



Comparison of visual and haptic feedback during training of lower extremities

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ABSTRACT

We compared the effects of visual and haptic modalities on the adaptation capabilities of healthy subjects to the virtual environment. The visual cueing (only the reference motion is presented) and visual feedback (the reference motion as well as the current tracking deviation are presented) were provided by a real-time visualization of a virtual teacher and a virtual self – avatar, using optical measurements. The subjects had to track the virtual teacher during stepping-in-place movements. The haptic feedback was provided by the actuated gait orthosis Lokomat programmed with the same stepping movements employing an impedance control algorithm. Both setups included auditory cueing. The stepping task was performed by engaging different modalities separately as well as combined. The results showed that (1) visual feedback alone yielded better tracking of the virtual teacher than visual cueing alone, (2) haptic feedback alone yielded better tracking than any visual modality alone, (3) haptic feedback and visual feedback combined yielded better tracking than haptic feedback alone, and (4) haptic feedback combined with visual cueing did not improve tracking performance compared to haptic feedback alone. In general, we observed a better task performance with the haptic modality compared to visual modality.

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1. Introduction

The number of studies and experimental applications exploiting virtual reality (VR) in the rehabilitation environment has been increasing rapidly over the last few years.

The literature has advanced from describing the potential benefits of VR to presenting actual working systems and clinical results with patients [1,26]. VR is a powerful tool in a rehabilitation environment, providing the patients with repetitive practice, feedback information, and motivation to endure practice. In a virtual environment, the feedback about performance can be augmented (e.g., the difference between desired and actual motion can be visualized in a simple, easily understandable fashion). Reprogrammable virtual tasks, virtual objects, and scenarios can enrich the training and motivate the patients to perform intensive therapies for longer durations and more often. Humans can learn motor skills in a virtual environment and can then transfer that motor learning to a real world environment [4–6]. Motor learning in a virtual environment has been suggested to be superior to motor learning alone in sensorimotor tasks such as table tennis and stepping over obstacles [7–9].

In the human body, performance criteria are obtained by proprioceptive and exteroceptive feedback of movements, contact forces, visual and auditory stimuli, etc. In patients with injuries of the central or peripheral nervous system the perception is often disturbed or missing due to lack of appropriate afferent input from the receptors. In such cases artificial sensors can be used for recording the performance quantities and feeding them back to the user. Non-affected perceptible modality can be chosen to substitute the affected sensory function and allow the patient to regain the unperceivable information. To make the artificial feedback signals perceptible and allow the patient to react to the signal, technical display devices are required, such as graphic (screens), auditory (loudspeakers), or haptic (robotic devices) displays. The goal is for the patients to feel present in a virtual environment. They are presented continuously with the information about their own motor performance during the training, in a simple and intuitive way.

A number of studies deal with sensorimotor control, visuomotor adaptation, and assessing the role of vision and proprioception when learning a specific task. Lateiner and Sainburg conclude in their study [2] that visual information has a dominant role in movement control when visual and proprioceptive inputs from VR are dissociated. Jones et al. [3] suggest that the CNS reduces the sensory signals from muscle spindles to resolve the conflict between visual and proprioceptive feedback. This effectively reduces the role of proprioception

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when such conflict exists. Furthermore, Scheidt et al. [30] suggest that visual and proprioceptive feedback are combined in fundamentally different ways during trajectory control, and therefore cannot be compared by simply assigning a fixed significance to each source of sensory information. Similarly, Smeets et al. report in their investigation [31] a stable subject-specific misalignment between vision and proprioception. They suggest a model of optimally combining both uncalibrated (i.e., inconsistent) sources of information. According to van Beers et al. [32], the visual and proprioceptive information in finding out the hand position with respect to the body are integrated with direction-dependent weights. These correspond to direction-dependent precision of the information, implying that vision and proprioception differ in precision of hand pose estimation in lateral and anterior directions. CNS uses the knowledge about direction-dependent precision to minimize position errors by adaptively assigning stronger significance to the more precise information and suppressing the less precise information.

VR allows us to present on a display a virtual teacher, who performs the task repeatedly. The teacher's movements enable the enhancement of learning by imitation. In our previous study [15] the subjects tracked a semi-transparent virtual teacher by observing and imitating its movements superimposed to their real-time movements visualized in VR (Fig. 1, middle). Virtual teacher's reference movements were presented as a stepping-in-place (SIP) task. SIP test has been applied in various clinical and rehabilitative applications [10–12]. A preliminary investigation [15] showed that healthy subjects can adapt to the virtual teacher very quickly.

In the present study we have combined the virtual teacher and a haptic modality. Haptic feedback was realised by a Lokomat system (Hocoma, AG; Fig. 1, right). Haptic information provided by the Lokomat includes force feedback and tactile feedback from the thigh and calf cuffs where the user is in contact with the orthosis. Subjects using the device are thus provided with a haptic experience combining proprioceptive (joint angles) and exteroceptive (tactile sensing, contact forces) feedback about their movements. Studies examining gait training with haptic feedback have showed significant improvements in overground walking speed, muscle strength and endurance in stroke and SCI patients [13,14].

The aim of the present study was to assess and compare the role of haptic and visual modalities in the adaptation of subjects to a virtual environment by employing both modalities in the same virtual scenario. It was our hypothesis that the combination of modalities leads to better adaptation than each feedback modality alone. To achieve this, SIP was performed in a group of healthy adults with visual-only, haptic-only and combined visual–haptic feedback. We assessed the spatial and temporal relationships between the virtual teacher's angles and the angles recorded from the subjects in all feedback modes.

2. Methods

2.1. Virtual mirror with visual feedback

Visualization of the subject's movements in the virtual environment was based on a simplified kinematic model of the human body. In order to calculate the joint angles, 11 active infrared markers were placed on the skin over anatomical landmarks of the human body [15]. The positions of the markers were acquired by the OptoTrak (Northern Digital, Inc.) system at a 70 Hz sample rate. Kinematic data calculated from OptoTrak measurements were used to animate the motion of the human figure in VR at a 35 Hz refresh rate in real time on a large screen – virtual mirror. No lag (latency) between motions of the subject and virtual figure was detected. During the SIP training the subject would see an additional semi-transparent figure in the virtual mirror, which represented the virtual teacher. The two figures were superimposed. The motion of the virtual teacher was pre-programmed with stepping movements. These presented a reference pattern that the subject was instructed to track. Ideally, both figures would be perfectly aligned at all times, indicating that the subject was performing the SIP simultaneously with the virtual teacher. The left and right shanks of the virtual figures were of different colors, providing a clearer visual reference for each extremity. A projection screen was placed 1.7 m away in front of the subject.

2.2. Virtual mirror with visual and haptic feedback

In the second setup haptic feedback was included by placing the subjects in the Lokomat system programmed with SIP pattern. An impedance-based control was employed instead of default control strategy. The orthosis actively guided subject's leg movements in the sagittal plane within highly repeatable predefined hip and knee joint trajectories. Lokomat's potentiometers provided real-time information of the subject's hip and knee angles. The measured joint angles were used to animate the subject's human figure in the virtual mirror, whereas the pre-programmed reference SIP pattern was used to animate the virtual teacher. In the haptic setting, the distance between the subject and projection screen was 1.3 m.

The default control strategy of the Lokomat system is position-based, making the orthosis feel stiff for the subjects (i.e., only negligible deviations from the reference trajectories are possible regardless of the amplitude of the applied opposing joint torques). A position controller would not allow any difference to be seen between the subject's figure and the virtual teacher in the virtual mirror, irrespective of the subject's efforts. This would diminish or cancel out the visual feedback loop

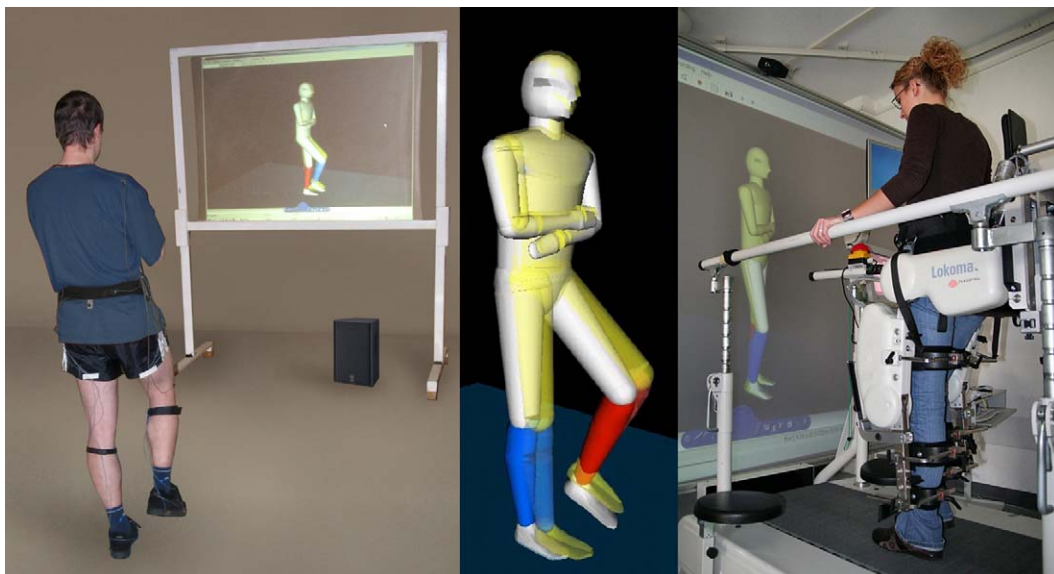


Fig. 1. The virtual mirror (middle) in visual modality (left) and combined visual–haptic modality (right).

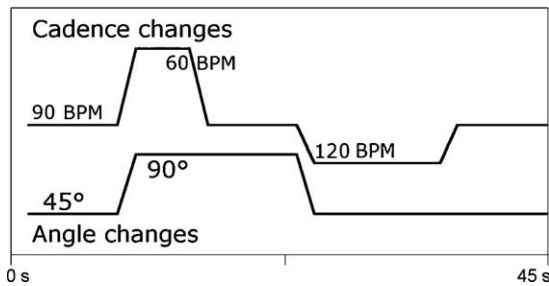


Fig. 2. Temporal and spatial parameters of the stepping-in-place task. Initial cadence is 90 steps/min, changed in first perturbation smoothly to 60 steps/min, then back to 90 steps/min, then increased to 120 steps/min, and back to 90 steps/min. Reference maximal hip angle in each step varies between 45° and 90° as shown.

completely. Instead, we employed an impedance-based control strategy [17,18]. An impedance controller allows variable deviations from a given leg trajectory rather than imposing a rigid pattern, making the orthosis feel compliant. The moment acting on the subject's leg is proportional to the angular deviation from the pre-programmed reference value. The stiffness of the orthosis is subject to the setting of the mechanical impedance value. Zero impedance, ideally, makes the Lokomat feel transparent (i.e., no haptic feedback can be experienced), whereas maximal impedance results in maximal stiffness – equal to the position controller. In reality, the Lokomat impedance controller does not compensate for inertia, which can cause the inertia of the orthosis' segments to be more noticeable in low impedance setting. The compromise had to be made between making the Lokomat compliant enough for the subjects (i.e., the subjects must exert voluntary effort to track the reference pattern), without being encumbered by the inertia of the heavy orthosis segments. We strived for the lowest reasonable impedance value in order to prevent the haptic feedback from being overly strong. It was defined experimentally by starting with 100% impedance value and decreasing the impedance parameter by 10% decrements to the point where subjects reported they began feeling the inertia of the Lokomat segments. The procedure was mirrored by starting with minimal impedance and increasing it by 10% increments. The impedance was then set to the lowest value at which the subjects did not report feeling the device's segment inertia. This was at 30% of the maximal Lokomat impedance.

2.3. SIP task

The subjects' ability to track the SIP movements of the virtual teacher was assessed by performing a task consisting of varying hip angles and cadences. The movements of the virtual teacher were obtained by capturing the steps of a healthy male subject (aged 25 years) well familiarized with the virtual mirror. Based on his average step a smooth, continuous pattern was synthesized, involving spatial (hip angle amplitude in each step) and temporal (cadence) perturbations (seen as changes in hip angle and cadence in Fig. 2). Spatial and temporal parameters of the task were based on performance expectations of healthy subjects, and are shown in Fig. 2. These parameters were based on results from our previous study [15] on assessing adaptation, where we observed that adaptation was affected more strongly by changing the cadence than the hip angles. The same reference pattern was used to animate the virtual teacher in both settings and Lokomat as well to provide the haptic feedback. The amplitudes of the angles were halved and smoothed in order to conform to the reachable range and limited degrees of freedom of the Lokomat. Cadence profile remained identical throughout the duration of the task in all modes.

The task was performed in two with visual-only modality, in two modes with haptic-visual modality, and in one mode with haptic-only modality. The modes with visual modality within both settings differed in presenting either both virtual figures superimposed (virtual teacher and the subject enabling visual feedback), or presenting only the virtual teacher (providing merely a visual cue). Features of all

Table 1

Combinations of the visual and haptic features engaged in the 5 modes of the stepping-in-place tracking task. Mode 1: visual-only feedback mode, mode 2: visual-only cue mode, mode 3: haptic-visual feedback mode, mode 4: haptic-visual cue mode; mode 5: haptic-only mode.

Mode	Visual cue	Visual feedback	Haptic feedback
1	✓	✓	–
2	✓	–	–
3	✓	✓	✓
4	✓	–	✓
5	–	–	✓

five modes are concisely summarized in Table 1. The order of performance of all modes was randomized for all subjects in both settings. Subjects completed a trial of the task before the actual measurements took place. Each subject performed a single run of each mode of the task. Participants were instructed to track the hip angles – height of knee lifting of the virtual teacher throughout the duration of the task. The comparison of adaptation in both settings was based on the observation that the tracking errors between constant low and high angles (refer to Fig. 2) did not differ significantly, neither within visual-only, nor within visual-haptic modes of the task.

The viewing angle of the virtual camera was set to a 3D view as seen in Fig. 1 in the middle, based on the optimal visibility of the lower extremities movements. It was the same for all subjects in both settings. An auditory cue was provided in all modes as a whistle sound indicating the exact heel-off moment in each step. The duration of the audio signal was 200 ms with pitches differing slightly for the left and right legs. Subjects were informed about auditory cues before performing the task.

2.4. Assessment of adaptation

We used a genuine real-time computing environment XPC Target (www.mathworks.com) to facilitate the experimental setup. Software-independent real-time functionality ensured only negligible delays between real world and visualization. The subject's and virtual teacher's figures were synchronized in the loop, ensuring that there was no on-screen delay. The adaptation of the subjects to the virtual environment was assessed by comparing their hip angles to the virtual teacher's. We used a method developed by Giese and Poggio [19], based on linear superposition of prototypical motion sequences. The procedure yields the optimal spatial and temporal mapping of the two patterns. The authors promote their method as being especially well-suited for analysis of biological motion patterns. A detailed description of the method is given in [19]. The importance of such spatial-temporal distinction is best demonstrated by an example where the subject's tracking is perfect in terms of amplitudes but slightly delayed. The proposed method in this case correctly identifies the zero spatial error component and a slight temporal delay (on the other hand the RMSE method yields an overly significant tracking error, providing no further information on tracking performance). The differences were addressed for all five modes of the task by first applying the described method for assessing spatial and temporal deviations and then performing the analysis of variance (ANOVA) to compare spatial and temporal tracking errors among all five modes.

2.5. Subjects

A test group for the visual-only modes consisted of 11 healthy subjects (23–30 years; age: 26.3 ± 2.3 years, height: 180 ± 6.8 cm, mass: 72.8 ± 11.0 kg). A test group for the visual-haptic and haptic-only modes consisted of 12 healthy subjects (23–32 years; age: 27.1 ± 2.4 years, height: 178 ± 7.6 cm, mass: 69.8 ± 12.4 kg). Subject recorded as virtual teacher: age: 25 years, height: 181 cm, mass: 74 kg. None of the subjects participated in both settings since the experiments were geographically and chronologically separated due to equipment availability. None of the subjects had a medical history of significant lower limb impairments. All subjects gave informed consent to participate in the study. Ethical consent was given by the local ethical committees.

3. Results

Results include spatial and temporal adaptation of the subjects to the virtual teacher by analyzing the hip angles in all five modes of the SIP task. Fig. 3 roughly indicates the differences between the visual-only feedback (mode 1, Fig. 3(a)) and the visual-haptic feedback (mode 3 Fig. 3(b)). Noticeably greater deviations from the reference can be observed in the visual-only feedback (mode 1), especially at the onsets of perturbations.

Spatial adaptation in the two visual-only modes (Fig. 4(a), modes 1 and 2) differed significantly ($p < 0.001$), showing that visual feedback yielded better adaptation (smaller error and variance) than visual cue. Temporal adaptation was also significantly better ($p < 0.001$) in the visual feedback mode (mode 1) than in the visual cue mode (mode 2) (Fig. 4(b), modes 1 and 2). Within the three haptic modes, the addition of the visual feedback improved both spatial (Fig. 4(c)) and temporal (Fig. 4(d)) adaptation ($p < 0.001$ for both observations); however, no significant differences were observed between the haptic-only mode (mode 5) and haptic-visual cue mode (mode 4). While including the visual feedback reduced both the median error and the error variance in spatial adaptation, it reduced only the error variance in temporal

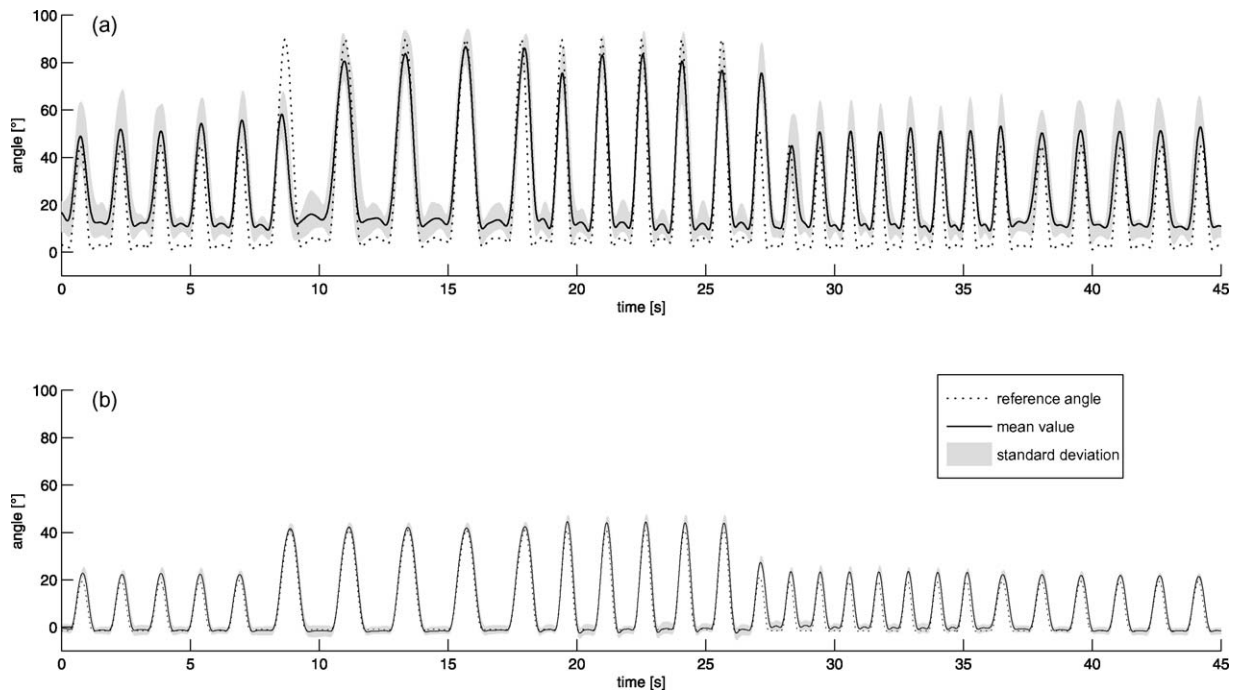


Fig. 3. Tracking in the visual-only feedback mode (a) and the visual-haptic feedback mode (b): the reference hip angle (dotted lines), mean value recorded among the subjects (solid lines), and standard deviation (grey bands).

adaptation. The median temporal error was fairly low in all haptic feedback modes. Comparing the three haptic modes to two visual-only modes showed that all haptic modes yielded significantly better spatial and temporal adaptation than any of the visual-only modes ($p < 0.001$ in all observations, except in the comparison of temporal adaptation of the haptic-only feedback mode (mode 5) and visual-only feedback mode (mode 1), where $p = 0.005$).

4. Discussion

The virtual mirror proved to be an intuitive, easy-to-learn virtual environment which enabled the comparison of visual and haptic modalities in lower extremities training. The virtual environment was sparse, consisting only of two virtual figures on a virtual floor without any textures. According to Zimmons and Panter [20], making the environment more elaborate (i.e., more details, finer rendering, textures, etc.) would not affect the experience of presence significantly. We focused rather on the real-time responsiveness, repeatability, and strong correlation of the actions in the real and virtual environments. The feature of learning by imitation ensured that the subjects could cope with the stepping task instantly. We observed no general improvement trend during the performances of the task in different modality combinations. The subjects who completed certain mode of the task last did not perform better than the subjects who completed the same mode first. Furthermore, no general diminishment of tracking error could be observed throughout the duration of each task mode (see Fig. 3). SIP was chosen instead of treadmill walking for this basic study since it does not impose a programmed walking speed. In this way there was no need for the subjects to adapt their movements to a moving treadmill. This allowed us to record their unbiased activity [21] based solely on the subjects' responses to the virtual environment.

One of the differences between both settings was that in Lokomat the subject's pelvis was secured firmly in the device to eliminate slipping; however, this prevented the subjects to move in anterior and lateral directions. The only freedom of pelvis

movement was up and down which affected subject's self-balancing during SIP. Therefore, the subjects were allowed and advised to hold the handrails of the Lokomat. In the visual-only setting there were no such aids since the subjects' freedom of movement was not impeded. These different constraints compromised the equivalence of conditions. On the other side, motion in sagittal plane was not impeded in either Lokomat or visual-only setting, making possible the comparison of hip angles between both settings.

The auditory cueing was included in all modes of the study a priori. Evidence from previous studies suggest that external auditory timing signals improve temporal stride symmetry and gait variability in healthy subjects and stroke patients [22,23]. Continuous auditory feedback improves the performance in obstacle avoidance task [28]. This implies that at least some amount of adaptation in our study was due to the auditory cues; however, it was the goal of this study to establish a quantitative comparison of visual and haptic modalities, rather than establishing the absolute measures and benchmarks of task-specific adaptation. Furthermore, the mechanical structure and motors of the Lokomat inevitably produce noise during active operation. Instead of muffling or suppressing this noise by headphones which is known to affect postural stability [24,25] we added a substantially more powerful auditory cue to the environment. A short, sharp whistle sound indicated the exact heel-off timing. By including the auditory cueing in all modes the validity of comparison in equivalent conditions was ensured.

In the visual-only setting we showed that the visual feedback (seeing the reference angle as well as the tracking deviation) improved spatial and temporal adaptation to the virtual environment considerably compared to visual cue (seeing only the reference). In general, this finding encourages the extended effort to obtain and adequately present the real-time measurements needed to create the feedback loop in non-haptic settings. The results of both settings suggest that haptic feedback yields better adaptation than any visual modality alone. Adding a visual feedback to haptic training can further improve the adaptation

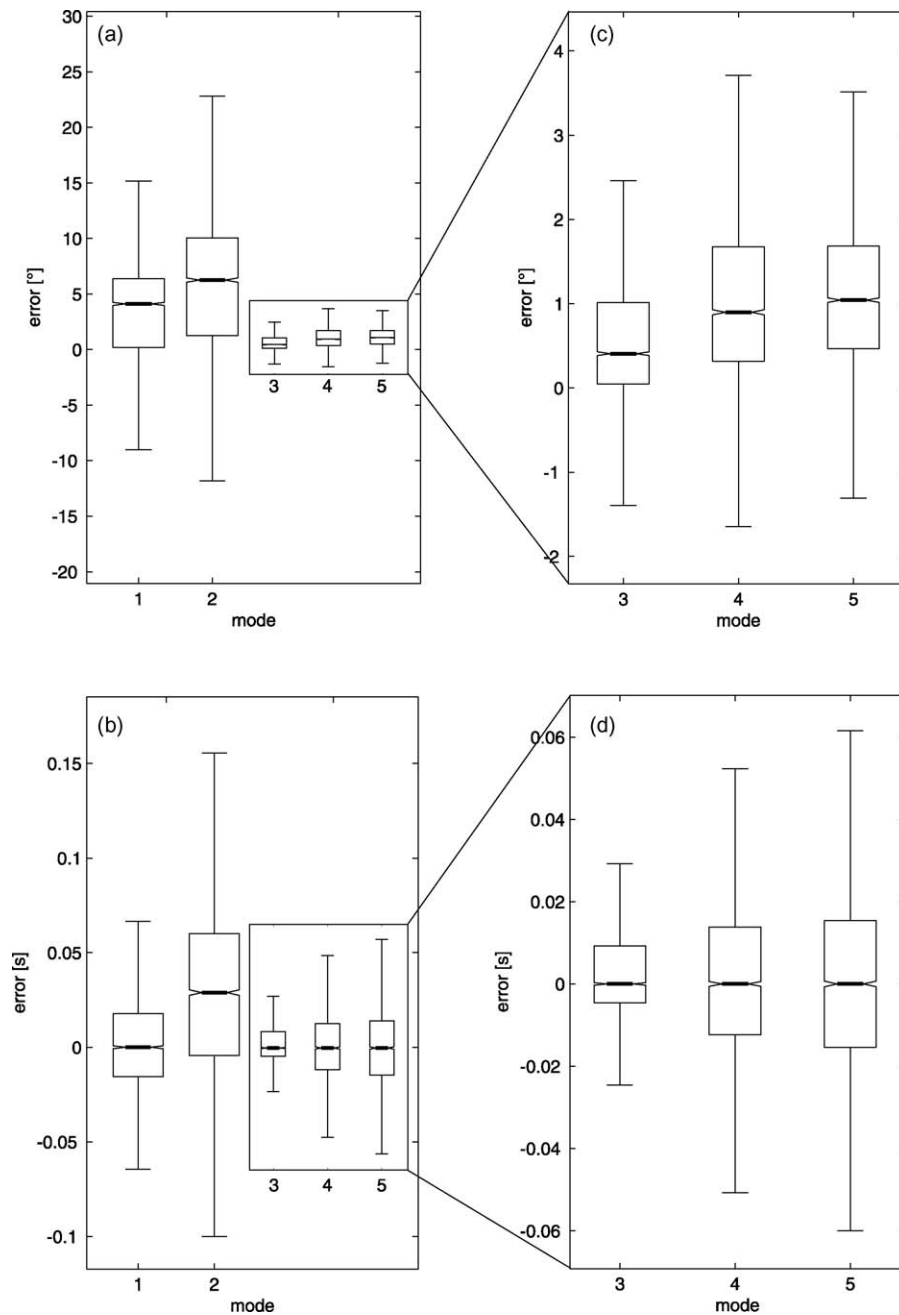


Fig. 4. Tracking in visual-only modes: spatial (a), temporal (b), and tracking in haptic–visual modes: spatial (c), temporal (d). Median values (bold solid lines), 25th and 75th percentile values (error boxes), 5th and 95th percentile values (error bars).

which confirmed our initial hypothesis. Real-time measurements needed to create a feedback loop are always needed for active haptics, and are, thus, conveniently available for use in such virtual environment.

Overwhelming majority of literature on the role of vision, proprioception, tactile and force feedback focuses on upper extremities. Ernst and Banks suggest in their study [29] on integrating visual and haptic information that a general maximum-likelihood estimation principle determines the degree to which vision or haptics dominates. The authors conclude that the nervous system combines the visual and haptic information in a statistically optimal fashion based on the variance estimation. The modality associated with lower estimation variance is supposed to prevail. According to their findings better tracking

in the haptic–visual setting in our investigation might suggest that haptic feedback provides better subjective estimation of the reference movements than visual modality. Both modalities complementing each other provide best estimation (i.e., the lowest estimation variance). Feygin et al. on the other hand came to an ambivalent conclusion in their study [33] reporting that visual training was better in spatial aspects of the task, whereas temporal aspects were more efficiently learned from haptic training. Furthermore, Gunn et al. report significant improvement in both accuracy and speed by introducing haptic guidance in a graphical virtual environment [34]. Strong bias toward haptic feedback in our investigation might reflect fundamental differences between the roles of upper and lower extremities in the activities of daily living. Continuous visual observation of manual

activities is essential for accomplishing most manual tasks. Walking, standing, and balancing rely heavily on proprioceptive and force information, employing vision rather than scan the surface for features and obstacles in advance without actually observing leg movements. It cannot be concluded from our results whether haptic feedback is dominant in lower extremities tasks since visual information was veridical in all modes. Further investigation employing dissociative visual information should be conducted to determine the role of various sensory inputs and to establish whether sensory integration in lower extremities differs from findings in upper extremities. We showed however, that combining haptics and vision can improve performance of lower extremities training. This should encourage further studies and attempts in developing enriched and improved rehabilitation applications for lower extremities.

Both haptic and visual experimental setups in this study involved relatively expensive equipment. Haptic interfaces are inherently elaborate and complicated devices. As such they are priced accordingly high which makes them suitable only for in-patient therapy. Their benefits in rehabilitation have been well established [13,14] whereas our findings suggest that therapy outcome could be further improved by including visual feedback in training. On the other hand, visual feedback alone for a specific task can be achieved more affordably by using simple measuring devices such as potentiometers and angular accelerometers. The current development of computer vision techniques in this field is also promising [27]. This implies that visual-only virtual environments have perhaps more potential in bringing the rehabilitation process closer to the patients – literally to their homes. Such applications could be introduced viably in a newly developing field of telerehabilitation [16].

When discussing the role of VR in rehabilitation it is important to keep in mind that VR is not a treatment in itself – and, thus, cannot be regarded as either an effective or ineffective means of motor rehabilitation. Rather, VR is a technological tool that can be exploited to enhance motor retraining. Holden concludes in [1] that future work on virtual environments should focus on identifying which types of patients will benefit most from VR treatment, what types of training routines will work best, and which system features are critical. In this aspect, our study offers a part of the answer to the last question by providing an insight in what to expect from employing different combinations of modalities in VR-enhanced lower extremities training.

5. Conclusion

This investigation assessed the influences and differences of visual and haptic modalities in virtual environment-based stepping task for lower extremities. The tracking task performance was found to be superior in the haptic modality than in the visual modality, and even better when combining both modalities. According to the results, we suggest that haptic feedback should be included wherever possible, whereas VR can be potentially beneficial for in-patient rehabilitation process following a stroke or other injury by upgrading the existing and new haptic interfaces with visual feedback. The future of visual-only environments might be in out-patient therapy employing more economically feasible measuring techniques and telerehabilitation services to bring the rehabilitation process to the patient's home.

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Conflicts of interest statement

The authors declare that no conflict of interest exists.

References

- [1] Holden MK. Virtual environments for motor rehabilitation: review. *Cyberpsychol Behav* 2005;8(3):187–211.
- [2] Lateiner JE, Sainburg RL. Differential contributions of vision and proprioception to movement accuracy. *Exp Brain Res* 2003;151:446–54.
- [3] Jones KE, Wessberg J, Vallbo A. Proprioceptive feedback is reduced during adaptation to a visuomotor transformation: preliminary findings. *Neuroreport* 2001;12(18):4029–33.
- [4] Theasby PJ. The virtues of virtual reality. *GEC Rev* 1992;7:131–45.
- [5] Bliss JP, Tidwell PD, Guest MA. The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence-Teleop Virt* 1997;6:73–86.
- [6] Schmelter A, Jansen-Osmann P, Heil M. Empirical evaluation of virtual environment technology as an experimental tool in developmental spatial cognition research. *Eur J Cogn Psychol* 2009;21(5):724–39.
- [7] Todorov E, Shadmur R, Bizzi E. Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *J Motor Behav* 1997;29:147–58.
- [8] Rose FD, Attree EA, Brooks BM, Parslow DM, Penn PR, Ambihapahan N. Training in virtual environments: transfer to real world tasks and equivalence to real task training. *Ergonomics* 2000;43:494–511.
- [9] Jaffe DL, Brown DA, Pierson-Carey CD, Buckley EL, Lew HL. Stepping over obstacles to improve walking in individuals with post-stroke hemiplegia. *J Rehabil Res Dev* 2004;41(3A):283–92.
- [10] Fukuda T. The stepping test. Two phases of the labyrinthine reflex. *Acta Otolaryngol* 1958;50:95–108.
- [11] Garcia RK, Nelson AJ, Ling W, Van Olden C. Comparing stepping-in-place and gait ability in adults with and without hemiplegia. *Arch Phys Med Rehabil* 2001;82(1):36–42.
- [12] Sasaki O, Taguchi K, Kikukawa M, Ogiba T. Stepping analysis in patients with spinocerebellar degeneration and Parkinson's disease. *Acta Otolaryngol* 1993;113(4):466–70.
- [13] Wirz M, Zemon DH, Rupp R, Scheel A, Colombo G, Dietz V, et al. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: a multicenter trial. *Arch Phys Med Rehabil* 2005;86(4):672–80.
- [14] Hornby TG, Zemon DH, Campbell D. Robotic-assisted, body-weight-supported treadmill training in individuals following motor incomplete spinal cord injury. *Phys Ther* 2005;85(1):52–66.
- [15] Koritnik T, Bajd T, Munih M. Virtual environment for lower-extremities training. *Gait Posture* 2008;27:323–30.
- [16] Kurillo G, Bajcsy R, Nahrstedt K, Kreylos O. Immersive 3D environment for remote collaboration and training of physical activities. In: *Proceedings of 2008 IEEE virtual reality conference*; 2008. p. 269–70.
- [17] Riener R, Lunenburger L, Jezernik S, Anderschitz M, Colombo G, Dietz V. Patient cooperative strategies for robot-aided treadmill training: first experimental results. *IEEE Trans Neur Syst Reh* 2005;13(3):380–94.
- [18] Riener R, Lunenburger L, Colombo G. Human-centered robotics applied to gait training and assessment. *J Rehabil Res Dev* 2006;43(5):679–94.
- [19] Giese MA, Poggio T. Synthesis and recognition of biological motion patterns based on linear superposition of prototypical motion sequences. In: *Proceedings of the 1999 IEEE Workshop on multi-view modeling and analysis of visual scene*; 1999. p. 73–80.
- [20] Zimmons P, Panter A. The influence of rendering quality on presence and task performance in a virtual environment. In: *Proceedings of the 2003 IEEE Virtual reality*; 2003. p. 293–4.
- [21] Alton F, Baldey L, Caplan S, Morrissey MC. A kinematic comparison of overground and treadmill walking. *Clin Biomech* 1998;13(6):434–40.
- [22] Thaut MH, McIntosh GC, Prassas SG, Rice RR. Effect of rhythmic auditory cuing on temporal stride parameters and EMG patterns in normal gait. *J Neurol Rehabil* 1992;6:185–90.
- [23] Prassas SG, Thaut MH, McIntosh GC, Rice RR. Effect of auditory rhythmic cuing on gait kinematic parameters of stroke patients. *Gait Posture* 1997;6(3):218–23.
- [24] Russolo M. Sound-evoked postural responses in normal subjects. *Acta Otolaryngol* 2002;122:21–7.
- [25] Polechonski J, Błaszczyk J. The effect of acoustic noise on postural sway in male and female subjects. *J Hum Kinet* 2006;15:37–52.
- [26] Krebs HI, Hogan N. Therapeutic robotics: a technology push. *Proc IEEE* 2006;94(9):1727–38.
- [27] Caillette F, Howard T. Real-time markerless human body tracking with multi-view 3-D voxel reconstruction. In: *Proceedings of the 2004 British machine vision conference*, vol. 2; 2004. p. 597–606.
- [28] Wellner M, Schaufelberger A, Zitzewitz J, Riener R. Evaluation of visual and auditory feedback in virtual obstacle walking. *Presence-Teleop Virt* 2008;17(5):512–24.
- [29] Ernst MO, Banks MS. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 2002;415(24):429–33.
- [30] Scheidt RA, Condit MA, Secco EL, Mussa-Ivaldi FA. Interaction of visual and proprioceptive feedback during adaptation of human reaching movements. *J Neurophysiol* 2005;93:3200–13.

- [31] Smeets JBJ, van den Dobbelaere JJ, de Grave DDJ, van Beers RJ, Brenner E. Sensory integration does not lead to sensory calibration. *Proc Natl Acad Sci* 2006;103(49):18781–6.
- [32] van Beers RJ, Sittig AC, van der Gon JJ. Integration of Proprioceptive and visual position-information: an experimentally supported model. *J Neurophysiol* 1999;81(3):1355–64.
- [33] Feygin D, Keehner M, Tendick F. Haptic guidance: experimental evaluation of a haptic training method for a perceptual motor skill. In: Proceedings of the 2002 symposium on haptic interfaces for virtual environment and teleoperator systems (HAPTICS'02); 2002. p. 40–7.
- [34] Gunn C, Muller W, Datta A. Performance improvement with haptic assistance: a quantitative assessment. In: Proceedings of the 2009 joint Eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems; 2009. p. 511–6.