for the lower speed and F(2,18) = 9.982, p = .001 for the higher speed). Post-hoc analysis identified that subjects were better able to hit the targets while increasing their step length, compared to shortening their step length (see Fig. 4).

Additionally, stepping errors (Fig. 5) were larger while subjects had to shorten their step length at the lower speed, compared to increasing their step length (F(2,18) = 26.081, p < .001), but not at the higher speed (F(2,18) = 2.039, p = .159). However, stepping error was found equally large at both training speeds (F(1,18) = 1.775, p = .199). The positive value of the averaged stepping errors indicates that subjects tend to overshoot their target.

4. Discussion

The main purpose of this study was to investigate the performance and learning capacities of subjects performing an augmented reality visuomotor walking task. In accordance to our hypothesis, the results indicate that executing such a task is intuitive for participants when the targets are projected in an augmented reality setting. Proprioception and vision do not have to be remapped in such a situation: step adjustments can directly be targeted and no learning is required (Bank, Roerdink, & Peper, 2011). Participants only have to focus on the task itself and do not have to perform a task, while remapping at the same time. Maximal training score after the first block of training was around 76% for the lower treadmill speed (2.3 km/h) and 54% for the higher treadmill speed (3.3 km/h), implicating that subjects had more difficulty to hit the targets correctly at the higher speed. Wezenberg, de Haan, van Bennekom, and Houdijk (2011) and Peper, Oorthuizen, and Roerdink (2012) indicate that both energy expenditure and attentional demands increase when subjects perform a visuomotor walking task, compared to regular walking without a stepping task. Peper, de Dreu, and Roerdink (2015) confirm this observation by showing that comfortable walking speed decreased when subjects had to perform a visuomotor stepping task, compared to uncued walking. Preferred walking speed thus decreases when task difficulty increases. The decreased performance that was observed at the imposed higher walking speed in this study is therefore assumed to be the result of an

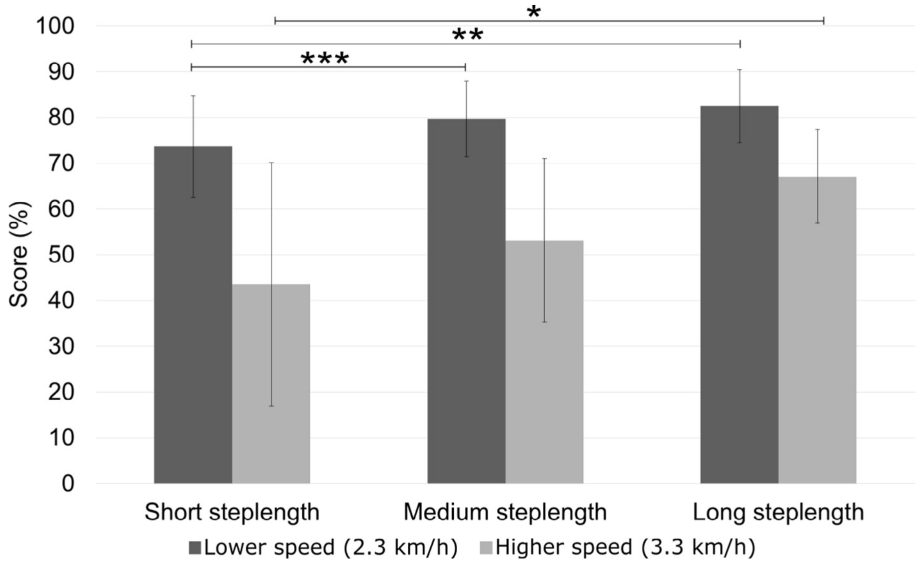

Fig. 4. Performance over different step lengths. Performance (% of correct hits) of short, medium and long steps of the entire training, at lower (dark grey) and higher (soft grey) speed. *p = .001; **p = .005; ***p = .024.

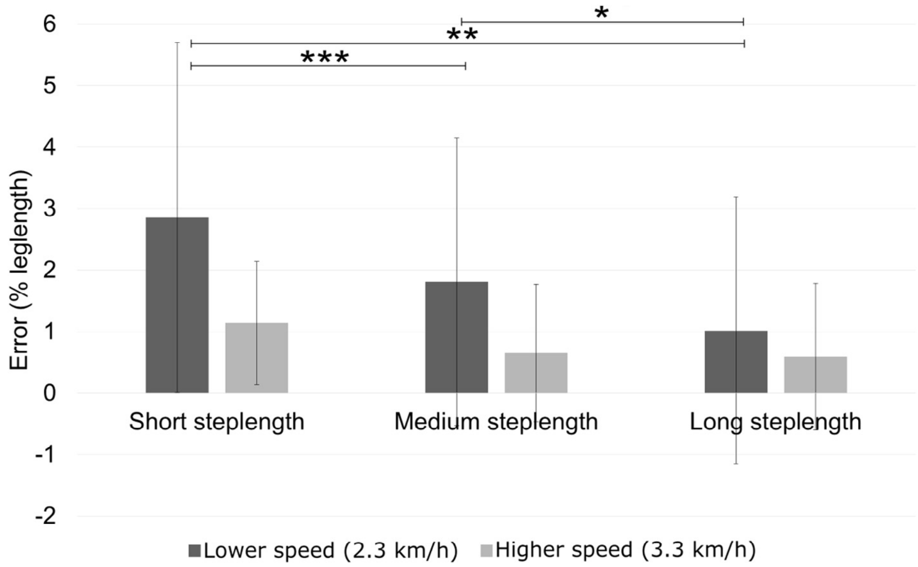

Fig. 5. Stepping error over different step lengths. Stepping error (% of leg length) of short, medium and long steps of the entire training, at lower and higher speed. *p = .017; **p < .001; ***p = .002.

increase in task difficulty: stepping time and speed dependent step-length preferences might be suboptimal at this training speed compared to the lower speed, thereby increasing task difficulty.

Performance scores indicate that, despite the intuitive character of augmented reality training, a certain room for improvement is still possible over the course of the trials, even at the lower walking speed. Task difficulty might again explain this observation. Although our results show relative high performance scores on initial try, several other studies illustrate the ability of subjects to reach performance scores of 100% while performing a visual stepping task on the C-Mill (Bank et al., 2011; Hoogkamer, Potocanac, & Duysens, 2015; Potocanac, Smulders, Pijnappels, Verschueren, & Duysens, 2015). These studies used stepping targets that were large in size, whereas our stepping targets were small in size and needed to be hit with the 5th metatarsal of the foot, thereby greatly increasing the difficulty of the stepping task. Although the subjects in our study approached all stepping targets with (some part of) their foot, failing to hit the target with the specific, marked, area of the foot still resulted in a negative performance score, thereby explaining the difference in performance score between these studies and our study. Additionally and contrary to our hypothesis, augmented reality training did not elicit any learning effects. Feedback presentation might have played an important role in this as Lamoth, Alingh, and Caljouw (2012) showed that visual feedback is of major importance in a computer-generated training environment. Additionally, the principle of error-based learning (Hidler & Sainburg, 2011) states that individuals do not improve on a task when they do not receive information about their mistakes. In particular in a high-precision task as the one that is performed in our study, subjects will not improve their performance scores when they are unaware of their incorrect foot placement. The influence of error-based feedback to motor task learning is further explained when observing the findings of virtual reality locomotor training by Choi et al. (2016), who used a similar study design but did observe increased performance over the training blocks (non-specific learning curve) and, additionally, a sequence-specific learning curve. The aspect that proprioceptive information needs to be remapped to what is seen on a screen might explain (part) of the non-specific learning curve in this study. However, the location and timing of the feedback might additionally be of great importance.

Feedback is presented on a screen in the virtual reality set-up by Choi et al. (2016), but under the feet of the subjects in the augmented reality set-up. Both Matthis and Fajen (2014) and Patla, Adkin, Martin, Holden, and Prentice (1996) found that individuals prefer obstacle appearances that are at least two step lengths ahead when walking on complex terrain, to have higher success rates. Individuals thus strongly focus on the next target, rather than to look closely to their current stepping location (Keller Chandra et al., 2011). As the feedback in our study was presented at the end of mid-stance (when the COP was on the stepping target), the distance between the feedback location and the next target is larger, i.e. further from the central field of vision (Matthis & Fajen, 2014). Chapman and Hollands (2006, 2007) confirm that subjects performing an accurate stepping task look away from the target around the moment of heel strike, i.e. before the end of mid-stance was reached. Even though no eye tracking methods have been performed that could confirm these assumptions, the location of feedback might have been suboptimal in our training set-up, thereby limiting the learning capacities of the subjects. It is therefore assumed that adapting the location of the visual feedback (closer to the central field of vision), or the method of providing feedback (auditory feedback), might be more suitable for use in the current augmented reality training set-up.

In accordance with previous observations by Patla, Prentice, Rietdyk, Allard, and Martin (1999) and in the virtual reality training set-up by Choi et al. (2016), we found that subjects experienced more difficulties in controlling shorter steps lengths compared to longer ones. Moreover, Patla et al. (1999) showed that subjects who anticipate to a wrongly chosen intended stepping location have a preference to overshoot their target. It is then energetically more beneficial to lengthening the step when a misinterpretation about the intended position was made. Subjects then do not have to reduce the forward linear momentum of their body and they gain additional time to correctly locate their foot at the new position. We have observed these findings in our results for all step lengths, indicating the difficulty of participants to correctly control the step length distance. A smaller overshoot in stepping error was present during the execution of longer steps compared to shorter steps at lower walking speed: subjects more often undershoot the stepping target when it was positioned at a long stepping distance compared to a short stepping distance. No deviation in stepping error was present between short and long stepping targets at higher walking speed.

The difficulty of subjects to interpret step length distances might be explained in another study by Patla (1997), which states that subjects prefer visual information about step length over proprioceptive information. In augmented reality training, both the stepping-target on the treadmill and the user move in opposite directions. This is in contrast to regular overground walking, in which only the subjects and not the stepping targets move. Reasonably, subjects might experience difficulties in interpreting relative distances between targets in the augmented reality training set-up, as the visual information might be disturbed in this situation. This aspect might, additionally to the suboptimal feedback presentation that was already mentioned, contribute to the lack of sequence learning that is observed in the augmented reality training set-up.

4.1. Study limitations

This study provides insight into the performance of subjects while executing a visuomotor walking task in an augmented reality training situation. The augmented reality training situation was composed of an instrumented treadmill with an embedded force platform, where the location of the foot (at the instant of the 5th metatarsal) was defined as the center of pressure (CoP) at the end of mid-stance. Although this assumption seems reasonable according to Winter, Patla, and Frank (1990), tracking the COP as a measure for the location of the 5th metatarsal, rather than using a motion capture system, introduces a small inaccuracy in the results. Specifically for situations where single stance durations shortens. This inaccuracy is believed to be rather small, as the trends that are shown in Fig. 4 of this manuscript are still similar to the work by Choi et al. (2016), Patla et al. (1999). However, this inaccuracy could have led to a small decrease in the performance scores: there might have been several occasions where the COP was not yet located underneath the 5th metatarsal at the end of mid-stance, even though the 5th metatarsal was located on top of the target.

Furthermore, one must one keep in mind that any type of computer generated training environment (either augmented or virtual reality) could be presented to users by using other methods, e.g. using head mounted displays (HMD) instead of computer screens, or using more complicated visual graphics during augmented reality training. The method used in our study is an example of an augmented reality training environment and many other set-ups also fall within the category of augmented reality training environments. Results as stated in this study could therefore not be translated to other situations.

In addition, no records were collected in this study that classify the (subjective) perception of performance of the users themselves or their perception of the difficulty of the task. This would have allowed to further specify the consequences of the feedback presentation in the training set-up.

4.2. Future research

It was suggested in this study that feedback location might have had a large effect on the performance score and learning abilities of subjects. Therefore, future research should test the suggestion made in the discussion section of this paper that learning effects could be obtained in augmented reality training when feedback was presented in a different manner, e.g. using auditory feedback.

In addition, in order to overcome the (believed small) inaccuracy in performance score that is introduced by the assumption that the location of the COP is underneath the 5th metatarsal at the end of mid-stance, stepping locations might be better expressed in terms of performed step lengths, rather than absolute foot placements. Specifically, as the COP location at the end of mid-stance is affected by cadence, walking speed and single support stance duration, the accuracy of the performance score might increase when performed step length is taken into account.

Furthermore, future work must extend the experiments to specific patient groups, as they might respond differently to the evaluated training situations. van Ooijen et al. (2015) already demonstrated improvements in training task after training with a similar augmented reality training set-up over a longer period of time. The lack of learning effects in healthy subjects that was found in this study might therefore not exclude learning effects in patient groups. It can be assumed based on the findings in this study and the intuitive character of augmented reality training, that such a training set-up is suitable for target groups (such as neurological patients) that specifically need to focus on the motor task itself and that should not be distracted by a complex environment or the performance of a dual task. Future work should point out whether conclusions hold for other groups of subjects.

In addition to this latter aspect, future work should investigate success rates at additional walking speeds. The highest speed that was used in this study (3.3 km/h) is a relatively low speed for healthy subjects, while walking on a treadmill. Although it was observed that the success rate of subjects is speed dependent, its exact relation is not yet clear. This relation might specifically be of importance while using an augmented reality training environment for patients.

5. Conclusion

This study demonstrates that although performing a high-precision stepping task in an augmented reality training environment was intuitive to the users, performance scores did not increase over the course of the trials. Subjects thus did not show non-specific learning effects, nor did the subjects show the ability to learn a sequenced walking task. Main reason for the lack of improvement seemed to be the suboptimal feedback presentation in the used training set-up in combination with the difficulty of the stepping task. Furthermore, subjects seemed to show difficulty in controlling step length variations while performing a stepping task.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2017.10.005.

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