Advantages of haptic feedback in virtual reality supported balance training: a pilot study

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ABSTRACT

Repetitive and goal based task supported with virtual reality technology have proven successful in balance training of stroke population. However, adding a haptic experience can besides increasing the difficulty level of the task enable postural responses assessment. We demonstrated in a single subject with stroke that haptic feedback can be used not only for interaction with virtual environment, but also for the assessment of postural responses. After the virtual reality and standing frame supported balance training the subject was introduced to the haptic floor. The acceleration of the standing frame/body provided sufficient information to identify the direction of the postural response that could be critical for fall. The outcomes were comparable with neurologically intact population and could be applied for objective postural response evaluation.

1. INTRODUCTION

Restoration of static and dynamic balance is the major issue for rehabilitation in stroke population. The outcomes have demonstrated that intensive therapy with repetitive and targeted tasks should be applied (Kwakkel et al, 1999). Appropriate assisting devices (active e.g. KineAssistTM, kinea design llc, USA or passive e.g. BalanceTrainer, medica MedizinTechnik, Germany) can assure safety, body weight support, trunk and pelvis stabilization. The active device can maintain the desired posture, but the passive devices only limiting the balance range require certain amount of subject’s activity. However, both types can assure repeatable conditions and free the therapist of strenuous manual work. In combination with the information-communication technologies (ICT) the goal based tasks are carried out in virtual reality (VR), enabling the user to gradually increase the difficulty level, to supervise the repeatability of the rehabilitation process and to change the virtual environment (VE) without changing the basic goal of the task (Holden et al, 2005). Several authors reported on improvement of motor functions in gait, posture and balance (Yang et al, 2008, Visell et al, 2009, Cikajlo et al, 2009, 2012) using VR. Adding a haptic interface to the VR task may enhance action/reaction activities in lower extremities (Vissel et al, 2009). We introduced a haptic floor (Cikajlo et al 2011) to the VR supported balance training, which required from the subject to respond to the postural perturbation at the moment of collision with the obstacle in the virtual environment. The subject needed to activate the postural mechanisms (Jacobs et al, 2007) to return to the equilibrium without lifting or moving the feet. The purpose of the paper is to present the added value of the haptic floor in VR supported balance training. Besides clinical tests we indirectly measured the acceleration and tilt of the subject and acceleration of the haptic floor during task execution and expected that we can evaluate the postural response at the impact with the virtual obstacle.

2. METHODS

The haptic floor was designed as an add-on for the passive dynamic balance training frame (BTF). The passive BTF (Matjačić et al, 2008) enabled the participating subjects safe hands-free balancing during upright standing within pre-set limits. The user could also set up the mechanical stiffness of the supporting frame to increase the level of support. The tilt of the BTF resulted in the immediate action in the designed VE (VRML 2.0, blaxxun contact plug-in – www.blaxxun.com).
2.1 Equipment and control design

A passive BTF (Balance- Trainer, medica Medizintechnik GmbH, Germany, Matjačić et al, 2008) enabled full support for the subject during independent balance training. The BTF consists of aluminium frame, fixed to the steel base construction on four wheels and passive controllable springs defining the stiffness of the two degrees of freedom (2 DOF) standing frame (Fig. 1) and enable tilting in sagittal and frontal plane for 15°. The tilt of the BTF and acceleration of BTF and haptic floor were measured by 3-axis sensor (MTx, Xsens, Enchede, Netherlands). Haptic force plates were driven by DC motors (Maxon DC RE40, 150W, Switzerland) with reduction gearbox (Maxon, Planetary Gearhead GP 52, Switzerland) moving the aluminum plate in 2 degrees of freedom (Fig. 1.). Each DC motor was equipped with encoder (Maxon Encoder HEDS 5540, Switzerland), A, B and index signals were measured with high-speed digital I/O (National Instruments (NI) 9403, USA) and decoded with software quadrature decoder written in Labview 8.5 FPGA (National Instruments). The haptic floor control was embedded in real-time (RT) controller (NI cRIO-9014, USA). The analogue output module (NI 9263 AO, USA) served as an actuator output for DC motors and was amplified with the servo amplifier Maxon 4-Q-DC servo amplifier (ADS 50/10, pulsed (PWM) 4-Q-DC Servo amplifier 50 V / 10 A).

![Figure 1. Haptic floor enables better interaction with task for virtual reality supported balance training (Cikajlo et al, 2011). At collision with the virtual object or on slippery floor (A) the haptic plates suddenly moves in the opposite direction, generating a postural perturbation (B).](image)

Two control loops were designed to control the haptic floor. The outer control loop interacted with the VR world; the collision took place and according to the impact speed the amplitude (reference position) for haptic floor displacement was calculated and sent over TCP/IP to the RT. The inner control loop in RT comprised a PID controller. Ziegler- Nichols tuning method was applied to set the PID. Optional proportional gain (P) and derivative time set up in the way that step response would have minimal (<10%) overshoot and the response would be quick enough (>60% of the amplitude in <500ms, Loram et al, 2006). The integral windup was overcome by setting the integral component to the P/8.

2.2 Subject and protocol

A patient of University rehabilitation hospital (hemiparesis l. sin., F, age 55 years, 80 kg, 167 cm, 5 months after stroke, no neglect, MMSE: 27/30.) participated in the short-term VR supported balance training. Before VR supported balance training (VRBT), after 3 weeks and the follow up after 2 weeks the clinical tests Timed Up&Go (TUG), 10m walk test (10MWT), standing on healthy extremity (SHE) and Berg Balance Scale (BBS) were carried out. The VRBT protocol (Cikajlo et al, 2012) consisted of 3 x 5 min. of active balance training with resting time around 1 min between the sessions for 3 weeks in hospital environment and additional 2 weeks in smart-home environment (Smart Home Iris, www.dom-iris.si/en/).
After the first 3 weeks of VRBT we added a difficulty level upgrade with haptic floor. The subject “moved” forward/backward in the VR environment by leaning in anterior/posterior direction and turned by transferring the load to the opposite leg and tilting the whole body/frame left or right. When the subject hit the virtual object, the collision was detected. According to the speed and angle of impact the reference direction, speed and position of the haptic floor were calculated.

2.2 Postural response assessment

The haptic floor was designed to generate a step response at the time of collision with virtual object and thus present an interaction with the VR environment. Between the onset of collision and conscious postural control (< 300 ms) the subject’s unconscious postural response was expected. The response was assessed by tilt and acceleration sensor mounted on the BTF. Gravitational and rotational components were subtracted from the measured acceleration. Further on, the signal in time & frequency space provided enough information to evaluate the postural response (Cikajlo et al 2009). However, we also considered that the haptic floor stopped and returned to the initial position (vertical posture) without generating any postural perturbation due to the smooth control with high damping.

3. RESULTS

Table 1. The subject’s clinical status rapidly improved in the first 3 weeks of VRBT.

<table>
<thead>
<tr>
<th>Measure</th>
<th>before VRBT</th>
<th>after VRBT</th>
<th>follow up</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBS</td>
<td>47</td>
<td>49</td>
<td>52</td>
</tr>
<tr>
<td>TUG</td>
<td>23,3</td>
<td>18,0</td>
<td>19,0</td>
</tr>
<tr>
<td>10MWT</td>
<td>17,1</td>
<td>15,7</td>
<td>13,0</td>
</tr>
<tr>
<td>SHE</td>
<td>8,8</td>
<td>22,3</td>
<td>15,7</td>
</tr>
</tbody>
</table>

The subject has also improved the VRBT game score (mean task time from 93,0s to 42,8s and number of collisions from 12 to 5) and after the rehabilitation was using a single crutch only.

![VRWORLD](image)

**Figure 2.** The collision within the VR task resulted in the haptic information and the subject “felt” the impact. At the same time the postural response was assessed and compared with normative (shaded) assessed in neuromuscular intact subjects (Cikajlo et al 2011).

4. DISCUSSION

The outcomes demonstrated that VR supported balance training had significant impact on the improvement of subject’s clinical score. Similar results (Cikajlo et al 2012) proved that VR balance training can be as effective as conventional in clinical environment, but require less physical effort. Additional haptic information in general increases the perception of the task and enables a better cooperation between the robot and the human (Schmidt et al 2005). The robot can adapt the level of support and thus influence on the difficulty level of the goal based task. Hereby the collision or slippery floor required postural responses that not only increased the difficulty level, but also generated expected and unexpected postural perturbations. Thus we monitored the changes in postural responses (Pailex et al 2005) by recalculated accelerations in
anterior/posterior or medial/lateral direction and compared them with the normative in neuromuscular intact subjects. In most cases the subject’s demonstrated premature actions and higher frequency movement at stabilisation (Fig. 2).

5. CONCLUSIONS

The goal based task in virtual environment motivated the subject who »forgot« to pay attention to his/her impairment. Thus more weight was transferred to the impaired lower limb. This was also one of major goals of balance training. Besides, the haptic feedback at the collision with the virtual objects also presented a postural perturbation. The subject's postural response was examined and evaluated. However, the major advantage of the haptic floor may be the assessment of postural responses during balance training. We came to the conclusion that the proposed system enable improved gradual increase of the task's difficulty level by adding haptic floor (Bisson et al 2007) and objective evaluation of postural responses (Cikajo et al, 2009). Such enhancements to the VR based targeted tasks may besides balance training also enable improvement of postural responses (Marigold et al, 2005).The differences in postural strategies between postural responses with w/o VR and/or haptic feedback will be also further examined with electromyography and assessment of the centre of pressure.

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