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Normative based clinical tool for objective evaluation of postural responses

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Abstract— **The paper presents a novel normative based method and apparatus for objective assessment of postural responses during unexpected perturbation in clinical environment. A modified standing frame (based on BalanceTrainer^{TM}) for standing-balance training in a fall-safe balancing environment equipped with electrical actuators to provide unexpected perturbations in eight directions during quiet standing was used. Ground reaction forces were recorded under both feet and center of pressure was calculated to derive postural response indicators. The set-up normative was based on consistent patterns assessed in seven neurologically intact volunteers. In clinical investigation the postural responses in two incomplete spinal cord injured persons and hemiparetic stroke patient were contrasted to the normative response. Thus the characteristic direction dependent deficiencies were identified and numerically evaluated. On the basis of our findings we may suggest that the method may become effective when substantial direction dependent quantitative evaluation of postural responses are required in clinical & home environment.**

I. INTRODUCTION

Nowadays the evidence-based rehabilitation requires objective evaluation of functional capabilities before and after intervention and has become important as it facilitates optimization of interventions as well as the outcome of rehabilitation process in each individual patient. Efficient balance and postural control is one of the most important functional tasks. Currently, the assessment of postural control and balancing abilities is predominantly done by various clinical tests that are subjectively scored by healthcare professionals. Berg's Balance Scale (BBS) [1] is the most accepted and widely used, exhibits good within- and between-rater agreement and can be used as a predictor of potential fallers. However, clinical tests cannot provide insight into particular mechanisms of postural control, that can be obtained by studying kinematics, kinetics and dynamic electromyography of selected muscles during postural responses elicited by various perturbation modalities [2]. These modalities predominantly include moving platforms [3] with different strategies. A few existing clinically approved devices, based on moving standing platforms (Balance Master - NeuroCom Inc., Balance Quest - Micromedical Technologies Inc.) enable detailed examination of several aspects of postural control under different sensory conditions. These devices use fixed safety-support frame or safety harness and need dedicated laboratory space thereby represents a considerable financial investment aggravating their wide use.

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We have developed an apparatus for postural balance assessment, that in contrast to moving and rotating platform perturbation principles, delivers perturbation by applying force on the pelvis, while the subject is standing on firm surface. In this way the perturbing apparatus accompanies postural sway of subject, due to it's limited range of movement prevents fall without additional supporting aid and delivers perturbation in the transverse plane. Simplified apparatus [4] based on passive controllable spring defining the stiffness of the two-degrees of freedom standing frame became a clinically approved assisting device for balance training BalanceTrainer^{TM} (marketing Medica Medizintechnik GmbH, Germany). At our institute the apparatus was upgraded [5] into postural responses assessment tool by adding suitable hardware and software that can deliver perturbations in any direction in the transverse plane while simultaneously recording postural responses.

The objectives of this paper are 1) to present novel method for objective assessment of postural responses applicable in clinical practice; 2) to assess normative postural responses in a group of neurologically intact individuals; 3) and to explore postural responses in selected neurologically impaired individuals, contrast them to the normative data and quantify directional deviations.

II. METHODS AND SUBJECTS

A. Subjects

Seven neurologically intact volunteers (P1 - P7) were involved in normative assessment. These subjects were all male (26.6 $\pm$ 3.1 years, 178.3 $\pm$ 6.3 cm and 71.4 $\pm$ 7.9 kg). In the clinical investigation three neurologically impaired patients (P8 - P10) all male, 53.3 $\pm$ 10.4 years, 175.7 $\pm$ 11.0 cm, 85$\pm$ 7 kg, P8: incomplete SCI Th-3-4-5, 18 years ago; P9: Th osteoporosis, pathological SCI 3 years ago and P10: hemiparetic, stroke) in chronic stage participated. The volunteers had no musculoskeletal impairment of any disease that would affect balance capabilities. Subjects with neurological disorders fulfilled the participation criteria which was ability to stand and balance using the BalanceTrainer^{TM}. The methodology was approved by local ethics committee and the subjects gave informed consent.

B. Equipment and protocol

The apparatus [5] is made of steel base construction placed on four wheels, the standing frame is made of aluminium and fixed to the base with passive controllable spring defining the stiffness of the two degrees of freedom (2 DOF) standing frame. On the top of the standing frame a wooden table

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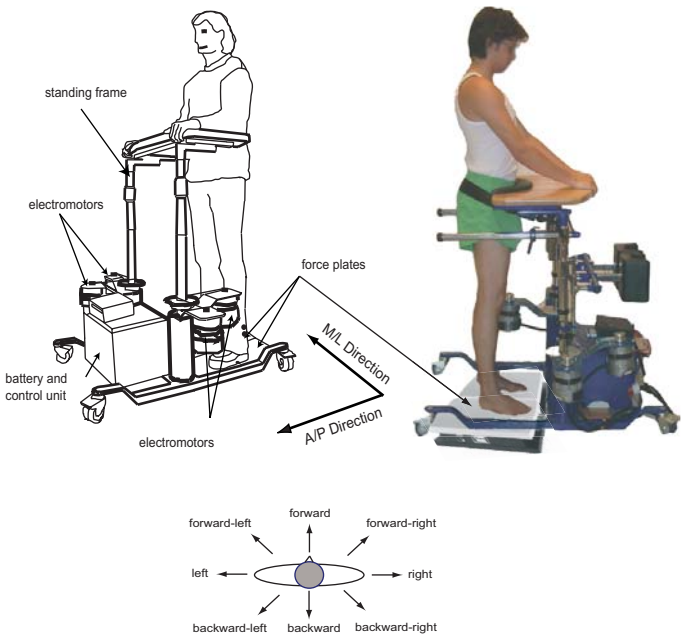

Fig. 1. Schematic presentation and photograph of apparatus for assessment of postural responses in clinical practice.

with safety belt for holding the subject at the level of pelvis was mounted (Fig. 1). Four battery powered electro-motors (Iskra Avtoelektrika d.d., Šempeter, Slovenia) were used to generate postural perturbations in eight major directions (forward, forward-right, right, back-right, back, back-left, left and forward-left). Subjects stood with each foot on separate force plates (AMTI OR6-5, AMTI Inc., Watertown, MA, USA) assessing 6-DOF data (3 forces, 3 moments, filtered within AMTI amplifier, A/D sampling frequency 100 Hz).

The electro-motors delivered constant torque of 3 Nm during selected duration of perturbation. 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 electro-motors each for corresponding principal direction. Subjects were instructed to stand comfortably with feet in parallel, each on separate force plate. The following instructions were to stand still prior to the perturbation and try to attain the same posture when recovering from perturbation. The perturbation direction or perturbation commencement which was 1 s (user set up) after the operator pressed the button were chosen randomly without notifying the subject. The total assessment time was set to 6 s due to longer perturbation response recovery time. Each subject took part in 32 trials, 4 for each direction.

C. Computation of evaluation indicators

For each perturbation trial a set of 6 DOF data (forces and moments in x (anterior-posterior direction; A-P), y (medial-lateral direction; M-L) and z (vertical) axis) for each foot were recorded using two force plates. Sampled (100Hz) and filtered (4th order Butterworth filter, 15Hz cut-off frequency) data from each force plates were transformed from local coordinate system to the global coordinate system. Using transformed data assessed a common center of pressure (CoP) was calculated [6].

The mean ($\overline{CoP}$) and the standard deviation (σ) of the CoP in the group of neurologically intact volunteers were used to built up a normative. The normative set of data was based on overall mean and 2σ. Further on the data assessed in each individual neurologically impaired subject were contrasted to the normative. The directional deviations from the normative in CoP time-course were quantitatively evaluated by two indicators (Fig. 2, upper left): a delayed response time (T_r [ms]), and response amplitude overshoot (P_{OVR} [% $\overline{OVR}$], where $\overline{OVR}$ is the mean overshoot of all neurologically intact subject). The T_r was defined as a time delay between normative and actual response. The response amplitude overshoot P_{OVR} was defined as maximal overshoot in percentage of the normative mean overshoot ([% $\overline{OVR}$]).

$$\begin{aligned} 100\% - \sigma \leq P_{OVR} \leq 100\% + \sigma \\ T_r \leq \sigma[ms] \quad (200ms) \end{aligned} \tag{1}$$

When conditions (Eq. 1) were fulfilled, the postural response was considered OK. If only one condition was true, the response was considered acceptable, but alerting. Therefore more detailed graph analysis was suggested before making decisions on response status. When none of the above conditions were true, the directional response was assigned as critical.

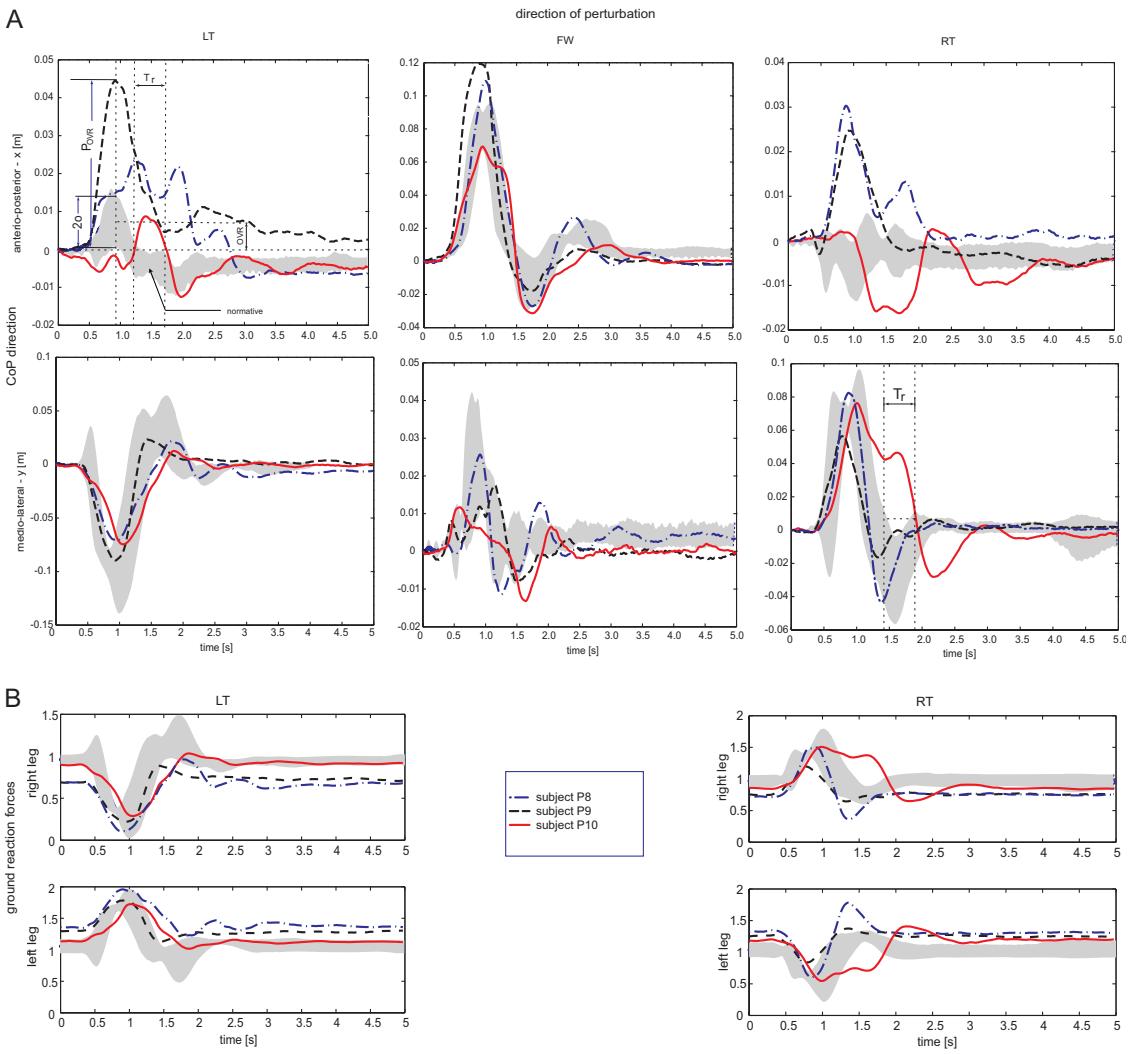

Fig. 2. **A**. The figure shows time-courses of CoP in both planes x (A-P) and y (M-L) for the perturbations in FW, LT and RT directions. In subject P8 and P9 a displacement of the CoP show difficulties in keeping the postural balance in all other directions (P_{OVR} [% $\overline{OVR}$] = 80% - 250%) than the perturbation direction. The hemiparetic subject P10 was able to follow the normative (gray shaded area) of the CoP but with noticeable disturbances (P_{OVR} [% $\overline{OVR}$] = 67% - 89%) and prolonged postural response ($T_r = 23 - 200$ms) while recovering from the perturbation in all directions except the perturbations where the right leg was the postural balance key (P_{OVR} [% $\overline{OVR}$] = 103%, $T_r = 505$ms). **B**. Vertical ground reaction forces (normalized to subject's mass $\frac{\|F_z\|}{m/2}$) where similar deficits can be noticed present a complementary information for each foot in corresponding perturbation direction (LT, RT).

III. RESULTS

The figure (Fig. 2) demonstrates specific directional difficulties in postural responses for each of the participating neurologically impaired subject in both planes x (A-P) and y (M-L) for the perturbations in FW, LT and RT directions. In subjects P8 and P9 a displacement of the CoP shows difficulties in keeping the postural balance in all other directions (P_{OVR} [% $\overline{OVR}$] = 80% - 250%) than the perturbation direction. The subject P10 was quite able to follow the normative of the CoP with noticeable undershoots (P_{OVR} [% $\overline{OVR}$] = 67% - 89%), except in directions of the affected side. In that case the response was delayed due to the weight transfer from right to left side (middle right graph: prolonged postural response - $T_r \sim 500$ms).

In Table I subject P10 data contrasted to the CoP normative are presented. Slightly decreased response amplitudes were noticed in FW (in AP direction 78% of normative mean) and FR (in ML direction 79% of normative mean) directions. Considering the standard deviation σ at the undershoot instant (σ = 9%) the response was assigned as OK (tick mark). The subject P10 was suffering from right side hemiparesis noticeable as difficulties in RT and BR directions. The response to the perturbation in RT direction was delayed for $T_r = 505$ms in principal movement direction ML and for $T_r = 350$ms in AP direction. The later may be neglected due to the negligible mean response amplitude ($\overline{OVR}$ = 0.5cm). Similar was for BR direction. In both CoP directions, AP and ML, significant response delays ($T_r = 750$ms, $T_r = 454$ms, respectively) were found and in ML direction undershoot was significant (P_{OVR} = 68%). Both perturbation directions were

TABLE I

SUBJECT P10 DATA CONTRASTED TO THE NORMATIVE $\surd$ - OK $\triangle$ - CONDITIONAL X - CRITICAL

CoP direction	Parameter	FL	FW	FR	LT	RT	BL	BW	BR
AP	P_{OVR} [% $\overline{OVR}$]	**89**	**78**	92	0	300	154	100	85
	$\overline{OVR}$ [cm]	8.8	8.8	7.8	0.6	-0.5	-2.4	-3.8	-4.1
	σ [% $\overline{OVR}$]	5	8	16	66	200	125	21	30
	T_r [ms]	**200**	23	0	-	**350**	**300**	**430**	**750**
ML	P_{OVR} [% $\overline{OVR}$]	**75**	67	**79**	**64**	103	**73**	76	**68**
	$\overline{OVR}$ [cm]	-9.3	1.8	9.9	-11.8	7.4	-8.9	1.7	7.2
	σ [% $\overline{OVR}$]	12	50	9	11	6	8	176	8
	T_r [ms]	196	-	140	168	**505**	85	-	**454**
		$\triangle$	$\surd$	$\surd$	$\triangle$	X	$\triangle$	$\triangle$	X

assigned as critical for the subject P10 (marked X). In other perturbation directions (FL, LT, BL and BW) minor difficulties were found. FL direction was conditionally acceptable as only response delays were critical. The response undershoots errors in FL and LT were within 10% ($P_{OVR} \pm \sigma \sim$100%). In BL and BW direction response delays ($T_r = 300$ms, $T_r = 430$ms, respectively) were a reason for conditionally acceptable assignment (triangle mark).

IV. CONCLUSIONS AND FUTURE WORKS

The clinical practice has been in need for objective assessment tool that will supplement the subjective tests that have been in use for a decade [2]. Furman [7] reported that the objective posturography provide information of impact on balance difficulties on various activities. In contrast some authors [8] disagreed and suggested that posturography may not provide information beyond the one provided by standardized clinical test [1]. Anyway, the results of the present investigation show that the developed apparatus and method can provide reliable information on balance status of particular individuals, which incorporates directional aspects of postural control. This way the critical direction can be identified and targeted within therapeutical intervention. The time needed to collect a complete set of postural responses is similar to the time needed to assess BBS.

Values (marked bold) from the Table I that were subject of evaluation by an expert, a trained physiotherapist, indicated postural response disorders for the individuals in each perturbation direction. The assigned remarks indicating an inadequate responses demonstrate directions which may be critical for balance impaired person who may present a potential faller. These associations are significant for a clinical report that can be issued before and after the rehabilitation procedure. Such clinical service may reach higher efficiency level when data are assessed in clinical environment with mobile standing assessment platforms (AccuSway^{PLUS} - AMTI Inc.) or even simplified own-built platforms to increase the mobility of the device instead of the currently used fixed laboratory based AMTI force plates. The presence of the evaluation expert is not a must but the data assessment can be accomplished by clinical staff who is already familiar with the device and sent for analysis.

The results of the clinical assessment using the presented apparatus are encouraging and offer new opportunities for the objective clinical evaluation of neurologically impaired subjects. The data assessed in each individual subject together with normative based on healthy volunteers provide enough information for skilled personnel to objectively evaluate the subject's postural response abilities and eventually evaluate the recovery of standing balance after stroke or other neurological disorder. In the future the easy-to-use and easy-to-move apparatus that guarantee fall-safe postural responses assessment and force the subject into active cooperation as no fixed supporting aid (body weight support, handles, safety harness etc.) is available may be located at remote center or even combined with balance training device on subject's home and provide assessed data to the specialized consultant via broadband internet.

V. ACKNOWLEDGMENTS

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