A haptic floor for interaction and diagnostics with goal based tasks during virtual reality supported balance training

Haptična tla za interakcijo in diagnostiko s ciljno zasnovano nalogo vaditi ravnotežje, podprti z navideznim okoljem

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Abstract

Background: Balance training of patients after stroke is one of the primary tasks of physiotherapy after the hospitalization. It is based on the intensive training, which consists of simple, repetitive, goal-based tasks. The tasks are carried out by physiotherapists, who follow predefined protocols. Introduction of a standing frame and a virtual reality decrease the physical load and number of required physiotherapists. The patients benefit in terms of safety and increased motivation. Additional feedback – haptic floor can enhance the virtual reality experience, add additional level of difficulty and could be also used for generating postural perturbations. The purpose of this article is to examine whether haptic information can be used to identify specific anomalies in dynamic posturography.

Methods: The performance and stability of closed-loop system of the haptic floor were tested using frequency analysis. A postural response normative was set up from data assessed in four healthy individuals who were exposed to unexpected movements of the haptic floor in eight directions. Postural responses of a patient after stroke participating in virtual reality supported balance training, where collisions resulted in floor movements, were assessed and contrasted to the normative.

Results: Haptic floor system was stable and controllable up to the frequency of 1.1 Hz, sufficient for the generation of postural perturbations. Responses obtained after perturbations in two major directions for a patient after stroke demonstrated noticeable deviations from the normative.

Conclusions: Haptic floor design, together with a standing frame and a virtual reality used for balance training, enables an assessment of directionally specific postural responses. The system was designed to identify postural disorders during balance training and rehabilitation progress outside specialized clinics, e.g. at patient's home.

Izvleček

Izhodišča: Rehabilitacija ravnotežja pri ljudeh po možganski kapi sodi med primarne naloge zdravljenja po hospitalizaciji in temelji na intenzivni vadbi, ki je sestavljena iz enostavnih, ponavljajočih se, ciljno usmerjenih nalog. Naloge izvajajo fizioterapevti, ki sledijo predpisanim protokolom. Uvedba podporne stojke in navideznega okolja olajša delo in zmanjšuje število potrebnih fizioterapevtov, bolniku pa zagotavlja ustrezno varnost in predstavlja dodatno motivacijo. S povratno informacijo – premičnimi haptičnimi tlemi, dodamo novo izkustveno razsežnost, uvedemo dodatno težavnostno stopnjo, hkrati pa jih uporabimo za vzbujanje posturalnih odzivov. Namen članka je preveriti, ali lahko haptično informacijo uporabimo tudi za prepoznavanje specifičnih težav pri dinamičnem ravnotežju.

Metode: Zmogljivost in stabilnost zaprtozančnega sistema haptičnih tal smo preverili s frekvečno analizo. Iz meritev odzivov na štirih zdravih osebah smo izdelali normativ odzivov na nenadne premike haptične plošče v osmih smereh. Izmerili smo posturalne odzive osebe po možganski kapi med stojo in vadbo ravnotežja z navideznim okoljem, kjer je bil rezultat trkov nenadni premik haptičnih tal. Dobljene posturalne odzive smo primerjali z normativom.

Rezultati: Sistem haptičnih tal je stabilen, uporaben do frekvence vzbujanja 1.1 Hz, kar zadošča za vzbujanje posturalnih odzivov. Izmerjeni posturalni odzivi v smereh desno nazaj in levo nazaj pri osebi po možganski kapi zelo odstopajo od normativa.

Zaključki: Sorazmerno enostavna zasnova haptičnih tal, skupaj s podporno stojko in navideznim okoljem, omogoča poleg vadbe ravnotežja tudi zajem posturalnih odzivov v posameznih smereh. Tak sistem omogoča spremljanje poteka rehabilitacije ravnotežja tudi zunaj specializiranih kliničnih ustanov, npr. na bolnikovem domu.

Introduction

It is estimated that in addition to current 6 million stroke survivors, 1.1 million new stroke events occur each year in the European Union alone (4000/year in Slovenia – National Institute of Public Health). Due to changing demography, it is expected that this number will rise up to 1.5 million by the year 2025.[1] Stroke is one of the major causes of neurological injury and often results in an acute hemiparesis of upper and/or lower limbs. As a consequence of weakened sensory-motor capabilities, balance capabilities are often reduced, regardless of age, sex and side of the stroke.[2,3] Reduced postural stability and poor balance limit the subject's functional capabilities that often result in falls and reduced quality of life. Falls constitute a serious problem for patients because they are fairly common after discharge from hospital.[4] Often they could be identified using simple clinical tools[5] and thus decrease their frequency.[6] However, this is usually effective at hospital/inpatient treatment only (average 43.75 falls or slips per year during rehabilitation of patients after stroke between 2008 and 2011, URI-Soča, Slovenia). Any fall within the hospital results in changes of the therapeutic program and serious injury may also interrupt the rehabilitation. Restoration of balance capabilities is a rather complex task, as postural control involves various sensory and motor systems controlled by the central nervous system. There have been several attempts to "replace" natural sensors and actuators with artificial[7] ones or apply human-computer interfaces between the neuromuscular system and sensory-motor systems,[8] but numerous studies have shown that intensive physiotherapy with goal-oriented approach in acute, sub-acute and chronic phase could increase the effectiveness of neurorehabilitation treatment of patients with sensory-motor difficulties.[9] These studies gained the importance of neurorehabilitation.

The most commonly applied physiotherapy for balance restoration has been a conventional balance training (CBT) that consists of exercises being performed during standing between the parallel bars. With support of verbal and tactile cues patients holding the parallel bars gradually shift weight bearing to the affected lower limb. The level of difficulty is increased with weight shifts in various directions and addition of arm activities. Those activities require both arms and hands action, e.g. reaching for a ball. Often two physiotherapists help the patient after stroke to maintain upright posture while exercising. The task is rather exhausting for all and is nearly impossible to ensure reproducibility.[9] Introducing a standing frame[10] to help the patient maintain an upright posture may decrease physical effort of the physiotherapist and also ensure safe balancing. The standing frame equipped with passive springs enabled two-degrees of freedom inclination in the sagittal and frontal plane at the level of the pelvis and prevent the patient from falling.

Adding biofeedback may draw attention and increase the motivation of the participating patients. Using virtual reality (VR) as visual biofeedback offers several advantages, while it does not have any negative impact on the motor learning ability of a patient.[11,12] The VR provides a promising tool for designing simulated, interactive and multi-dimensional environments. Designed task could be adapted to the progress of the individual's cognitive and motor capabilities, enabling gradual neuro-motor control learning. Among the advantages of the VR supported rehabilitation is that physiotherapist is relieved of strenuous and repetitive work, and the subject can immerse into the given task and interact with the virtual environment. Besides, the system can assess data and analyse information to complement the clinical tests in functional assessment.[13]

Recently several successful applications of VR in neurorehabilitation of upper-limb dysfunction,[14,15] balance training[16] (e.g. BalanceMaster, NeuroCom, USA, and Wii-Fit Balance Board, Nintendo, Japan)[19,20] and gait[17,18] in patients with impairments of the neuromuscular system have been demonstrated. Nintendo, introducing Wii in 2006 with accelerometers in the handle, has made a great success in the recreation of elderly people[19]. Later it was also introduced to the rehabilitation medicine, more successfully for upper extremity re-education, but also with pilot trials of balance training in people after stroke.[20] BalanceMaster comprises handles or/and harness for support in the case of fall, while the low-cost game-oriented systems like Wii do not offer any safety option for people with neuromuscular impairments. In spite of rapid grow of VR technology supported devices, some studies reported on limitations, such as transfer of experience in the real world,[21] dizziness when using 3D applications,[22] etc. Some of the applications for the upper extremities[23] were combined with haptic interfaces not only to interact with VR environment, but also to provide the necessary adaptive support, e.g. rehabilitation robots.[23] However, we have not found any VR interactive haptic interface for balance training, except for studies reporting on findings on postural control strategies that applied devices for mechanical/hydraulic postural perturbations.[25] Besides, generating postural perturbations to elicit postural responses has been an issue for decades. Successful trials with horizontal platform movement[25,31] as well as perturbation at the level of the pelvis are reported[10,26] Thus we considered developing a universal platform for balance training and directional postural response assessment.

The aim of this paper was to present development of a novel device which enables postural response assessment in multiple directions during VR supported balance training. In a short proof of concept study we demonstrated the capabilities of the device and the principle of balance disorder assessment.

Methods

Subjects

Normative setting group (NG) consisted of four male subjects, without any neurological, visual or orthopaedic disorders, with the mean age 28 (s.d. 3.7) years, mean height 1.77 (s.d. 0.07) m and mean weight 75.5 (s.d. 11.9) kg. Additionally a patient after stroke participated in the study; a female 55 years of age, height 1.67 m and weight 80 kg, left side hemiparetic, 5 months after the ischemic stroke, required assistance during walking, but could maintain vertical posture, with acceptable vision abilities and a mini–mental state examination (MMSE) score of 27/30. The post-stroke patient was selected on the basis of the following inclusion criteria: 1) ability to maintain upright posture and balance while standing in a standing frame, 2) stable medical condition, no other neurological or musculo-skeletal impairments or heart failure (New York Heart Association Classification Class I and II), 3) without psychotropic medications, and 4) with sufficient cognitive abilities – performed well on simple tests of short term memory and be able to follow two-step directions.

All participating subjects gave their informed consent to participate. The study was approved by the ethics committee of the University Rehabilitation Institute of the Republic of Slovenia on 4 June 2012.

Equipment

The apparatus comprised haptic floor that enabled mechanical postural perturbations in all directions of the transversal plane, while perturbations were triggered by events in VR environment. As supporting device for balance training, a commercially available balance training and standing frame (BalanceTrainer, Medica Medizintechnik, Germany) was used.[10] The upper frame was fixed to the base with passive controllable springs defining the stiffness of the two degrees of freedom (2 DOF) standing frame. The standing frame could tilt in sagittal and frontal planes for 15°. The tilt and acceleration of the balance standing frame was measured by a commercially available Kalman-filter-based three-axis sensor (MTx, XSens Technologies, Enschede, The Netherlands).

Haptic floor was designed to fit in the balance training frame and enabled movement in all directions in transversal plane. The bottom part of the device was constructed using aluminium profiles and guide rails on which plates resided in two layers. The lower layer with its DC motor (Maxon Encoder HEDS 5540, Switzerland) connected to the lower plate with steel wire served for movement in medio-lateral (M/L) directions

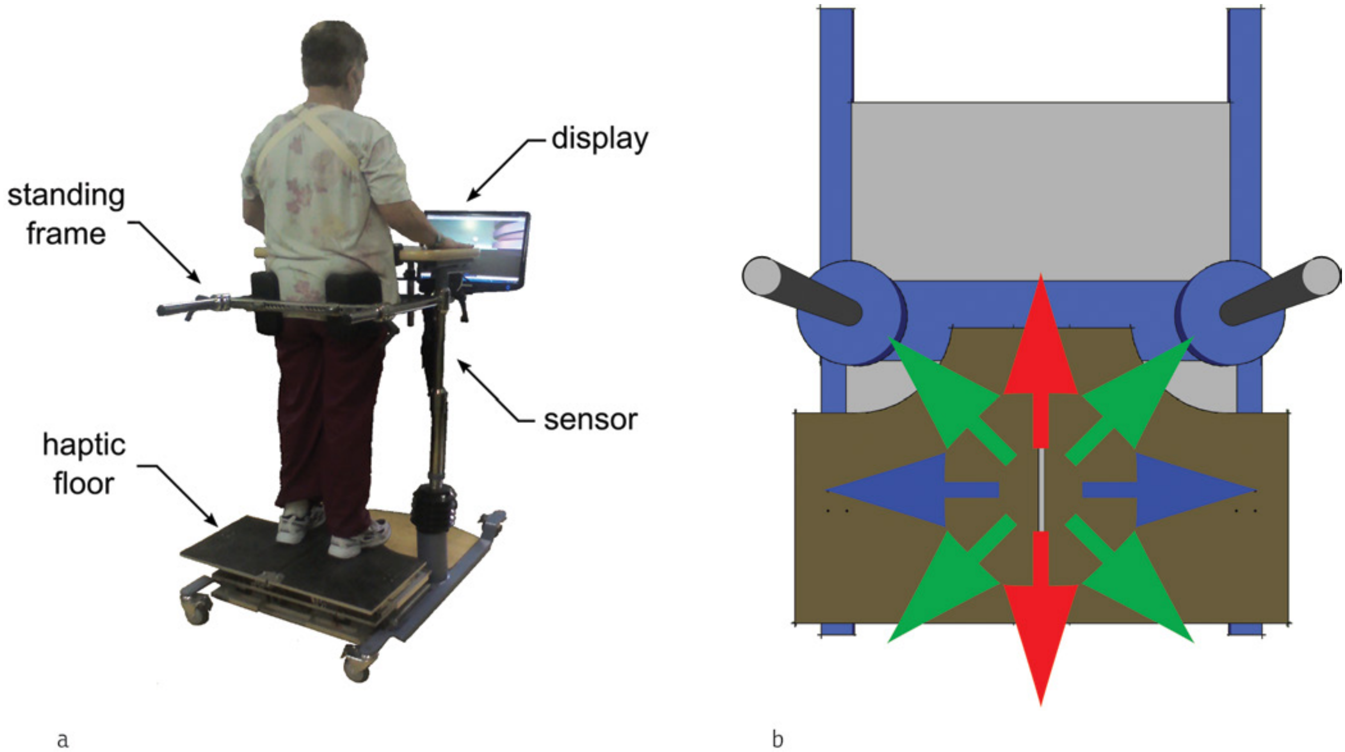


Figure 1: a) Patient in a standing frame during virtual reality supported balance training supplemented with haptic floor. b) A top view of a standing frame together with haptic floor is depicted. Arrows show possible directions of horizontal surface translations – perturbations, from the centre position.

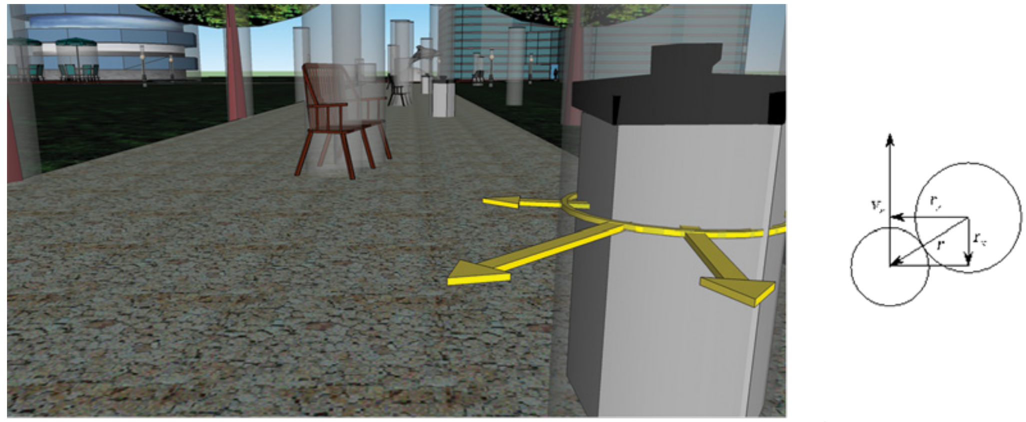
and the upper layer served for movement in anterio-posterior (A/P) directions. Both DC motors (Maxon DC RE40, 150W, Switzerland) with reduction gearboxes (Maxon, Planetary Gearhead GP 52, Switzerland) were equipped with encoders. A, B direction , and index signals (I) from the encoders were sampled with National Instruments (NI) high-speed digital I/O module (NI 9403, USA), while the real-time quadrature decoding and control algorithm, written in Labview 8.5 FPGA (NI) were implemented in real-time controller (NI cRIO-9014, USA). The analogue output (NI 9263 AO, USA) served as an actuator output for DC motors and was amplified with the servoamplifier Maxon 4-Q-DC (ADS 50/10, pulsed (PWM) 4-QDC Servoamplifier 50 V / 10 A). Applied quadrature decoders currently support the range of ± 30000 steps, with 10000 steps/cm resolution system, and at the time of assessment managed horizontal translations of ± 3 cm from centre position in A/P and M/L directions. An additional MTx accelerometer sensor was added to the top of the haptic floor. Sudden change of the sensor output was considered as the onset of the floor movement and as an initial time in data analysis.

Goal-based task – Virtual Reality

VR environment was modelled in VRML 2.0 and run in Matlab's (MathWorks, USA).[27] A goal-based task chosen by the physiotherapist consisted of movement along the path, which was filled with obstacles (benches, trees and trashcans) and designed to force the patients shifting the weight to the affected lower limb.

The inclination (tilt) of the standing frame resulted in immediate action in the designed VR. M/L tilt caused a rotation of view in vertical axis and A/P tilt enabled movement in forward or backward direction. The speed of movement in the VR world was proportional to the A/P tilt.

Every obstacle was encapsulated with vertical cylinder that was invisible for the user (Figure 2.a). When the relative distance between the centre of obstacle and the centre of avatar was less than the sum of cylinder's and avatar's radius, a collision with virtual object took place. At the time of the collision the ideal collision law was taken into calculation of the direction of haptic floor movement. The haptic floor, causing a translational postural perturbation, moved in the



a b

Figure 2: a) A view of virtual environment augmented with cylinders that represent obstacles. Arrows, which represents vector r and its *x* and *y* components, also shown in b), correspond to the floor displacement direction. Vector va represents patient's movement direction inside VR.

opposite direction with respect to the centre of the virtual obstacle (Figure 2b).

Control of the haptic floor

The control of the haptic floor consisted of two control loops; the inner control loop was running at 1 kHz and presented a position controller for each DC motor (Figure 3.a) and the outer control loop consisted of VR engine, haptic controller, haptic plates and feedback tilt information (Figure 3b).

Desired directions and amplitudes of haptic floor translation were used as a reference signal set as PID controller's *reference* input, expressed as the number of encoders' counts for each direction (forward/backward and left/right). The optical encoders provided the PID controller a calculated actual position of the haptic floor. The PID controller was designed to provide an actuator signal for DC motors to assure the required dynamics (< 500 ms to reach the 60 % of the reference position). The selected DC motors pulled the steel-wires and moved the haptic floor to the desired reference position.

Table 1: Clinical assessment of balance capabilities of the patient after stroke before and after 3 weeks of the VR supported balance training. Improvement can be seen in each assessment: a higher Berg's Balance Score (BBS) and shorter times in Timed Up & Go (TUG) and 10 meter walk test (10 MWT).

	Before rehab.	After 3 weeks
BBS	47	49
TUG [s]	23.3 (s.d. 1.0)	18.0 (s.d. 0.8)*
10 MWT [s]	17.1 (s.d. 0.3)	(s.d. 0.5)*

*Significant $p < 0.05$

The PID parameters of both controllers (A/P, M/L) were set using the Ziegler-Nichols tuning method. Optimization for proportional gain (P) and derivative time was performed to set up the parameters in the way that step response would have minimal (< 10 %) overshoot and the response would be still quick enough –> 60 % of the amplitude in < 500 ms. The integral windup was overcome by setting the integral component (I) to the P/8 or less to trade-off the system shaking.

Assessment protocol

Subjects were positioned firmly into the standing frame with their arms crossed and palms touching shoulders. Height of the support frame was adjusted to be in the level of subject's pelvis. Feet were positioned on the moving support surface, so that the subject's body was in parallel with standing frame vertical rods, side by side, in their natural standing position 5–7 cm apart. Participants from NG group were asked to stand still for about 160 seconds. Perturbations in eight different directions (forward, forward/right, right, back/right, back, back/left, left, forward/left) were generated in random order by horizontal movement of the haptic floor. Time interval between two consecutive perturbations was chosen randomly in the range between 3 and 10 seconds. The same procedure was used in the patient after stroke. Besides, the patient after stroke also participated in the VR-supported balance training lasting for 3 consecutive weeks. The physiotherapist carried out specific clinical tests to estimate the patient's motor and balance

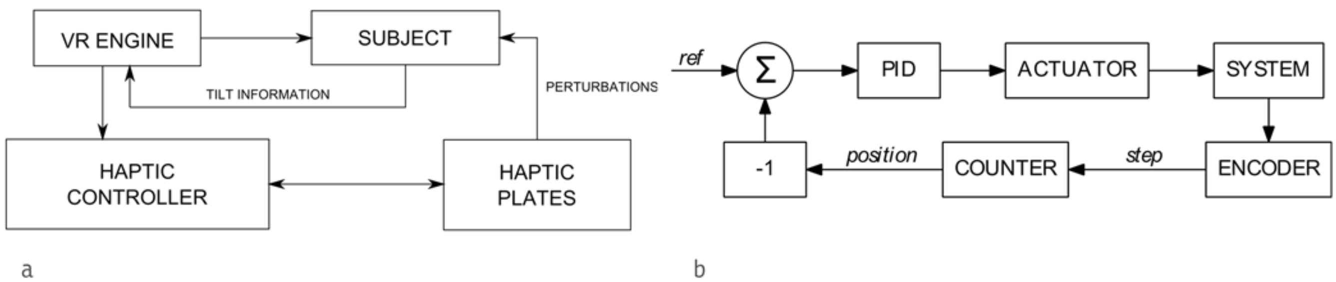


Figure 3: a) Outer control loop between host running virtual reality (VR) engine and haptic controller. b) Inner control loop with reference position signal *ref* given in *steps*. Encoders mounted on motor shafts supply quadrature decoder with step signals required to detect single step and its (rotation) direction. Decoder updates its internal position counter accordingly and outputs it as *position*.

capabilities. Berg Balance Score (BBS), a 14-item balance test, Timed Up & Go (TUG)–a stability and motor test that required standing up and walking, and 10 m walk test (10 MWT) were the tests carried out at the beginning and also at the end of the balance training period. Each VR session lasted 5 minutes and the patient after stroke carried out 3 sessions per day, 5 days per week.[28]

Testing of dynamic characteristics of the haptic floor

In order to demonstrate the system's constant damping and desired displacement amplitude under load, a frequency response of the haptic floor was measured. Such analysis was required to check the stability of the system with controller and find the system's cut off frequency. The reference signal was a pseudo-random signal with linearly rising frequencies up to 5 Hz. The signals A, B and I from both optical encoders were sampled at 1 kHz and the position was calculated within the quadrature decoder. Six measurements were conducted separately for A/P and M/L directions with displacement amplitude of 3 cm from the centre; a) three with the fixed load of 80 kg and b) three without the load.

Data analysis

The data assessed were filtered with a second-order low-pass bidirectional Butterworth filter with a cut-off frequency of 25 Hz. Haptic floor displacement data were interpolated with smoothing spline with degree of three to enable more accurate frequency analysis. Phase margin and the gain margin of the Bode plot were calculated to check the stability of the haptic floor system. We expected that the gain cross the frequency (f_g, phase @ 0dB) would be less than the phase cross the frequency (f_{ph}, gain @ phase = 180°), which would mean that our haptic floor closed-loop system was stable. The cut-off frequency of the system was determined by the set of data assessed around attenuation of -3 dB. Statistically relevant data within 2σ were used to calculate the bandwidth of the closed-loop system. The bandwidth represented the frequency range where the haptic floor system can assure failure free translational movement without significant amplitude attenuation.

Data assessed in NG group was used to build up the normative. For that purpose the mean and standard deviation of the acceleration (a_{abs}) of the standing frame (body) at the level of the pelvis from the onset of the haptic floor were calculated. Absolute acceleration was calculated by rotating sensor's coordinate system to a global by angles of the standing frame's inclination and subtracting the acceleration due to the gravity.[1] Only x and y components of $\boldsymbol{a}_{abs}$ $\boldsymbol{a}_{abs}$ were observed as they represent acceleration in A/P and M/L directions in transversal plane, thus the determination of $\boldsymbol{a}_{gravity}$ $\boldsymbol{a}_{gravity}$ was not necessary.

$$\boldsymbol{a}_{abs} = R_{\theta}^{AP} R_{\phi}^{ML} \boldsymbol{a}_{sensor} - \boldsymbol{a}_{gravity} \qquad (1)$$

The postural response lasted less than 500ms,[29] after that we could expect a return to the equilibrium (upright posture). However, the postural response of the patient with impairments of neuromuscular system was expected to show significant deviations, especially in the diagonal perturbation directions. The back-left and back-right directions of perturbations (haptic floor translations) were considered the most critical and the most frequent in the specific VR task during balance training. . Therefore, only those data were contrasted to the normative and

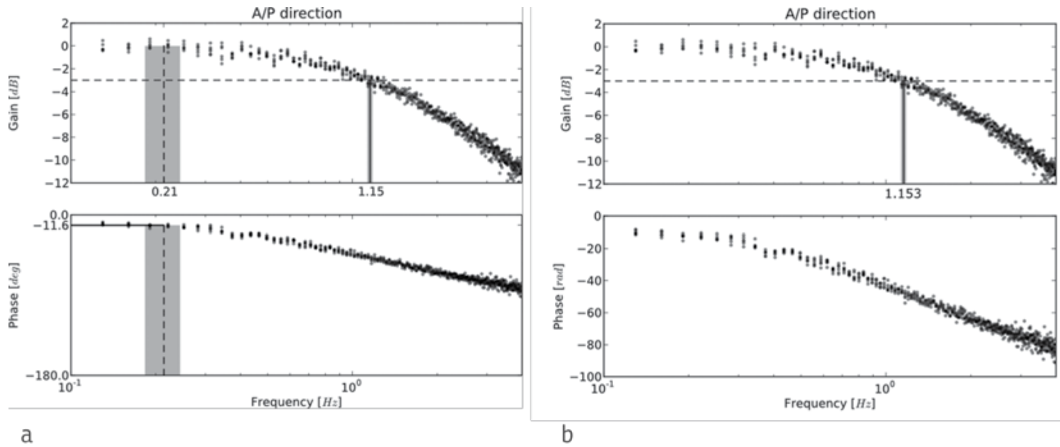


Figure 4: Responsiveness of the constructed haptic floor shown using Bode diagram, for displacement in A/P direction on a) and M/L direction on b). Bandwidth is determined by the frequency where amplitude falls to 70.7 % (3 dB) of the amplitude at 0 Hz and is depicted with solid vertical line with its associated standard deviation drawn as shaded area.

relative amplitude of the first response (A_{res}) and its time delay (T_{del}) were examined.

Additionally, clinical tests carried out prior and after the rehabilitation were statistically tested. The mean value and standard deviation of the outcomes were calculated (SPSS 14, SPSS Inc., Chicago IL, USA) and statistical differences between both assessments were tested with repeated measures analysis of variance with significant level ($p < 0.05$).

Results

The haptic floor's frequency responses were analysed using Bode plot for A/P (Figure 4a) and M/L directions (Figure 4b). The measured cut-off frequency at -3 dB was 1.153 (s.d. 0.024) Hz for A/P and 0.966 (s.d. 0.086) Hz for M/L direction. The measured gain cross frequency f_g was 0.21 (s.d. 0.030) Hz with phase margin 164.4° in A/P and 0.22 (s.d. 0.013) Hz with phase margin 166° in M/L direction. Phase cross frequency f_{ph} was beyond the range of conducted test, thereby criterion $f_g << f_{ph}$ for system stability was satisfied in both directions.[30] The bandwidths of the haptic floor from the Bode plot were 1.15 Hz and 0.97 Hz for A/P and M/L directions, respectively. The step response of the unloaded haptic floor resulted in a floor movement with the acceleration of 4.62 cm/s^2.

Figure 5a shows filtered normative responses to horizontal postural perturbations in all eight directions. If the haptic floor moves forward, the body responds with accelerated backward movement and vice versa. If the haptic floor moves right, the body responds with accelerated movement to the left. Time to peak response is 200 ms (195 ± 27) ms on average. Figure 5b demonstrates the response of the patient after stroke to perturbations in the back/right direction with peak-to-peak delays $T_{MLdel} = 20$ ms, $T_{APdel} = -46$ ms and amplitude difference $A_{APres} = 4.7$ cm/s^2 and $A_{MLres} = 39.4$ cm/s^2, and in the back-left direction with peak-to-peak delays $T_{MLdel} = 95$ ms, $T_{APdel} = 21$ ms and amplitude difference $A_{APres} = 30$ cm/s^2, $A_{MLres} = 23.4$ cm/s^2. AP and ML in subscripts denote A/P and M/L directions. In the back/left perturbation a weaker response was demonstrated than in the more critical direction back-right that required support on the opposite extremity, i.e. the affected right side.

Table 1 reports on a slight improvement (non-siginificant) of the patient's balance capabilities according to the BBS; from 47/56 up to 49/56. Mobility tests demonstrated a significant improvement of TUG (> 5 s) and 10 MWT (~ 2s) in 3-week VR supported balance training.

Discussion

In our paper, a haptic floor as a novel biofeedback for VR supported balance training and as a promising postural response assessment tool was introduced. Generation of sufficient postural perturbation to invoke postural responses has been an issue for decades due to their dynamic requirements. Multidirectional horizontal translations were managed by expensive and large hydraulic platforms[31,32] and perturbations at the level of the pelvis[26] were carried out by powerful electro-motors. However, the principle or large scale was not appropriate for the existing telerehabilitation system for balance training[28] therefore we

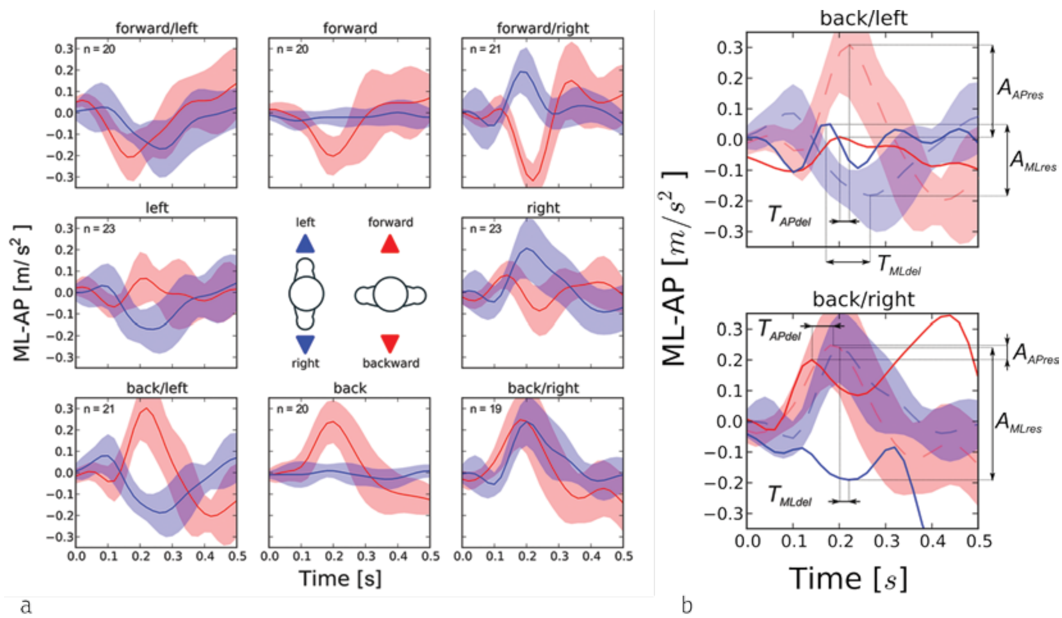


Figure 5: a) a normative measured in 4 neurologically intact subjects for each of the eight perturbation directions with standard deviation drawn as shaded area. Red color represents an absolute acceleration in the A/P direction and blue in the M/L direction. On b) a response of patient after stroke, shown for back/right direction differs from the normative. This could be used to monitor rehabilitation progress and to estimate critical directions associated with a higher risk of fall.

designed a novel haptic floor that could be further enhanced to enable translations for each foot individually. The designed haptic floor has passed the dynamic and stability tests, despite their lower bandwidth with respect to hydraulic platforms (1.15 Hz), but could still generate horizontal perturbation and reach the final position in less than 400 ms. More important was the setting of damping and PID parameters to assure the stability of the system. The system instability may cause uncontrolled forces and movements, which may damage the equipment and/or the patient. The applied Bode plot stability analysis[30] on the closed-loop system demonstrated controllable stability and responsiveness in the bandwidth of at least 1 Hz. We may assume that the phase crossover[30] takes place at a higher frequency. However, the mechanical constraints of the device did not allow testing up to very high frequencies, meaning that the instable situation is most likely out of range. Besides the device safety, the standing frame protects the participating patient from fall in case of e.g. haptic floor failure, postural instability or loss of balance.

Centre of pressure (CoP) is the most common way to follow-up the balance training outcomes and evaluate balance and postural capabilities.[33] The findings of Sayenko et al. suggested that postural responses could be significantly improved on short term during balance training.[34] However, it is questionable whether a short-term balance training and/or postural perturbation also have a long-term improvement effect due to the natural recovery from the acute state. But changes in postural response delays often arise from the neurological impairment of the patient, i.e. slow sensory or motor conduction.[25] Patients usually compensate for delayed postural response by increasing the amplitude of the response and applying more voluntary control. The strategies reported were different; ankle, hip and mixed, depending on biomechanical and neural constraints.[25] The more accurate analysis of the postural response strategies were examined using electromyography (EMG) of specific muscle groups; antagonist, planar flexors, quadriceps, hamstrings, tensor fascia lata, abdominal muscle groups and erectus spinae.[35] In our case, we assumed that the subjects in most cases applied mixed strategy (ankle and hip muscle groups activated) rather than ankle muscle synergy only because the table was mounted on the standing frame. The mechanism of postural responses could be further explained by extensive EMG analysis,[25] but hereby we were limited to the assessment without any sensors on human body only due to the future strategy of development of telerehabilitation/telediagnostics device. We suggested an indirect assessment of postural responses by measuring the acceleration of the body through the standing frame, similar to the one reported by Yu et al,[36] demonstrating that COM acceleration significantly and highly correlated with COM-COP in both A/P and M/L directions for young, elderly and stroke patients. Thus the COM acceleration could be applied as an alternative for the evaluation of postural control. Our outcomes in a single patient with stroke suggest that for both backward directions (left and right) the patient's postural control was rather weak and deviated from the normative and its standard deviation. On the left the patient applied ankle strategy, keeping the body as still as possible and on the right the response in M/L direction was rather weak, resulting in larger body – COM acceleration a while after the onset of perturbation. This was expected as the reaction of the patient had been transferring the load on the left, affected extremity. Such information on directional postural responses to the perturbations with or without VR environment may present valuable complementary information in addition to the clinical tests[37] for the physician who is evaluating the rehabilitation progress remotely. E.g., the participating patient with stroke took part in the rehabilitation programme and the 3-week VR supported balance training, demonstrating clinical improvements in balance (BBS), mobility score (10 MWT) and combined mobility test (TUG). The physiotherapist may not need to repeat the tests frequently, but only when specific changes are noticed remotely in postural responses.

Conclusions

We have demonstrated that the haptic floor has a potential to contribute to the biofeedback and thus enhance the immersive experience of VR supported balance training[28] and also enable a new feature – assessment of postural responses. Technically, the system has proven capable of generating adequate postural perturbations in terms of system stability[30] and bandwidth. The standing frame prevents the risk of fall and ensures that the patient is safe during posture, balancing and postural perturbation. The electronic and power circuitries were entirely separated from the user.

In clinical terms, we may expect that the contribution of the haptic floor to the feedback for VR supported balance training would have similar therapeutic end effect as conventional balance training,[28] but with less physical effort by the physiotherapist[23]. But the most important features, the generation of postural perturbations in several directions and postural response assessment, may significantly contribute to the complementation of clinical test. Thus, the rehabilitation programs in a patient with stroke using rehabilitation robots and other devices could be more targeted and effective.[38] In the future we may see haptic floor in combination with a telerehabilitation system,[28] installed in the environment where an expert cannot be present, e.g. in patient's home. By using appropriate mathematical tools, physiotherapist could assess patient's postural abilities in various directions, which may be critical and present a risk of fall and therefore the patient is sent to outpatient examination only when necessary. However, a study on a large group of stroke patients is required to confirm the applicability of the proposed approach in clinical settings.

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References

1. Truelsen T, Ekman M, Boysen G. Cost of stroke in Europe. Eur J Neurol 2005; 12 Suppl 1: 78–84.
2. Tyson S, Hanley M, Chillala J, Selley A, Tallis RC. Balance Disability After Stroke. Phys Ther 2006; 86: 30–8.
3. Kuo AD, Zajac FE. Human standing and posture: multi-joint movement strategies based on biomechanical constrains in Progress on Brain research (ed. Allum et al) 1993; 97: 349–358

4. Lim JY, Jung SH, Kim WS, Paik NJ. Incidence and risk factors of poststroke falls after discharge from inpatient rehabilitation. PM&R 2012; 4: 945–53
5. Nyström A, Hellström K. Fall risk six weeks from onset of stroke and the ability of the Prediction of Falls in Rehabilitation Settings Tool and motor function to predict falls. Clin Rehabil 2013; 27: 473–9
6. Mackintosh SF, Hill K, Dodd KJ, Goldie P, Culham E. Falls and injury prevention should be part of every stroke rehabilitation plan. Clin Rehabil 2005; 19: 441–51
7. Rushton D. Functional electrical stimulation. Physiol Meas 1997; 18: 241–75
8. Tong K, Chan S, Wong W, Lui K, Tang K, Gao X, et al. BCI-FES training system design and implementation for rehabilitation of stroke patients. IJCNN 2008; 2008 Jun 1–8; Hong Kong, China.
9. Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ, Koetsier JC. Intensity of leg and arm training after primary middle-cerebral-artery stroke: a randomised trial. Lancet 1999; 354: 191–6.
10. Matjačić Z, Hesse S, Sinkjaer T. BalanceReTrainer: a new standing-balance training apparatus and methods applied to a chronic hemiparetic subject with a neglect syndrome. NeuroRehabilitation 2003; 18: 251–9.
11. Yang Y, Tsai M, Chuang T, Sung W, Wang R. Virtual reality-based training improves community ambulation in individuals with stroke: A randomized controlled trial. Gait Posture 2008; 28: 201–6.
12. Holden M. Virtual environments for motor rehabilitation: review. Cyberpsychol Behav 2005; 8: 187–219.
13. Kenyon RV, Leigh J, Keshner EA. Considerations for the future development of virtual technology as a rehabilitation tool. J Neuroeng Rehabil 2004; 1: 13.
14. Burdea G, Popescu V, Hentz V, Colbert K. Virtual Reality-Based Orthopedic Telerehabilitation. IEEE T Rehabil Eng 2000; 8: 430–2.
15. Adamovich SV, Fluet GG, Tunik E, Merians AS. Sensorimotor training in virtual reality: A review. NeuroRehabilitation 2009; 25: 29–44.
16. Bisson E, Contant B, Sveistrup H, Lajoie Y. Functional balance and dual-task reaction times in older adults are improved by virtual reality and biofeedback training. Cyberpsychol Behav 2007; 10: 16–23.
17. Deutsch JE, Mirelman A. Virtual reality-based approaches to enable walking for people poststroke. Top Stroke Rehabil 2007; 14: 45–53.
18. Koenig A, Wellner M, Köneke S, Meyer-Heim A, Lünenburger L, Riener R. Virtual gait training for children with cerebral palsy using the Lokomat gait orthosis. St Heal T 2008; 132: 204–9.
19. Padala KP, Padala PR, Malloy TR, Geske JA, Dubbert PM, Dennis RA, Garner KK, Bopp MM, Burkeand WJ, Sullivan DH. Wii-Fit for Improving Gait and Balance in an Assisted Living Facility: A Pilot Study. J Aging Res 2012; Article ID 597573, 1–6
20. Brown R, Sugarman H, Burstin A. Use of the nintendo wii fit for the treatment of balance problems in an elderly patient with stroke: A case report. Int J Rehabil Res 2009; 32: 109–110.
21. Crosbie JH, Lennon S, Basford JR, McDonough SM. Virtual reality in stroke rehabilitation: still more virtual than real. Disabil Rehabil 2007; 29: 1139–52.
22. Nyberg L, Lundin-Olsson L, Sondell B, Backman A, Holmlund K, Eriksson S, et al. Using a virtual reality system to study balance and walking in a virtual outdoor environment: a pilot study. Cyberpsychol Behav 2006; 9: 388–95.
23. Bardorfer A, Munih M, Zupan A, Čeru B. Upper limb functional assessment using haptic interface. Zdrav Vestn 2004; 73: 19–24
24. Merians AS, Fluet GG, Qiu Q, Lafond I, Adamovich SV. Learning in a virtual environment using haptic systems for movement re-education: can this medium be used for remodeling other behaviors and actions? J Diabetes Sci Technol 2011; 5: 301–8.
25. Horak F, Henry S, Shumway-Cook A. Postural Perturbations: New Insights for Treatment of Balance Disorders. Phys Ther 1997; 77: 517–33.
26. Cikajlo I, Matjačić Z. Directionally specific objective postural response assessment tool for treatment evaluation in stroke patients. IEEE T Neur Sys Reh 2009; 17: 91–100.
27. Cikajlo I, Rudolf M, Goljar N, Matjačić Z. Virtual reality task for telerehabilitation dynamic balance training in stroke subjects. Virtual Rehabilitation International Conference 2009; 2009 Jun 29-Jul 2; Haifa, Israel.
28. Cikajlo I, Rudolf M, Goljar N, Burger H, Matjačić Z. Telerehabilitation using virtual reality task can improve balance in patients with stroke. Disabil Rehabil 2012; 34: 13–8.
29. Loram ID, Gawthrop PJ, Lakie M. The frequency of human, manual adjustments in balancing an inverted pendulum is constrained by intrinsic physiological factors. J Psychol 2006; 557: 417–32.
30. Varmah H. Control Systems. New Delhi: Tata McGraw Hill Education Private Limited; 2010.
31. Nashner LM. Adapting reflexes controlling the human posture. Exp Brain Res 1976; 26: 59–72.
32. Moore SP, Rushmer DS, Windus SL, Nashner LM. Human automatic postural responses: responses to horizontal perturbations of stance in multiple directions. Exp Brain Res 1988; 73: 648–58.
33. Krebs DE, McGibbon CA, Goldvasser D. Analysis of postural perturbation responses. IEEE T Neur Sys Reh 2001; 9: 76–80.
34. Sayenko DG, Masani K, Vette AH, Alekhina MI, Popovic MR, Nakazawa K. Effects of balance training with visual feedback during mechanically unperturbed standing on postural corrective responses. Gait Posture 2012; 35: 339–44.
35. Cikajlo I, Krpič A, Gorišek-Humar M. Changes in EMG Latencies during Balance Therapy Using Enhanced Virtual Reality with Haptic Floor. 35th Annual International Conference of the IEEE EMBS Osaka, Japan, 3–7 July, 2013: 4129–132
36. Yu E, Abe M, Masani K, Kawashima N, Eto F, Haga N, et al. Evaluation of postural control in quiet standing using center of mass acceleration: comparison among the young, the elderly, and people with stroke. Arch Phys Med Rehabil 2008; 89: 1133–9.
37. Baetens T, De Kegel A, Calders P, Vanderstraeten G, Cambier D. Prediction of falling among stroke patients in rehabilitation. J Rehabil Med 2011; 43: 876–83
38. Popović BD, Popović MB. New trends in neurorehabilitation of subjects with central nervous system lesions. Zdrav Vestn 2010; 79: 296–301.