APPARATUS FOR CLINICAL ASSESSMENT OF POSTURAL BALANCING ABILITIES

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Abstract: A novel strategy for clinical assessment of postural balancing has been set up. Artificially induced perturbations in four principal and in four combinations of principal directions were provided to the modified clinically approved BalanceTrainer standing frame. A person standing in the standing frame was exposed to postural perturbations while simultaneously EMG of major standing muscles were recorded and center of pressure was calculated. In the study seven healthy subjects were involved to set up the normative and then the apparatus was tested in three neurologically impaired person. The patterns were nearly consistent between healthy subject, but showed noticeable differences significant for each individual impaired person. The outcomes were promising and call for further clinical studies to confirm the clinical applicability of the presented apparatus.

Introduction

Our group has been involved in gait and posture for several decades.Besides we have studied methods and techniques of therapy for gait restoration in the rehabilitation unit and also put an emphasis on studies of functional postural standing [1]. The main issue was the identification of central neural system (CNS) control strategies by observing the kinetics, kinematics and muscle activities during quiet and perturbed stance. For that purpose several standing frames were developed, but mostly hydraulically driven [1]. Hydraulic actuators were used for stiffness control and artificially invoked perturbation. Due to the clinical unacceptability of the research device most of the postural response studies and evaluations were limited to the laboratory research work.

The prevalent and well accepted Berg Balance Scale did not satisfy our's needs for postural response and balance evaluation due to the subjectivity of the test. The Scale is based on visual evaluation only and may raise a question to someone who is in need for the objective evaluation. On the other hand few clinically approved, sophisticated objective evaluation devices have been available to the market (e.g. Pro BalanceMaster, Neurocom International Inc.). Most of those appreciated devices are unfortunately large in size that may be an impediment for several laboratories and clinics where space is limited. We need scarcely mention that cost of those devices are usually beyond the financial possibilities of the institution.

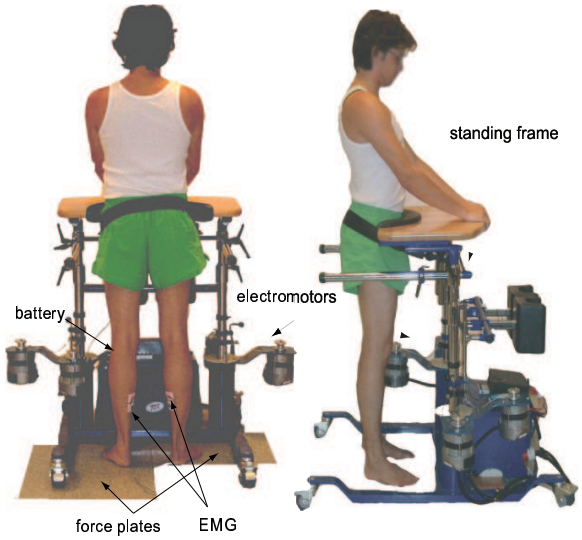

Figure 1: Apparatus for clinical assessment of postural responses in clinical practice. The subject stands in the fall-safe, easy-to-use device. Electromyography (EMG) and force plates (center of pressure) measurements as well as postural perturbation pulses were managed by personal computer.

Therefore a lot of effort was needed to develop an assessment and research tool for postural response [2] that became later a simplified balance training device for use in clinical environment. The research apparatus did not fulfill the requirements for clinical application and was intended for the research purposes only. But the simplification excluding all the actuators and based on passive controllable spring defining the stiffness of the two-degrees of freedom standing frame lead to development of the simplified apparatus that became a clinically approved assisting device for balance training BalanceTrainer (commercial marketing Medica Medizintechnik GmbH, Germany) and in use in several rehabilitation centers worldwide.

Objective of the paper is a further development of the postural response assessment apparatus where the experiences of research tool and BalanceTrainer were joined and resulted in new apparatus for postural assessment that may find a way to the clinical practice. Electro motors and correspondent control electronics replaced the hy-

ISSN: 1727-1983

Table 1: Subjects, mass, height and perturbation parameters

Subject	Age	Weight	Height	Injury Type	Perturbation amplitude
AO	25	67	172	-	strong
GW	32	64	174	-	strong
DA	25	71	177	-	strong
UR	24	66	182	-	strong
VE	25	69	180	-	strong
RO	25	87	190	-	strong
IC	30	76	173	-	strong
TV	65	77	165	incomplete SCI,Th osteoporosis	weak
BJ	45	90	187	incomplete SCI,Th 3-4-5	strong
PA	50	88	175	hemiplegic	middle

draulic torque generators and the two degrees of freedom standing frame was adopted from BalanceTrainer. The modified setup was supported by assessment setup (force plates, electromyography) that has been in clinical practice at our institute as well as worldwide for many years. The aim of the preliminary testing was building a normative based on participating healthy volunteers and the analysis of postural response data in participating neurologically impaired subjects. The expected outcome comprises continuing explanatory characteristics of neurologically impaired persons assessed by the apparatus. In such manner the developed apparatus, a light, easy-to-move, easy-to-use, safe and transferable device may simplify the objective postural response evaluation practice in clinical environment.

Materials and Methods

Subjects

Seven healthy subjects ranging in age from 24 to 32 years (all male, mean 26.6 SD 3.1 years, mean 178.3 SD 6.3 cm and mean 71.4 SD 7.9 kg) and 3 outdoor patients (all male, mean 53.3 SD 10.4 years, mean 175.7 SD 11.0 cm, mean 85 SD 7 kg) with known neurological disorders (incomplete SCI Th-3-4-5, 18 years ago, Th osteoporosis, pathological SCI 3 years ago and one was hemiplegic with affected right side) participated in the study. The criteria for participation in the study was: 1) no neurological and musculoskeletal impairments that may affect balance for the healthy subjects 2) patients with neurological or musculoskeletal impairment and ability to stand and balance using the BalanceTrainer. The local ethics committee at the Institute for Rehabilitation, Republic of Slovenia has approved the testing of the apparatus and the method.

Hardware and assessment protocol

A novel postural training device BalanceTrainer has been modified in a way that artificial postural perturbation in eight different directions may be applied to the person standing in the frame. Four battery powered electro-motors, where two in pairs are delivering perturbations at the level of pelvis of a standing subject by means of a two degrees of freedom (2-DOF) in anterior-posterior (A-P) and medial-lateral (M-L) directions, were mounted on apparatus. A simple control unit with fast safety thermal cutouts for each motor together with personal computer equipped with IO Card were supervising the apparatus and simultaneously managing the data assessment. Subjects stood with each foot on separate force plates (AMTI OR6-5, AMTI Inc., Watertown, MA, USA) assessing 6-DOF data (3 forces and 3 moments, filtered within AMTI amplifier, A/D sampling frequency 100 Hz). During the postural perturbations and recovery the electromyography (EMG) of the selected muscles was recorded. The skin was carefully shaved, before the electrodes (3M^{TM} Red Dot^{TM} Repositionable Electrodes) were carefully placed on tibialis anterior (TA), soleus (SOL), tensor fascia latae (TFL), vastus and rectus femoris (QUA) muscles. The EMG signals were amplified with Noraxon Inc. commercially available amplifier.

An operator was given a choice of perturbation direction that was then provided to the person standing in the frame without being notified about the direction of the provided perturbation. The power of perturbation (three levels: weak, medium, strong - equal to electric pulses duration 400-800 ms) was user-selectable and a choice of light, medium and high power is available. The generated pulses elicited perturbation in one of the four principal directions (Forward - FW Right - RT, Left - LT and Backward - BW) or in one of the four combination of the principal directions (Forward/Right - FR, Backward/Right - BR, Forward/Left - FL, Backward/Left - BL). The realization of perturbation in combined principal direction was managed by simultaneous action of two appropriate electro-motors each for corresponding principal direction. The perturbation amplitude was selected according to the subject's balance ability. For healthy subjects a strong perturbation was selected while patients were exposed from weak to strong perturbation (Table 1). The instruction were asking from subject to stand still prior to the perturbation and try to attain the same posture when recovering from perturbation. Before the assessment pro-

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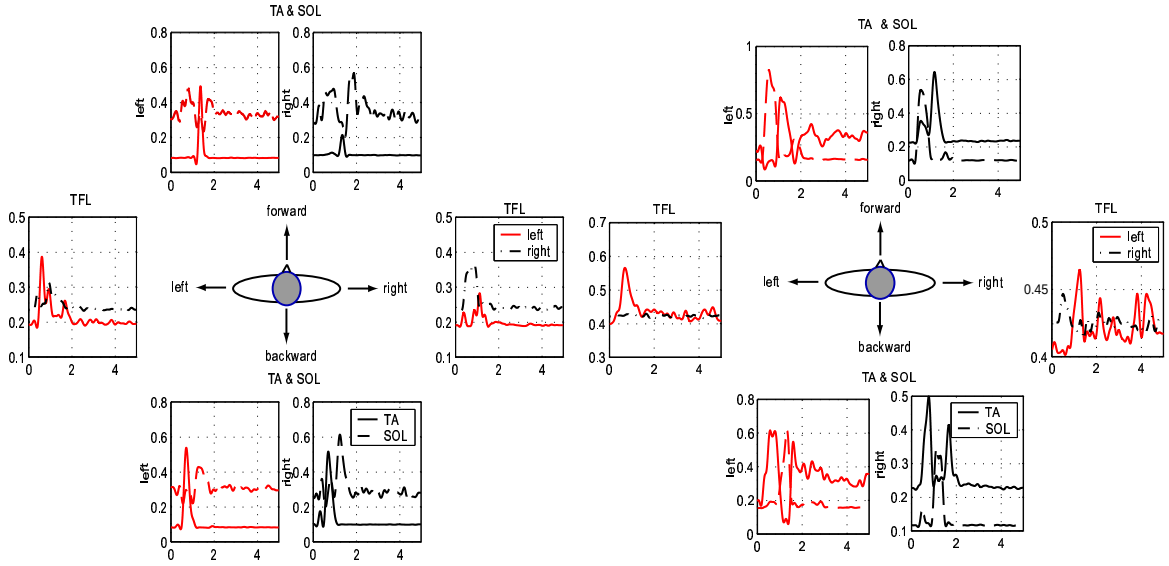

Figure 2: EMG activity timing of major muscles specific for principal perturbation direction for both legs of healthy subject (left) and incomplete SCI person TV (right). TA&SOL for forward&backward and TFL for left&right. Major differences can be noticed in RT (right side of the subject TV was more affected) direction during recovery from the perturbation.

cedure starts the operator, most likely the physiotherapist, sets up the level of stiffness support as regards the standing subject, especially neurologically impaired person. The level of stiffness should assure upright posture. The time instant of perturbation commencement was 1 s (user set up) after the operator pressed the button, but was unknown to the subject. The total time of data assessment was set to 6 s due to longer perturbation response recovery time in neurologically impaired subjects.

Each subject that participated in postural response data assessment took part in 32 trials, 4 for each direction. Perturbations were delivered in random order under the following experimental conditions: perturbation strength for each subject as in Table 1. Subject should stand with feet in parallel in a comfortable way, each on separate force plate in a way that the ground reaction force is distributed symmetrically among both sides, if that is possible.

Apparatus testing and data processing

The apparatus reliability and repeatability were examined and verified prior to the postural response assessment to enhance our confidence in obtained results. A concern has been expressed whether the apparatus perturbation delay was independent of the direction of perturbation that might be a cause of several inconveniences in computation and data analysis for later clinical use. Measurements of time-delay and a one-way analysis of variance, ANOVA [3], to tests differences between groups of perturbation directions that are only classified on one independent variable were performed to give anxiety a wide berth. Dependent variable was defined as time-delay after the electric pulse for perturbation commencement was delivered to electro-motors while the independent variable were all eight perturbation directions.

The EMG signals were rectified and low-pass filtered at 7 Hz (4^{th} order zero lag Butterworth filter). The cut-off frequency was selected according to the spectral analysis of the assessed EMG signal considering the recommendations from the literature [4]. For presentation of EMG signals in space where EMG activity is presented in polar diagram for each perturbation direction a norm of the EMG signal of each muscle was calculated (Fig. 3).

For each perturbation trial a set of 6 DOF data (forces and moments in x (A-P direction), y (M-L direction) and z (vertical) axis) for each foot were recorded using two force plates. A valuable information is provided in common vertical force (vertical ground reaction force, GRF) norm ($\|F_z\| = \frac{F_z}{m}$), a suitable information for analysis of balance [5]. Occasionally a wider perspective and more reliable information was found in center of pressure (CoP) as the calculation took into account moments in A-P and M-L direction. Sampled and filtered data from each force plates were transformed from local coordinate system located at the center of each force plates to the global coordinate system applying the following equations. The mean ($\overline{CoP}$) and the standard deviation (σ) of the CoP served as a reference in further analysis of the data assessed in each individual neurologically impaired subject. In detailed analysis not only the direction of perturbation and the direction of recovery from the perturbation were of great importance, but also the time-course. The time-course served as a source of information for determining the two major evaluation values: a delayed recovery (T_{dr}/ms) from perturbation, and disturbance am-

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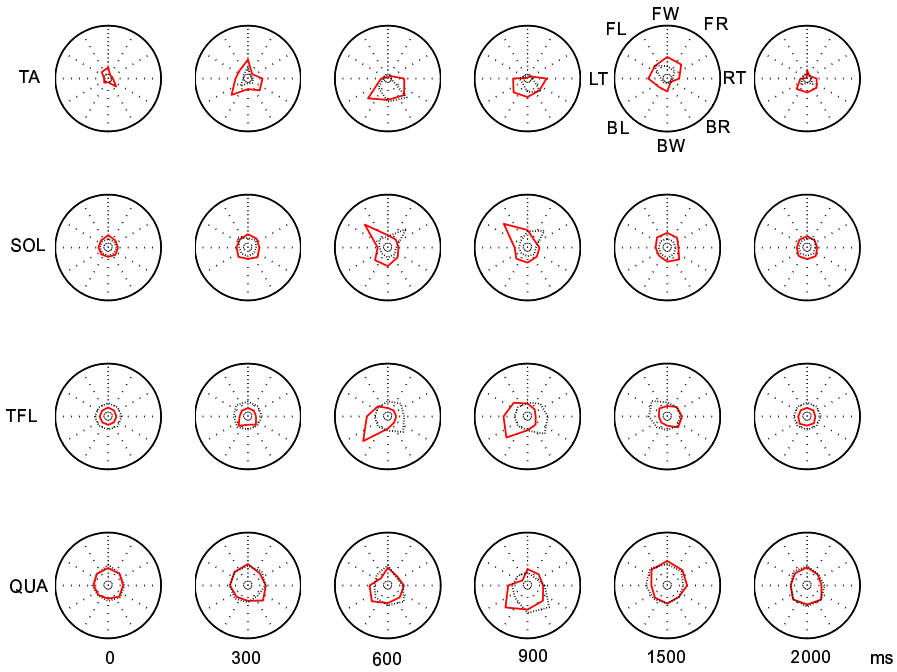

Figure 3: EMG activity presented in each perturbation direction (Forward-FW, Backward-BW, Left-LT, Right-RT, Forward&Right-FR, Forward&Left-FL, Backward&Right-BR and Backward&Left-BL) for four major muscles (tibialis anterior-TA, soleus-SOL, tensor fascia latae-TFL, vastus-QUA) for time instants 0, 300, 600, 900, 1500 and 2000 ms in healthy subject. Solid line represents the left and the dotted line the right extremity muscles.

plitude ($Dst_{AP,ML}$ / ÷ of σ).

Results

The calculus of ANOVA considered time-delay measurements of healthy subjects (in 6 subjects 4 trials and 1 subject 3 trials in total) in total 208 measurements. Expected outcome of the statistical hypothesis the non-significant difference between time-delay means in perturbation directions has been proven with $P = 0.143$, since the criteria for significance was $P < 0.05$.

As demonstrated in Fig. 2 the time-courses of principal muscles EMG were correlated to the direction of perturbation. In healthy subject (left) the muscles TA and SOL prevailed in both forward and backward perturbation direction. In forward direction the SOL response was rather fast to compensate the leaning forward, followed by TA which compensated the backward inclination as a consequence of returning to the standing position while both lean toward faster recovery from the perturbation. When the perturbation direction was pointed backward the muscle responses were reversed. The EMG analysis in left and right perturbation direction showed intensive activity of the TFL muscle, in compliance with the direction. The consequence of the perturbation to the left was the left TFL activity and equally on the right. The pattern of directionality in the magnitude of the EMG responses was rather uniform between healthy subjects. Similar EMG activities were found in incomplete SCI subject TV (BJ) but noticeable differences, characteristic of neurologically impaired subjects appeared. The TFL time-course was winking on disturbance during perturbation in the right direction that was in fact expected since the subject's right side was more affected than the left one (Fig.2, right). Subject's response on perturbation in backward direction showed delicate panic response while recovering from perturbation. The TA muscle which responded with normal delay (200∼350ms for healthy subjects) showed intensive activity even after the subject recovered from the perturbation. The SOL muscle response demonstrated similar response activity as in healthy subjects. More general overview of the subject's postural response capabilities is given in Fig. 3.

The polar plot presents EMG postural responses in each perturbation direction (Forward-FW, Backward-BW, Left-LT, Right-RT, Forward&Right-FR, Forward&Left-FL, Backward&Right-BR and Backward&Left-BL) for four principal muscles (tibialis anterior-TA, soleus-SOL, tensor fascia latae-TFL, vastus-QUA) for time instants 0, 300, 600, 900, 1500 and 2000 ms. The magnitude of each EMG response at specific time instant was normalized to the maximum amplitude of the corresponding muscle time-course in each perturbation direction and the mean response of 4 trials for each subject was calculated. The selection of time instants was based on time-courses and satisfy the general representation of selected EMG responses for all subjects in spite the time instants may vary from subject

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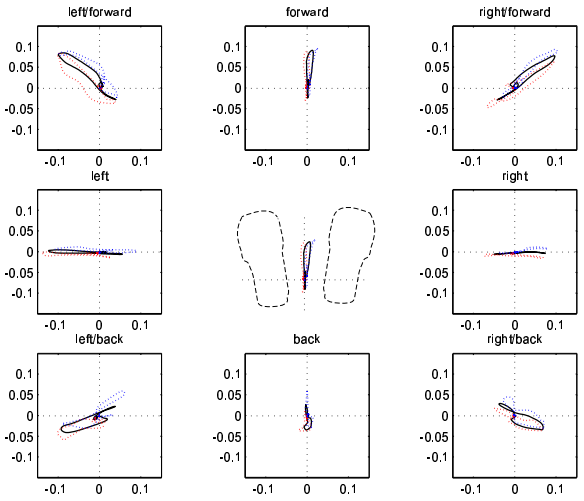

Figure 4: CoP normative computed from the group of healthy subjects. The mean (solid line) and the standard deviation (dotted line) are presented for each perturbation direction.

to subject. The TA responded rapidly in BW, BR, BL directions followed by SOL that responded inversely when the subject was already recovering from perturbation. The role of both muscles changed in FW, FR, FL perturbation directions. TFL muscle showed intensified response activity in all diagonal perturbation directions, especially intensified in BL and BR directions. The QUA muscles showed constant weak activity during the whole trial and noticeable intensive activity during the perturbations in all directions.

For the CoP standard-setting purpose a normative has been set using the mean and standard deviation of postural response trials in the group of healthy subjects. The Fig. 4 presents the common CoP normative applied in our method. After the CoP normative was set a method was applied to neurologically impaired subjects, TV, BJ and PA. For the sake of detailed presentation the time domain was selected (Fig. 5). The solid line presents the mean and the dotted lines the standard deviation of the healthy subjects. As expected the CoP time-course emphasized the characteristics of the participating subjects. The figure shows time-courses of CoP in both planes x (A-P) and y (M-L) for the perturbations in FW, LT and RT directions; the directions demonstrating the most specific responses for neurologically impaired subject. The upper left graph (FW perturbation, CoP in A-P) shows almost no difficulties for non of the neurologically impaired subject, while minor disturbances appeared in CoP of M-L direction (lower left graph). The lower middle graph (LT perturbation, CoP in M-L) shows no difficulties, the disturbances appear in CoP A-P, the perpendicular axis to the perturbation direction. In subjects TV and BJ a displacement of the CoP shows difficulties in keeping the postural balance in all other directions than the perturbation direction. The hemiplegic subject PA was able to follow the normative of the CoP with noticeable disturbances ($Dst_{AP,ML}$ / 120-150 $\div$ of σ) while recovering from the perturbation in almost all directions except the perturbations where the right leg was the key of postural balance. The lower right graph clearly displays the prolonged postural response ($T_{dr} \sim 75 - 600ms$) and the upper right graph presents difficulties with postural balance during and after the perturbation.

Discussion

The development of the new apparatus for postural response evaluation in clinical environment was necessary mostly for two reasons: 1) more extensive evaluation for stroke patients who usually suffer from unexpected fall as a consequence of unexpected perturbation and have already participated in the balance re-training program. Such perturbation may occur in everyday life in public. Therefore the quantitative evaluation of the subject's postural response abilities is recommended before releasing the patient from the rehabilitation institution. 2) evaluation of overall postural abilities in clinical environment that was not possible until recently since the research balance frame [1] was not approved for the use in clinical practice. Another reason is hidden in a fact described in the Introduction. Simply the existing objective postural response platforms (the perturbation method is also different) require more space in clinical environment and are due to the high price out of many institution financial capabilities.

The evaluation of the apparatus itself was necessary to ensure the assessment repeatability and begin the data assessment with increased confidence in the new postural response assessment apparatus reliability. The outcome of the statistical analysis indicated that the time delay between the moment when the electronic pulse was delivered to the apparatus and the instant of actual frame movement was irrespective of the perturbation direction. Thus the mean time delay (39 ms) was taken into account in data analysis. After the hardware has passed the statistical test a normative was set-up from healthy subjects measurements. This way a reference has been set for abnormal postural response evaluation. As presented the three neurologically impaired persons showed noticeable differences in responses in all directions that were anyhow connected to their impairment. It was not difficult to see the major postural difficulties from the EMG data that were in line with other studies [6] or even more precisely from the CoP in space and time domain.

Conclusions

The results of the clinical assessment using the presented apparatus are encouraging and offer new opportunities for objective clinical data assessment and evaluation of neurologically impaired subjects before being released from the rehabilitation institute. In a way we might expect that some subject will "learn" how to compensate

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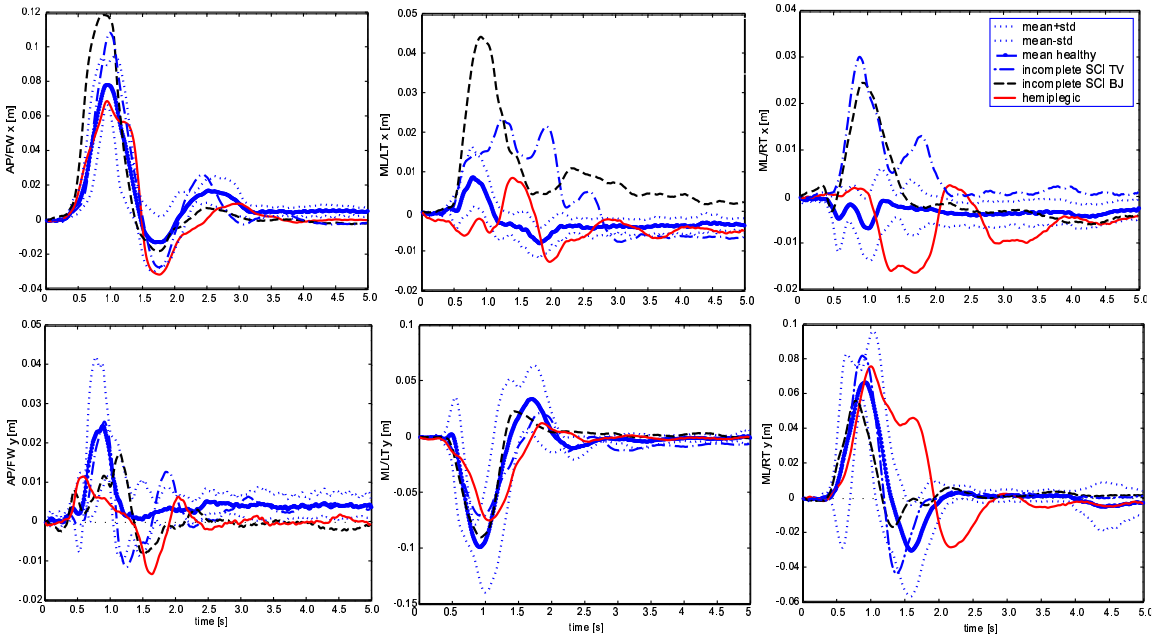

Figure 5: The figure shows time-courses of CoP in both planes x (A-P) and y (M-L) for the perturbations in FW, LT and RT directions. In subject TV and BJ a displacement of the CoP show difficulties in keeping the postural balance in all other directions than the perturbation direction. The hemiplegic subject PA was able to follow the normative of the CoP with noticeable disturbances ($Dst_{AP,ML}$ / 120-150 $\div$ of σ) and prolonged postural response ($T_{dr} \sim 75 - 600ms$) while recovering from the perturbation in almost all directions except the perturbations where the right leg was the postural balance key.

such unexpected perturbation and transfer this ability to outdoor life. The apparatus itself may with applied several modifications even become a commercial upgrade of the inexpensive, easy-to-use and safe of the former standing frame. Such application of the developed technology and rehabilitation method as presented in this paper will be a subject of further clinical studies most likely in stroke and traumatic brain injury subjects.

Acknowledgments

The authors express their gratitude to the volunteers that participated in this study and wish to acknowledge the financial support of the Slovenian Research Agency. Special thanks for assistance to Georg Worms, MSc and Pavla Obreza, PT.

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ISSN: 1727-1983