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Impact of virtual-reality feedback on human balance training when using a haptic support surface in rehabilitation medicine

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Abstract. Balance training and postural response assessment have been for decades two separate tasks in the rehabilitation medicine. The former concerns physiotherapy and the latter diagnostics. The virtual-reality technology does not only enhance the possibilities of balance training, but in combination with a haptic floor enables the subjects to gain a postural imbalance experience. The differences in the kinematic postural responses of three neurologically intact young adults are examined during an active postural perturbation caused by a horizontal translation of the haptic floor without virtual-reality feedback. The response latencies are extracted from measurements of ankle, knee and hip joints kinematics from the onset of the perturbation. The results demonstrate significant differences for knee and hip joints kinematics, however a larger number of subjects should be studied to strengthen the findings.

Keywords: balance rehabilitation, post-stroke

Vpliv navidezne resničnosti kot povratne informacije na vadbo ravnotežja človeka ob uporabi haptičnih tal v rehabilitacijski medicini

Vadba ravnotežja in ocena ravnotežnih odzivov sta že dve desetletji obravnavani kot ločeni nalogi v rehabilitacijski medicini. Prva se nanaša na fizioterapijo, slednja na diagnostiko. Navidezna resničnost poleg možnosti, ki jih nudi pri vadbi ravnotežja, v kombinaciji s haptičnimi tlemi omogoča osebam, da izkusijo tudi posturalno nestabilnost. Raziskali smo kinematične razlike v posturalnih odzivih pri treh nevrološko nepoškodovanih mladih osebah pri aktivni posturalni motnji, ki jo povzroči horizontalni pomik haptičnih tal v kombinaciji z oz. navidezne resničnosti. Zakasnitve odzivov smo spremljali v gležnju, kolenu in kolku od trenutka, ko nastopi motnja, izračunali pa smo jih iz izmerjenih kinematičnih parametrov. Rezultati kažejo na statistično značilne razlike v odzivih le v kolenu in kolku, vendar bi bilo potrebno rezultate podkrepiti z meritvami pri večjem številu oseb.

1 INTRODUCTION

Balance has been one of the major concerns in the increasing population with stroke in EU (about 1.1 million occurrences of stroke per year) as it presents an important issue in returning to a normal life. Therefore, most of the rehabilitation programs dedicate a significant attention to balance training. In the last decade it has been shown that repetitive target-oriented training tasks increase the effectiveness of the neurorehabilitation treatment of subjects with sensory-motor difficulties [8]. The target-based training tasks request from the subject to perform a specific motion in order to complete the task. Nowadays, instead of the physiotherapist's manual assistance, such training combined with contemporary environments and objects in the virtual reality relieves the physiotherapist from the repetitive work and enables subjects to immerse into a given task [7]. The use of virtual reality in rehabilitation has proven as very effective and useful [6], but it is incorrect to say that it is much better than the conventional rehabilitation. We demonstrate that using a balance trainer in combination with the virtual reality and telerehabilitation can be effective in balance recovery of subjects after stroke, however, similar outcomes have also been achieved with conventional balance training programs [5] which require a lot of manual assistance.

In addition to the balance training, a postural response assessment has been developed in order to evaluate the dynamic balancing [10]. However, the balance training and assessment have been two separate tasks in rehabilitation medicine since ever. Thus we propose a novel apparatus to enhance the balance training with tasks in a virtual environment with a haptic information [4]. The haptic information is applied as surface horizontal translations and may serve as a postural-response assessment. Eventually, such device may in future provide also postural assessment during the home-based balance training [5].

In our study we examined the possibility of evaluation of the postural responses based on the kinematics of the human body. Therefore, an assessment under two conditions was made; conventional postural perturbation

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and postural perturbation as a consequence of an action in the virtual environment. We expected a changed postural strategy [3] and hypothesized that the kinematic postural-response latencies would shorten in subjects anticipating implications of a collision in the virtual environment.

2 Methodology

2.1 Subjects

Three neurologically intact volunteers (two males, one female, aged 27.7 (SD 1.7), height 169.0 (SD 10.6) cm and weight 67.7 (SD 17.6) kg), without any visual or orthopedic disorders participated in the proof of concept study.

Each volunteer provided a written consent to participate. The methodology was approved by the Ethics Committee of the University Rehabilitation institute, Republic of Slovenia.

2.2 Device and equipment

A safe balance and posture were assured by the developed [9] and now commercially available BalanceTrainer (BT) standing frame (BalanceTrainer, Medica Medizintechnik, Germany). The BT consists of an upper part of a frame fixed to the base with passive controllable springs enabling movement in two degrees of freedom (2 DOF) in the range of $\pm 15^\circ$ in the sagittal and frontal plane. The tilt of the BT frame was assessed by three-axis tilt/inclination sensor (Oak USB, Toradex, Switzerland) and was used to control the VR environment (VRML, blaxxun plug-in). The BT frame tilt in the antero-posterior (A/P) direction moved the avatar in the forward/backward direction and the tilt in the mediolateral (M/L) direction rotated the avatar. The speed that was usually proportional to the tilt angle was constant. At the onset of collision between the avatar and an object in the VR environment, the information was sent to the haptic floor (HF) via UDP/IP. The haptic floor [4] provided adequate horizontal translations (perturbations) in eight directions in the transversal plane: forward (F), backward (B), left (L), right (R) and diagonal directions BL, BR, FR, FL.

The bottom part of the device (Fig. 1(a)) was made of the aluminum profiles and guide rails carrying aluminum plates in two layers. The lower layer carried a DC motor connected to the plate with a steel wire serving the movement in the M/L direction. The upper layer moved in the A/P direction. Both DC motors (Maxon DC RE40, 150W, Switzerland) used reduction gearboxes (Maxon, Planetary Gearhead GP 52, Switzerland) and were equipped with encoders (Maxon Encoder HEDS 5540, Switzerland). The quadrature decoders and the control algorithm were programmed in Labview 8.5 FPGA (NI) and managed by a real-time controller (NI cRIO-9014, USA). The encoder signals were assessed a with a high-speed digital I/O (NI 9403, USA) and the DC motors were controlled via analog output (NI 9263 AO, USA) signals amplified with the Maxon 4-Q-DC servoamplifier (ADS 50/10, pulsed (PWM) 4-Q-DC Servoamplifier $50V/10A$). Analog outputs provided information about the absolute position of the plates in A/P and M/L directions (by sampling the current values of the quadrature decoders). The HF position information and a trigger signal (step impulse lasting for 100 ms) at the onset of collision were sent to a laptop computer equipped with a Keithley PCMCIA-12AI data acquisition card.

The movement of the subject standing in the BT was assessed by three-axis inertial sensors (MTx, XSens Technologies, Enschede, The Netherlands). The computed angle (roll-pitch-yaw) information and acceleration of each single sensor attached to the body segment were sampled at 50 Hz. The sensors were attached to the shank (R_{SHANK}), thigh (R_{THIGH}) and thorax (R_{THORAX}) at the 10th Thoracic Vertebrae with local coordinate systems (Fig. 1(b)). An external trigger was used to synchronize the data with the NI data.

2.3 Assessment protocol

The subjects positioned firmly into the standing frame with their arms crossed and palms touching their shoulders. The height of the support frame was adjusted to be in the level of the pelvis. The legs were positioned on the haptic floor side by side, shoulders wide apart (Fig. 1(a)). The proof of the concept study consisted of two tasks;

- A perturbations in all directions (F, B, L, R, BL, BR, FR, FL) were induced in a random order. The subjects were not notified about the onset of perturbation. Instead the perturbation occurred randomly within five seconds. Three seconds after the perturbation occurrence the haptic floor slowly returned to its original position.
- B A modified VR task from the existing telerehabilitation system at URI-Soča was used [5]. The avatar was moving ahead at a constant speed while the subjects controlled the movement direction in the VR by tilting the body/BT frame in the M/L direction. At the onset of collision with a VR object, an adequate horizontal translation (perturbation) of HF occurred [4].

Each task took 80 s and was repeated three times. During the task, the subject's kinematic responses to the external perturbations were monitored.

2.4 Data analysis

The Data assessed from the sensors were bidirectionally filtered with a second-order high-pass Butterworth filter with a very low cutoff frequency of 1/30 Hz to eliminate the low frequency drift around the equilibrium position [11]. The assessed roll-pitch-yaw angles of each

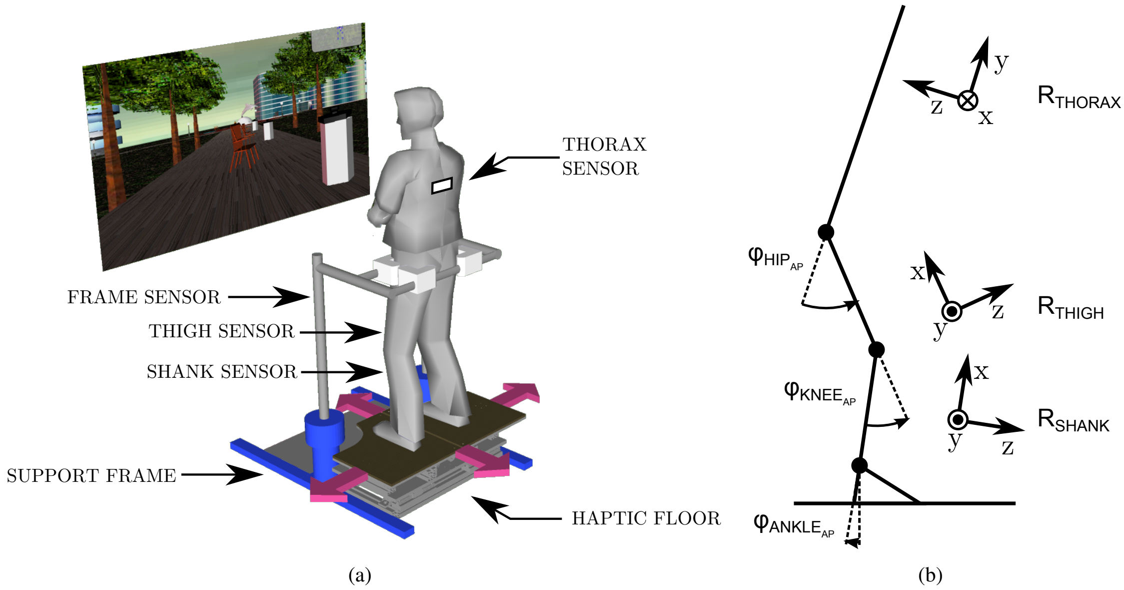

Figure 1. (a) standing frame with a movable support surface shown from behind. The arrows show the possible perturbation directions for each, sagittal and frontal plane. (b) shows the angles of interest in three segmented model of a human with coordinate systems of sensors attached on the body segments: $\mathbf{R}_{SHANK}$, $\mathbf{R}_{THIGH}$ and $\mathbf{R}_{THORAX}$.

sensor were filtered with a second-order Butterworth low-pass filter of 6 Hz to eliminate the unwanted noise [13]. Then a simplified three-segment biomechanical model [1] was used to calculate joint angles in the ankle, knee and hip (Fig. 1(b)). The model uses the body-segment dimensions and relative position and orientation of the local coordinate systems at the sensors to calculate the 3-D angles at all three joints. The simplified model uses Eq. 1, Eq. 2 and Eq. 3) where each **R** matrix denotes the body part and the axis of rotation and φ denotes the angle at a given body joint and observed direction.

$$\varphi_{ANKLE_{AP}} = -\mathbf{R}_{SHANK,Y} \tag{1}$$

$$\varphi_{KNEE_{AP}} = -\mathbf{R}_{SHANK,Y} - \mathbf{R}_{THIGH,Y} \tag{2}$$

$$\varphi_{HIP_{AP}} = \mathbf{R}_{THORAX,X} - \mathbf{R}_{THIGH,Y} \tag{3}$$

Our goal was to identify the major differences between the two tasks in terms of kinematics. Therefore, the peaks in the kinematic responses were identified (Fig. 2) and the latencies from the onset of collision were measured. The first low peak (t_0) and the first high peak (t_1) were identified (Fig. 2). The measured latencies in the responses to the perturbation were averaged for each direction of the perturbation and the standard deviation was calculated. The statistical differences between the two scenarios (task A and task B) were tested with a two-way ANOVA (with factors $2\times task$ and $3\times subject$) calculated for both latencies ($t_{0,x}$ and $t_{1,x}$) and all the three joints.

3 Results

Most collisions in task B were frontal (FL, FR and F). Thus, the adequate responses of HF were in the BR, BL and B directions. The results for the BL horizontal translation are presented.

The mean and standard deviations of the measured latencies t_0 and t_1 of each latency $\varphi_{ANKLE_{AP}}$, $\varphi_{KNEE_{AP}}$, $\varphi_{HIP_{AP}}$ for both tasks are presented in Table 1. The mean latencies at the task B latencies were smaller than those of task A for the hip joint, but larger for the knee joint. The latencies at the ankle joint were rather similar. The sample distribution of the measured latencies for the BL direction are given in Fig. 3.

The outcomes of the two-way ANOVA (Table 1) demonstrated significant ($p < 0.05$) differences between task A and task B for the following mean latencies: $t_{1,KNEE}$, $t_{0,HIP}$ and $t_{1,HIP}$. Significant differences were also found between the subjects for the mean latencies at $t_{1,ANKLE}$, $t_{0,KNEE}$ and $t_{0,HIP}$. However, the interaction ($task * subject$) was also found significant for the following mean latencies: $t_{1,KNEE}$, $t_{0,HIP}$ and $t_{1,HIP}$.

4 Discussion and Conclusion

According to the research findings of electromyography (EMG) obtained in the study [3], we expected that the presence of the visual feedback would enable faster postural responses also in terms of the body kinematics. Our results indicated that our assumption was true for the hip joint, while the ankle and knee joint demonstrated longer

	n		$t_{0,ANKLE}$	$t_{1,ANKLE}$	$t_{0,KNEE}$	$t_{1,KNEE}$	$t_{0,HIP}$	$t_{1,HIP}$
task A	9	AVG [ms]	70	266	53	184	72	305
(HF only)		SD	8.4	71.5	11.2	34.4	7.6	50.1
task B	12	AVG [ms]	70	284	52	239	56	241
(VR with HF)		SD	10.0	40.1	11.2	51.5	14.2	52.5
$task$		F	0.015	2.283	0.153	8.451	24.706	7.522
		p	0.906	0.155	0.701	0.012*	<0.001*	0.018*
$subject$		F	0.659	38.527	13.716	1.752	9.807	0.858
		p	0.532	<0.001*	<0.001*	0.212	0.002*	0.449
$task * subject$		F	0.391	0.529	1.050	4.351	11.237	4.212
		p	0.683	0.601	0.374	0.036*	0.001*	0.041*

Table 1. Average (AVG) and standard deviation (SD) of latencies (t_0) extracted from the responses to the perturbations for both performed tasks. A two-way ANOVA was applied to identify the differences in the response latencies between $tasks$, within $subjects$ or interaction $task * subject$. Asterisk sign (*) accompanied the p-values where the difference was considered significant ($p < 0.05$).

latencies of the first high peak, but almost no change in the first low peak of the postural response. However, only the hip latencies and the first high-peak latency in the knee joint demonstrated statistically significant differences between the tasks. This may lead to the fact that our subjects applied more hip strategy [2] and less ankle strategy. The choice of the postural strategy therefore depends on the availability of the sensory information. But to confirm such statement for the postural kinematics, a more comprehensive study with a larger number of subjects should be conducted. Partly because the findings revealed that some differences in the postural strategies also appeared in the subjects. Also, the pelvis rotation in hip adduction/abduction should be examined. The rotation of the pelvis may be crucial for the diagonal postural responses when the hip strategy is applied [12].

Our study was limited to a comparison of a single perturbation direction since most collisions in the VR environment were frontal. The controlled consequence of such collision was the HF horizontal translation in the backward-left-right direction. We assumed a symmetry between the left and right responses in healthy, neurologically intact subjects, thus we presented unilateral responses to the back-left perturbation only. Our findings with the muscle EMG [3] report that the presence of the haptic floor besides to VR activated the distal muscles, especially those of the ankle complex (TA, SOL, GAS) in the process of stabilizing the tibia. This may explain the rather small range of motion in the ankle joint and the non-significant differences in the response latencies.

All in all, the VR balance training system with the haptic feedback benefits from the balance training device [5] and the postural response assessment device the enabling balance training and assessment simultaneously with the same apparatus. We demonstrated feasibility of the postural-responses identification through kinematics, however, the way to the clinical practice requires comprehensive randomized clinical studies.

REFERENCES

[1] A. V. Alexandrov, A. A. Frolov, F. B. Horak, P. Carlson-Kuhta, and S. Park. Feedback equilibrium control during human standing. *Biological cybernetics*, 93(5):309–22, Nov. 2005.

[2] S. B. Bortolami, P. DiZio, E. Rabin, and J. R. Lackner. Analysis of human postural responses to recoverable falls. *Experimental brain research*, 151(3):387–404, Aug. 2003.

[3] I. Cikajlo, A. Krpič, and M. Gorišek. Enhanced telerehabilitation experience and telediagnostics with haptic floor. In *IEEE EMBC Proceedings, in print*, 2013.

[4] I. Cikajlo, J. Oblak, and Z. Matjačić. Haptic floor for virtual balance training. *2011 IEEE World Haptics Conference*, pages 179–184, June 2011.

[5] I. Cikajlo, M. Rudolf, N. Goljar, H. Burger, and Z. Matjačić. Telerehabilitation using virtual reality task can improve balance in patients with stroke. *Disability and rehabilitation*, 34(1):13–8, Jan. 2012.

[6] M. K. Holden. Virtual environments for motor rehabilitation: review. *Cyberpsychology & behavior : the impact of the Internet, multimedia and virtual reality on behavior and society*, 8(3):187–211; discussion 212–9, June 2005.

[7] R. V. Kenyon, J. Leigh, and E. a. Keshner. Considerations for the future development of virtual technology as a rehabilitation tool. *Journal of neuroengineering and rehabilitation*, 1(1):13, Dec. 2004.

[8] G. Kwakkel, R. C. Wagenaar, J. W. Twisk, G. J. Lankhorst, and J. C. Koetsier. Intensity of leg and arm training after primary middle-cerebral-artery stroke: a randomised trial. *Lancet*, 354(9174):191–6, July 1999.

[9] Z. Matjacić, S. Hesse, and T. Sinkjaer. BalanceReTrainer: a new standing-balance training apparatus and methods applied to a chronic hemiparetic subject with a neglect syndrome. *NeuroRehabilitation*, 18(3):251–9, Jan. 2003.

[10] S. P. Moore, D. S. Rushmer, S. L. Windus, and L. M. Nashner. Human automatic postural responses: responses to horizontal perturbations of stance in multiple directions. *Experimental brain research*, 73(3):648–58, Jan. 1988.

[11] I. J. Pinter, R. van Swigchem, A. J. K. van Soest, and L. a. Rozendaal. The dynamics of postural sway cannot be captured using a one-segment inverted pendulum model: a PCA on segment rotations during unperturbed stance. *Journal of neurophysiology*, 100(6):3197–208, Dec. 2008.

[12] D. A. Winter. Human balance and posture control during standing and walking. *Gait & posture*, 3(4):193–214, 1995.

[13] D. A. Winter. *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons, Inc., Hoboken, NJ, USA, Sept. 2009.

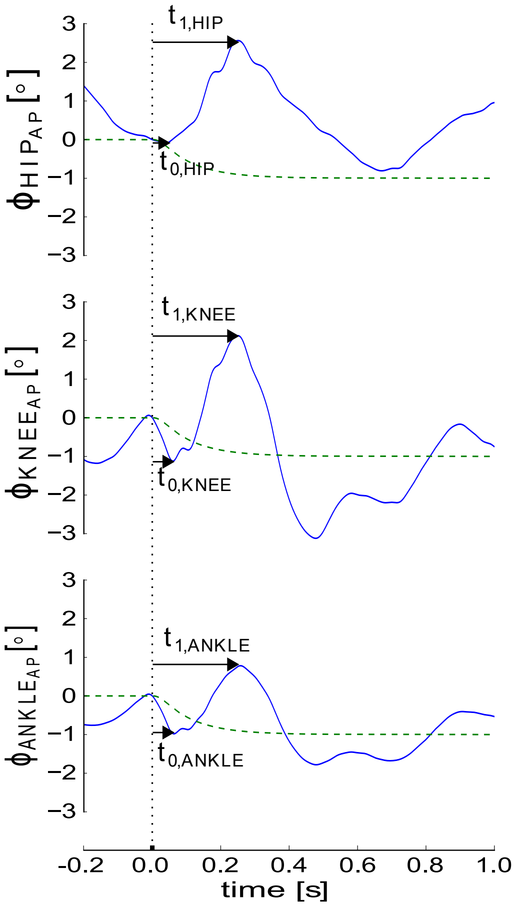

Figure 2. Kinematic postural responses in the A/P direction to the perturbation in the back-left (BL) direction are presented. The body kinematics responds to the external horizontal surface translation with changes in the joint angles at the ankle, knee and hip. Observed latencies $t_{0,HIP}$, $t_{1,HIP}$, $t_{0,KNEE}$, $t_{1,KNEE}$, $t_{0,ANKLE}$ and $t_{1,ANKLE}$ are shown with arrows from the onset of collision (vertical dotted line). The dashed line represents the actual haptic-floor translation (displacement was 3cm).

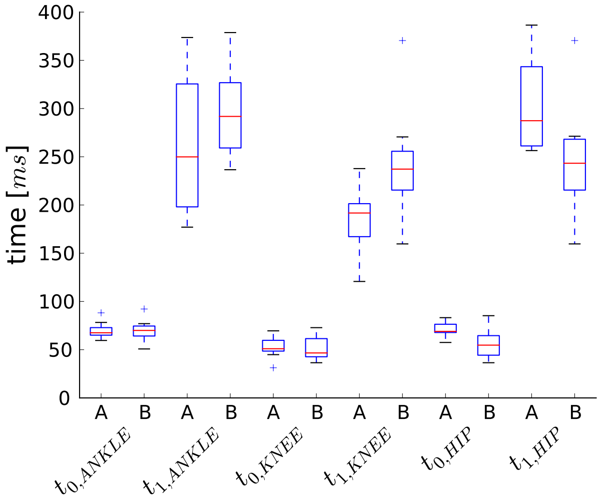

Figure 3. Medians of the response latencies and corresponding sample distribution for each observed body joint for task A and task B. The boxes denote the interquartile range (IQR) between Q1-Q3 and whiskers extend to the range for $1.5IQR$. The crosses denote outliers.

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