Directionally Specific Objective Postural Response Assessment Tool for Treatment Evaluation in Stroke Patients

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***Abstract*—The aim of the research is to develop an objective evaluation tool for use in stroke rehabilitation clinical practice. Stroke patients are prone to particularly high risk of fall, which may differ for various directions of movement. An apparatus enabling perturbations and postural response assessment in eight directions in transversal plane during standing was used to assess data in seven neurologically intact volunteers and 10 stroke patients before and after the rehabilitation. Ground reaction force and center of pressure were acquired during the perturbation, signal processed and compared to Berg Balance Scale (BBS), a clinical outcome measure of balance. The results of the weight load ratio between the affected and unaffected lower extremity demonstrated objective positive outcomes of the rehabilitation and also correlated with the clinical instrument BBS. Additionally, the center of pressure ratio between the anterior/posterior and medial/lateral peak for each perturbation direction have shown identifiable postural response strategies in selected directions of transverse plane. The directional postural information can be helpful when identifying and evaluating the objective rehabilitation progress which can lead to application of targeted rehabilitation techniques. The directional indicator also demonstrated correlation with the BBS in directions indicating rehabilitation progress. When considering the common use with the clinical instrument, the proposed objective rehabilitation progress evaluation tool may also become helpful in directional fall risk indication. The proposed tool may become a powerful instrument, when the balance training and postural response assessment will move to remote or home environment as a telerehabilitation service.**

***Index Terms*—Apparatus, balance training, Berg Balance Scale (BBS), center of pressure (COP), evaluation, fall, instrument, postural response, posture, rehabilitation, stroke, telerehabilitation, teletherapy.**

I. Introduction

OBJECTIVE evaluation of functional capabilities of the patients before and after the rehabilitation treatment is becoming increasingly important as it facilitates optimized, scheduled and comparable set of interventions and enables the optimization of rehabilitation outcomes in each individual patient. In stroke patients the efficient balance and postural control are among the most important functional abilities required to perform more complex functional task. The majority of the stroke patients coming to rehabilitation center are considered potential fallers and therefore their ability to balance and postural control evaluation is even more important. Analysis of postural control and balance abilities relies on clinical tests or instrumentation. Currently, the assessment is predominantly done by various tests that are subjectively scored by healthcare professionals. One of the most accepted and widely used in clinical institutions worldwide is the Berg's Balance Scale (BBS) [1], [2] as it is reliable and exhibits very good within- and between-rater agreement and can be used as a reliable predictor of potential fallers. BBS had originally been developed to measure balance in the elderly [3], not specifically in stroke patients [4]. On the other hand, postural assessment scale for stroke patients (PASS), which was derived from Fugl–Meyer [5] of balance and mobility, contains 12 four-level items of varying difficulties for assessing abilities to keep or change the posture [4]. However, clinical tests cannot provide insight into particular mechanisms of postural control that can be obtained by studying kinematics, kinetics and dynamic electromyography (EMG) of selected muscles during postural responses elicited by various perturbation modalities [6]. These modalities predominantly include moving [7] and rotating standing platforms with different strategies and perturbation techniques [8]. A few existing devices, based on moving standing platforms (e.g., Balance Master: NeuroCom Inc.,Clackamas, OR; Balance Quest—Micromedical Technologies Inc., Chatham, IL) or moving frame and fixed standing platforms enable detailed examination of several aspects of postural control under different sensory conditions [9]. These devices in general use the information from force plates mounted in standing platforms to calculate and monitor the center of pressure (COP) shift and thus estimate the balance capabilities and postural control of the user.

The majority of the computerized objective tests on subjects use different variations of the COP to evaluate the postural standing and response behavior. It was reported that the COP of the neurologically impaired subjects displaced in lateral direction towards the affected side and that the affected subjects have shown larger total COP area and larger medial–lateral movement of the COP than neurologically intact subjects [10]. The COP trajectory provides information on the body movement control that is essential in maintaining a standing posture or diminishing the postural disturbances [11]. The COP changes in hemiplegic subjects during rehabilitation treatment have been demonstrated followed by the report revealing that mathematical analysis of COP can provide clinically relevant information [11]. Clinical relevancy has been demonstrated also

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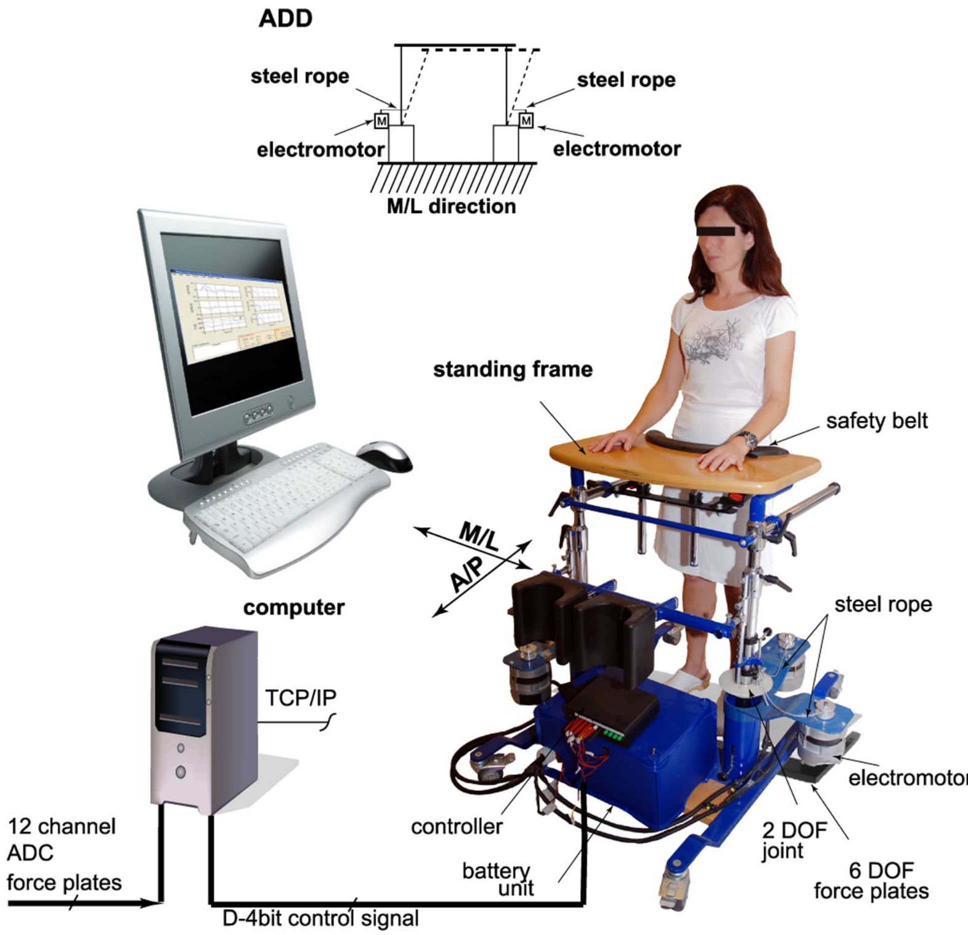

Fig. 1. Apparatus in use for balance training in clinical and home environment now enable postural response evaluation. Equipped with four electromotors providing perturbations to the standing frame, battery power, and PC-based control system may present a powerful tool for postural response assessment and balance training in a forthcoming home-based therapy and telerehabilitation. ADD: Perturbation principle. To perturb the frame in a certain direction the appropriate electric motor winded up the rope and pulled the frame away from its upright position. This leaded to a corresponding perturbation being applied to the subject standing in the frame.

in EMG and force platform measurement as both correlated well with the functional mobility capability (FIM) in subjects after stroke [12]. Furthermore, relationships between EMG, force platform measurements, and the clinical evaluation of balance (BBS) was found during quiet standing in subjects with chronic hemiparesis after stroke [13].

The reported clinical relevancies of the COP in most cases demonstrate correlations during quiet standing or show correlations in response latencies [11]–[13] and were encouraging for introduction of COP-based postural response assessment to clinical balance training. The described methods for objective COP-based balance assessment were not appropriate for evaluation of both, acute and posttreatment, phases as the existing commercially available orthopedic or sport balance training systems can not meet our requirements for stroke population due to applicability in clinical environment and also safety requirements. The stroke subjects are usually not capable of balancing without support in acute phase and therefore hold the safety handle or "rest" in the safety harness. Both safety aids were considered unacceptable while resulting in incomparable acute/post treatment outcomes. Besides, trends in rehabilitation show toward devices and assessment tools that can be used in clinical and home environment, e.g., for balance training and for evaluation purposes. Therefore, a dedicated postural response assessment apparatus was developed in the manner that can besides balance training provide postural perturbations in eight directions in transversal plane and guarantee safety in clinical environment [14]. The apparatus is based on previous experiences with balance training device [15] that was designed as a fixed platform and moving standing frame type device and has been clinically approved, designated as patient safe and later on commercialized (BalanceTrainer Medica, Medizintechnik GmbH, Germany). As the COP has proven clinically relevant and provide neuromuscular response information to the imbalance of the center of mass [16], the aim of our present work was to develop an objective assessment tool for evaluation of balance during standing and compare it with clinically accepted outcome measure BBS in a group of acute stroke subjects before and after the training. The goal of our study was to obtain a reliable assessment tool that besides correlating with clinically accepted outcome measures provides additional information on directionality that is important for further treatment and fall prevention activities.

II. Subjects and Methods

A. Subjects

Ten stroke subjects (61.0 SD 12.1 years, 69.0 SD 12.4 kg, 169.3 SD 9.6 cm, right side hemiplegia/hemiparesis) and seven neurologically intact volunteers (26.6 SD 3.1 years, 71.4 SD 7.9 kg, 178.3 SD 6.3 cm) participated in the tool development and preliminary evaluation. The volunteers had no muscular–skeletal impairment or any disease that would affect their balance capabilities. Stroke subjects volunteers were required to show minimal ability to maintain upright posture and balance while standing in the device frame, which was established in clinical examination by healthcare personnel.

The methodology was approved by local ethics committee and the subjects gave informed consent.

B. Equipment

The apparatus [14] was made of steel base construction placed on four wheels, the standing frame was made of aluminum and fixed to the base with passive controllable spring defining the stiffness of the two degrees-of-freedom (2 DOF) standing frame (Fig. 1). On the top of the standing frame a wooden table with safety belt for holding the subject at the level of pelvis was mounted. Four battery powered electric motors (Iskra Avtoelektrika d.d.,Šempeter, Slovenia), connected via ropes to the frame, were used to generate postural perturbations in eight directions (forward: FW; forward/right: FR; right: RT; backward/right: BR; backward: BW; backward/left: BL; left: LT; forward/left: FL). Each electrical motor delivered constant torque of 3 Nm during selected duration of perturbation.

The realization of perturbation and moving the standing frame in combined principal direction was managed by simultaneous action of two electro-motors each for corresponding principal direction (FW, BW, RT, LT) on the command from personal computer. The command was realized as pulses generated by multipurpose PCI board (NI 6259, National Instruments, Austin, TX) and dedicated computer software. To perturb the frame in a certain direction the appropriate electric motor winded up the rope and pulled the frame away from its upright position. This leaded to a corresponding perturbation being applied to the frame and consequently the subject standing in the frame (Fig. 1 ADD). Participating subjects stood with each foot on separate force plates (AMTI OR6–5, AMTI Inc., Watertown, MA) assessing 6-DOF data (three forces, three moments, filtered within AMTI amplifier). Data assessment (sampled $F_s = 100$ Hz) was managed via developed Matlab software (The MathWorks, Inc., Natick, MA) based graphical user interface controlling the multipurpose PCI board.

C. Protocol

BBS consists of 14 tasks, graded on a five-point scale, that require the subject to maintain the static position, to change orientation of the center of the mass with respect to base of support and to diminish the support base [1]. The BBS was assessed in stroke subjects before and after the medical intervention.

Subjects were instructed to straight their vision ahead, with eyes open, maintain the upright posture and stand barefoot comfortably with selected feet position, each on the separate force plate, while standing in the standing frame. The chosen feet position (but not to wide [17]) was kept constant throughout the assessment [18]. Further instructions requested to stand still prior to the perturbation and try to attain the upright posture when recovering from perturbation without lifting any foot. The subjects were allowed to hold the table, which moved together with the frame. The height of the table was adjusted for each individual. The perturbation direction and the perturbation commencement were defined randomly, but within 1 s (user setup) after the operator pressed the button without prior notification of the subject. The imposed perturbation provoked sudden imbalance of the participating subject, who managed to attain the primary posture as requested. The perturbation intensity in neurologically intact subjects was set to the level that imbalanced the participating subject, while in impaired subjects was set to the level that none of the subjects expressed any inconvenience (but still imbalanced the subject) and was equal for all stroke subject in both assessment, prior and post-treatment. The total assessment time was set to 6 s due to longer response recovery time. Each subject took part in 32 trials, four trials for each perturbation direction. In stroke subjects data were collected before and after the rehabilitation treatment in the four weeks period. The stroke subjects were patients of the Institute's Clinical hospital and received therapy (leg raise, leg lateral movement, stair climbing, one leg standing, knees-bending—exercises for balance training) for 20 min/day, four weeks. The subjects with better balance capabilities also managed to sit on the giant ball, walk on the foam pad, and catch a ball. In neurologically intact volunteers one assessment session was carried out. For each perturbation trial a set of 6 DOF data (forces and moments in anterior–posterior direction (AP), medial–lateral direction (ML), and vertical axis) for each foot were recorded using two force platforms. Data assessed were object of kinematic transformation to compute the common COP [16].

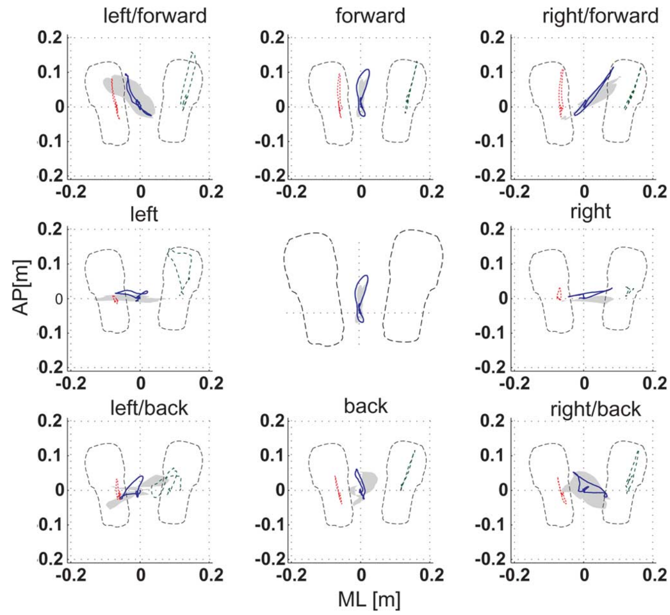

Fig. 2. COP motion under left (dotted), right (dashed) foot, and the common COP motion (solid line) during postural perturbations in eight directions in transverse plane for one of the participating stroke subject after the treatment. Additionally the normative (shaded) assessed in neurologically intact subjects is projected to monitor the deviations.

D. Force Plates' Data Analysis

Data assessed and filtered (fouth-order Butterworth filter, 15-Hz cutoff frequency) in each force platform were used to

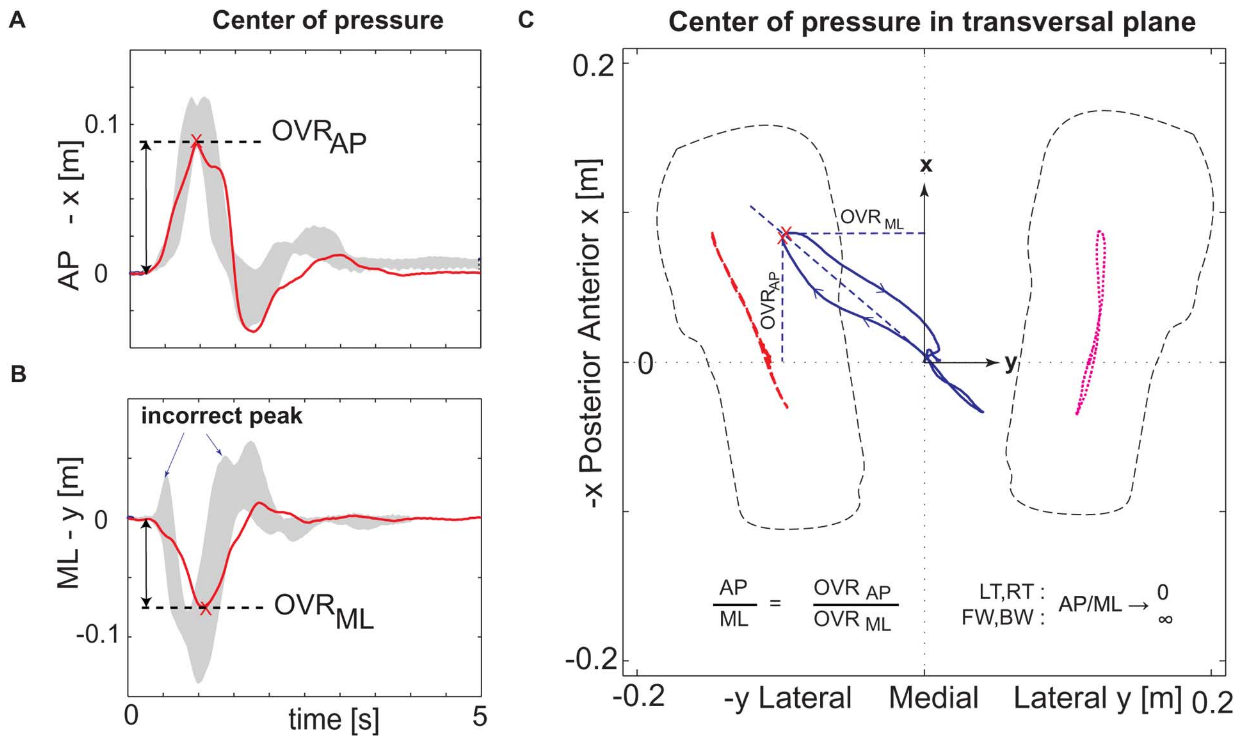

Fig. 3. (a) Postural response (solid line) in AP direction contrasted to the normative (shaded area). The first peak in the center of pressure (COP) after the quiet standing presents the postural response peak $\mathrm{OVR}_{\mathrm{AP}}$. The contra directional peak presents the COP undershoot. (b) Postural response in ML direction. The COP (solid line) peak $\mathrm{OVR}_{\mathrm{ML}}$ is contrasted to the normative (shaded area). The marked incorrect peaks were eliminated by the algorithm. (c) The COP in transverse plane for both feet (left: dashed; right: dotted) and the common COP (solid) with delineated response peaks and AP/ML ratio explanation. In ideal conditions for the left (LT) and right (RT) perturbation directions the ratio approaches 0 and for the forward (FW) and backward (BW) perturbation direction increases.

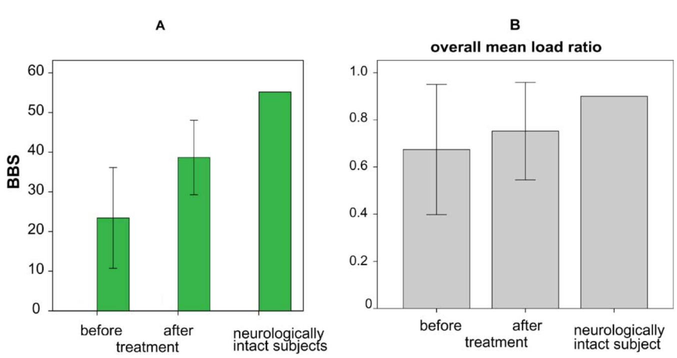

Fig. 4. (A) BBS in the group of stroke subjects has increased during the rehabilitation (from 23 SD 15 to 39 SD 11, normative 56). Some subjects had very low BBS at the beginning of the treatment what may be reason for greater SD, but the BBS has increased in all subjects. (B) The stroke subjects were able to put more weight on the affected lower extremity after the rehabilitation treatment. The trend shows towards the improved weight balance. The data were assessed after the subject had already recovered from the perturbation.

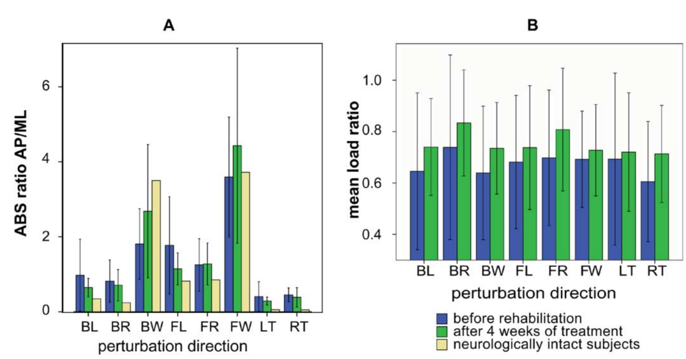

Fig. 5. (a) Center of pressure absolute (ABS) ratio between the anterior-posterior (AP) and medial-lateral (ML) component of postural response peak is presented for each perturbation direction (back-left [BL], back-right [BR], back [BW], forward-left [FL], forward-right [FR], forward [FW], left [LT] and right [RT] before and after the treatment and in comparison with the normative. The results show a tendency toward the normative assessed in neurologically intact subjects for all perturbation directions except forward, which could be considered acceptable also at the beginning of the treatment. (b) After the rehabilitation treatment the subjects were able to put more weight on the affected lower extremity in all directions. Load ratio was assessed after the subject had recovered from the perturbation.

quantitatively analyze the postural responses for each perturbation direction. Common ground reaction force (GRF) was calculated from each force platform and divided into time sections. The undershoot peak that appeared immediately after the postural response during the recovery from the perturbation was expected to show differences in stroke subjects before and after the treatment [10]. Using the GRF the mean load ratio (i.e., the ratio between the vertical force in unaffected and in the affected lower extremity during quiet standing when the subject recovered from the perturbation) was calculated to show the progress in loading the affected lower extremity in stroke subjects rehabilitation.

Further on the data assessed in each force platform were used to calculate the COP motion under each foot [16]. The COPs under left and right foot (Fig. 2) were transformed from local coordinate system located at the center of each force plate to

TABLE I
LINEAR REGRESSION BETWEEN BBS AND AP/ML RATIO AND MEAN LOAD RATIO (VERTICAL GRF AFFECTED/UNAFFECTED LEG) PRIOR–AFTER TREATMENT

		Perturbation direction							
Results	Variable	BL	BR	BW	FL	FR	FW	LT	RT
AP/ML vs BBS	R	-0.287	-0.110	0.868	-0.541	-0.138	0.229	-0.550	-0.345
	p	0.117	0.328	**0.00**	**0.008**	0.286	0.157	0.07	0.074
Mean load ratio prior(after) therapy	mean	0.65 (0.74)	0.74 (0.83)	0.64 (0.74)	0.68 (0.74)	0.70 (0.81)	0.69 (0.73)	0.69 (0.72)	0.61 (0.71)
	std	0.31 (0.19)	0.36 (0.21)	0.26 (0.18)	0.26 (0.24)	0.27 (0.24)	0.19 (0.18)	0.33 (0.23)	0.23 (0.19)
	p*	0.131	0.101	**0.050**	0.254	**0.042**	0.336	0.644	**0.018**

R - Pearson's coefficient
*paired T-test (statistically significant - $p < 0.05$)

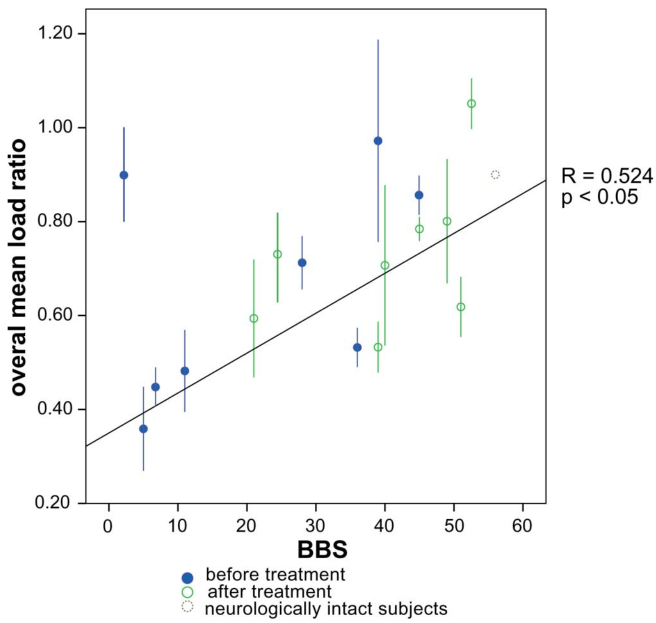

Fig. 6. Overall mean load ratio (the vertical component of the GRF between the affected and unaffected lower extremity) demonstrated reasonably high correlation ($R = 0.524, p < 0.05$) with the clinical instrument BBS. The points presents subjects with the same BBS and the mean load ratio with standard deviation.

the global coordinate system [19] which was centered automatically for each participating subject depending on his/her initial position. In the group of neurologically intact volunteers a mean value of the within subject mean COP and the belonging standard deviation were determined and contrasted to the COP to monitor the deviations [14] as presented in Fig. 2 (shaded area). The obtained mean data were considered as normative data (Fig. 3 shaded area).

The peak value of the postural response [Fig. 3(a), first peak] was determined by computer algorithm [14] in COP for both directions, anterior–posterior $(\mathrm{OVR}_{\mathrm{AP}})$ and medial–lateral $(\mathrm{OVR}_{\mathrm{ML}})$. During quiet standing (the first 500 ms–1 s) the initial COP position was determined, followed by peak detection of the postural response (OVR). In cases when the postural response peak was not explicitly defined [Fig. 3(b)] in one of the directions (e.g., $\mathrm{OVR}_{\mathrm{ML}}$ in BW postural response) then the peak was determined using a cross-correlation function. COP time-courses of both directions were object of the cross-correlation, filtering, and signal processing to calculate the time-delay between the signals [14]. The time-delay and the postural response peak of the well-defined response were used to calculate the poor-defined postural response peak. The relative difference between the initial COP position and the postural response peak in the COP of both directions defined the $\mathrm{OVR}_{\mathrm{AP}}$ and $\mathrm{OVR}_{\mathrm{ML}}$ [Fig. 3(a) and (b)].

For each perturbation direction a quotient between the calculated postural response peaks was determined

$$\frac{\mathbf{AP}}{\mathbf{ML}} = \frac{\mathbf{OVR}_{\mathrm{AP}}}{\mathbf{OVR}_{\mathrm{ML}}}. \tag{1}$$

The calculated AP/ML ratio characterizes the line that tends towards perturbation direction [Fig. 3(c)]. The absolute value of the ratio changes according to the COP motion and in perfect conditions gives the following results for the selected perturbation direction:

$$\mathbf{LR}, \mathbf{RT}: \frac{\mathbf{AP}}{\mathbf{ML}} \to 0$$
$$\mathbf{FW}, \mathbf{BW}: \frac{\mathbf{AP}}{\mathbf{ML}} \to \infty. \tag{2}$$

The perfect conditions nearly equals to neurologically intact subject's response.

E. Statistical Analysis

The BBSs of the stroke subjects were assessed by physiotherapist before and after the rehabilitation treatment and the means and the standard deviations were calculated using SPSS 14 (LEAD Technologies, Inc., Charlotte, NC). Statistical T-test analysis has been done for the load ratio between the affected and unaffected lower extremity after the recovery from the perturbation before and after the treatment. For overall load ratio (all perturbation directions) a linear regression (Pearson's coefficient $\mathbf{R}$) between the BBS and the load ratio was calculated to test the relationship between the clinical and the proposed outcome measures.

The mean and standard deviation of the AP/ML ratio assessed in neurologically intact volunteers and stroke subjects before and after the rehabilitation intervention have been calculated for each perturbation direction. ANOVA was used to test the significance of the data. For each perturbation direction a linear regression (Pearson's coefficient $\mathbf{R}$) between the BBS and the AP/ML ratio was calculated to test the relationship between the clinical and the proposed outcome measures.

The GRF's undershoot during perturbed standing was statistically analyzed. The emphasis was on critical perturbation directions (BR, FR, and RT) before and after the treatment. Additionally the linear regression (Pearson's coefficient $\mathbf{R}$) between the normalized GRF undershoot and BBS was calculated.

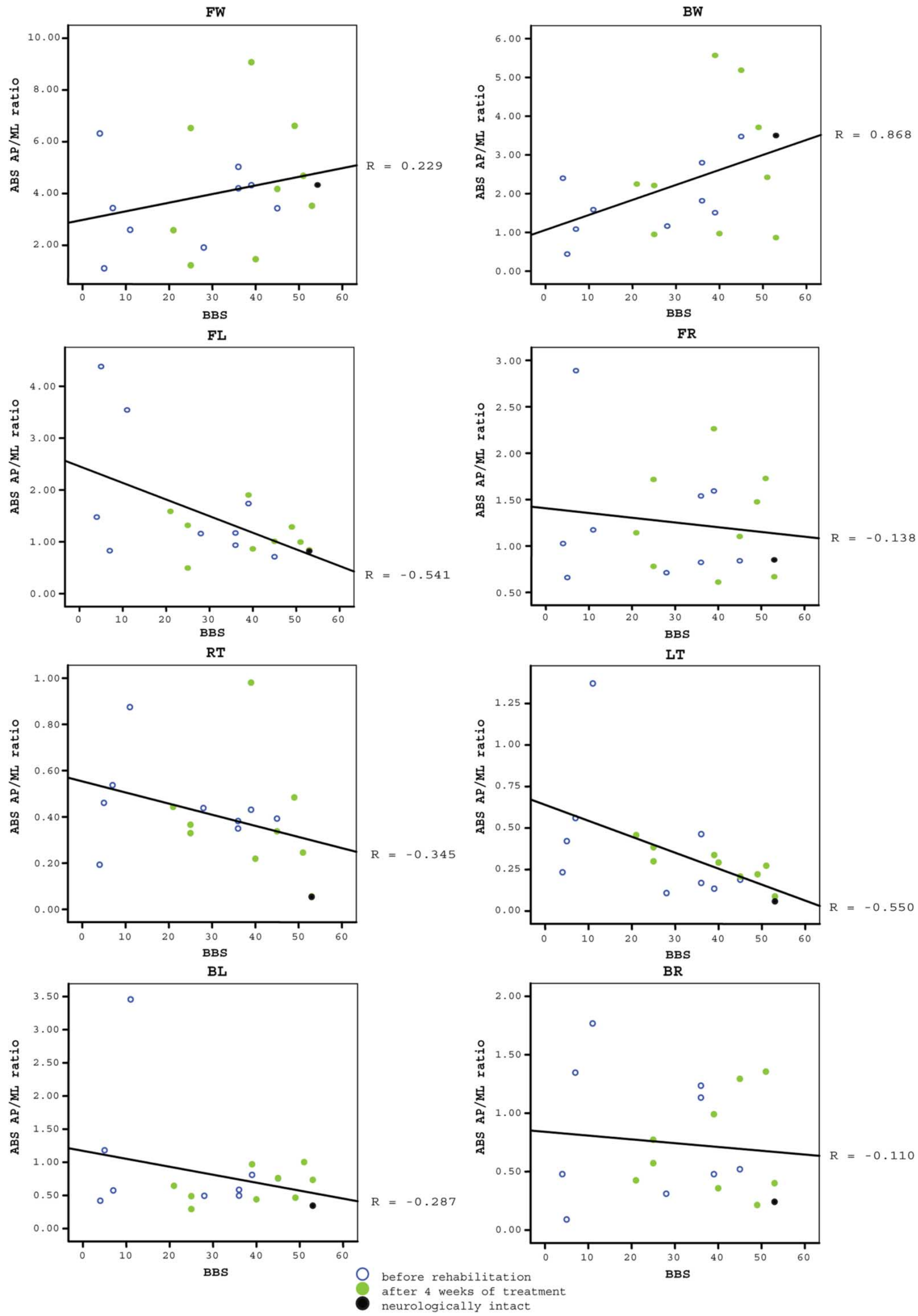

Fig. 7. Linear regression between BBS and AP/ML ratio for all perturbation directions. The Pearson's coefficient R was found low for the FR ($R = -0.138$, $p = 0.286$) and BR ($R = -0.110$, $p = 0.328$) perturbation directions, while relatively high correlations were found in FL ($R = -0.541$, $p = 0.008$), LT ($R = -0.550$, $p = 0.07$), and BW ($R = 0.868$, $p = 0.00$) directions.

III. Results

The mean BBS assessed before the rehabilitation treatment in stroke subjects was significantly ($p = 0.00$) lower (23 SD 15) than after the treatment (39 SD 11). It was considered that neurologically intact volunteers have maximal BBS, i.e., 56 [Fig. 4(a)].

The overall weight distribution (load ratio between the affected and unaffected lower extremity) has improved during the rehabilitation treatment [Fig. 4(b)] toward the neurologically intact subjects (from 0.67 SD 0.27 to 0.75 SD 0.21, $p = 0.00$). The stroke subjects were able to put more weight on the affected lower extremity after the rehabilitation treatment for each perturbation direction in transverse plane [Fig. 5(b) and Table I].

The following AP/ML ratios $(\mathrm{mean} \pm \mathrm{SD})$ were calculated for each perturbation direction and have moved toward neurologically intact subjects' normative; before rehabilitation treatment [left column in Fig. 5(a)] the mean value for BL perturbation direction was 0.97 ± 0.96 and after the treatment [middle column in Fig. 5(a)] the mean was 0.64 ± 0.24, while in neurologically intact volunteers' normative the mean value added up to 0.34 [right column in Fig. 5(a)]. The values for other directions are also presented in the Fig. 5(a): for BR 0.82 ± 0.57 (before treatment), 0.71 ± 0.42 (after treatment) and 0.24 (normative), for BW 1.81 ± 0.94 (before treatment), 2.68 ± 1.78 (after treatment) and 3.50 (normative), for FL 1.77 ± 1.30 (before treatment), 1.14 ± 0.43 (after treatment) and 0.82 (normative), for FR 1.25 ± 0.70 (before treatment), 1.27 ± 0.56 (after treatment) and 0.85 (normative), for LT 0.41 ± 0.39 (before treatment), 0.28 ± 0.11 (after treatment) and 0.06 (normative) and for RT 0.45 ± 0.18 (before treatment), 0.38 ± 0.26 (after treatment) and 0.05 (normative). The AP/ML ratio for perturbation in FW direction increased in greater extent (3.59 ± 1.60 (before treatment), 4.43 ± 2.60 (after treatment) and 3.72 (normative). The standard deviations were rather high, but the changes in the all perturbation directions were still significant $(P < 0.05)$.

The linear regression between the overall mean load ratio and the clinical instrument BBS demonstrated reasonably high correlation [Fig. 6; $R = 0.524$ $(p < 0.05)$].

The linear regressions for each perturbation direction are shown in Fig. 7 and Table I. The Fig. 7 presents the AP/ML ratio of all stroke subjects versus BBS before and after the treatment with neurologically intact subject's mean at $\mathrm{BBS} = 56$. Additionally the linear regression line is presented. The Pearson's coefficient R was found low for the FR $(R = -0.138)$ and BR $(R = -0.110)$ perturbation directions, while relatively high correlations were found in FL $(R = -0.541)$, LT $(R = -0.550)$ and BW $(R = 0.868)$ directions. Besides linear correlation with the BBS $(R = 0.868)$, the AP/ML ratio for the BW perturbation direction showed significant improvement toward the normative [Fig. 5(a)]. In spite of low correlation for some perturbation directions with BBS the BR, BL, RT demonstrated improvement of the AP/ML ratio toward the normative.

Changes were also noticed in the GRF undershoot. In directions BR, FR, and RT, which were foreseen critical for right side affected stroke subjects, the GRF undershoot after the postural response has decreased [Fig. 8(a)]. The standard deviation was rather high, but the changes in the critical directions were still significant $(P < 0.05)$, while in other directions insignificant $(P > 0.05)$. The confidence interval (CI) of GRF undershoot that contains 95% of all stroke subjects' data has decreased [Fig. 8(b)], but considered insignificant $(P > 0.05)$. Besides, the GRF undershoot did not correlate with the BBS $(R = 0.03)$ [Fig. 8(c)].

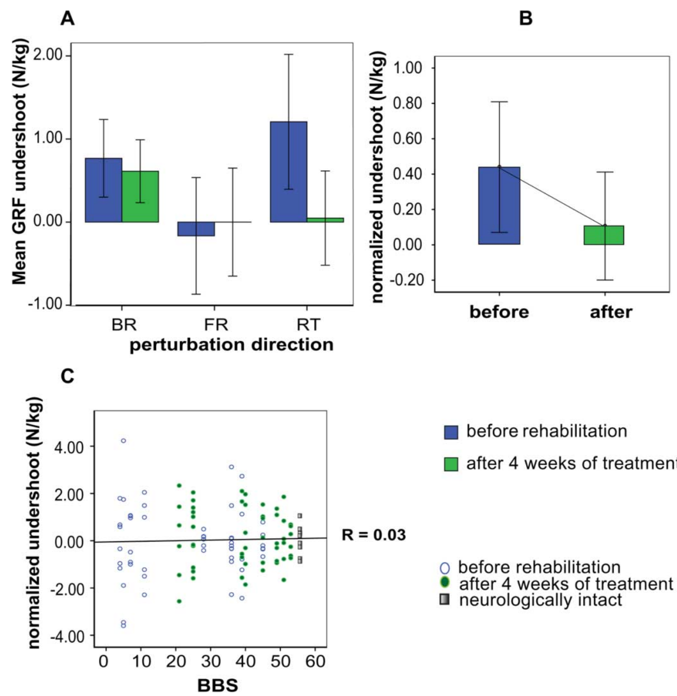

Fig. 8. (A) Ground reaction force (GRF) undershoot after the postural response has decreased in critical directions (for right side stroke subjects) and in general (B) what is considered positive, but data do not correlate with clinical instrument BBS (C) The correlation between the GRF undershoot and the BBS was rather low $(R = 0.03, p = 0.381)$.

IV. Discussion

Stroke patients have been frequently identified as persons liable to particularly high risk of fall [20]. Andersson *et al.* [21] presented one of the options how to identify potential faller in a stroke unit, using subjectively oriented clinical instruments, BBS, stop walking when talking (SWWT), timed up and go (TUG). Subjects scoring BBS less than 45 were identified with the increased risk to fall at the follow up. The outcomes of other tests applied needed to be combined with the BBS to show reliable results [21]. As an alternative to the subjective BBS a reliability test of the objective balance master limits of stability test (BMLOST) was carried out [22]. The BMLOST required increased level of concentration, attention span and static upright posture, but served as a good tool in conjunction with the BBS [22]. Bortolami *et al.* [23] pointed out some of the drawbacks of current perturbation techniques in objective oriented computerized tool for postural response assessment. Most of the techniques that do not include vertical drops must somehow displace or deform the body posture. For such task a relatively large force and short time were required, which frequently could not be achieved. Therefore, only slow postural responses could be assessed [23].

Numerous studies have identified the pathophysiological aspects of standing balance control in patients with stroke, some of them pointed out the effects of force feedback training, unperturbed stance control, visual information, and perturbation training while using different perturbation techniques [24]. The effects of any training or rehabilitation treatment is most likely examined by clinical test (BBS, SWWT, TUG, etc.) or/and with physiological measures to determine the functional changes in postural control. Garland *et al.* [25] reported that neurologic recovery must have taken place when functional changes were accompanied by physiological changes assessed by COP measurement after four-weeks of rehabilitation treatment. Besides,

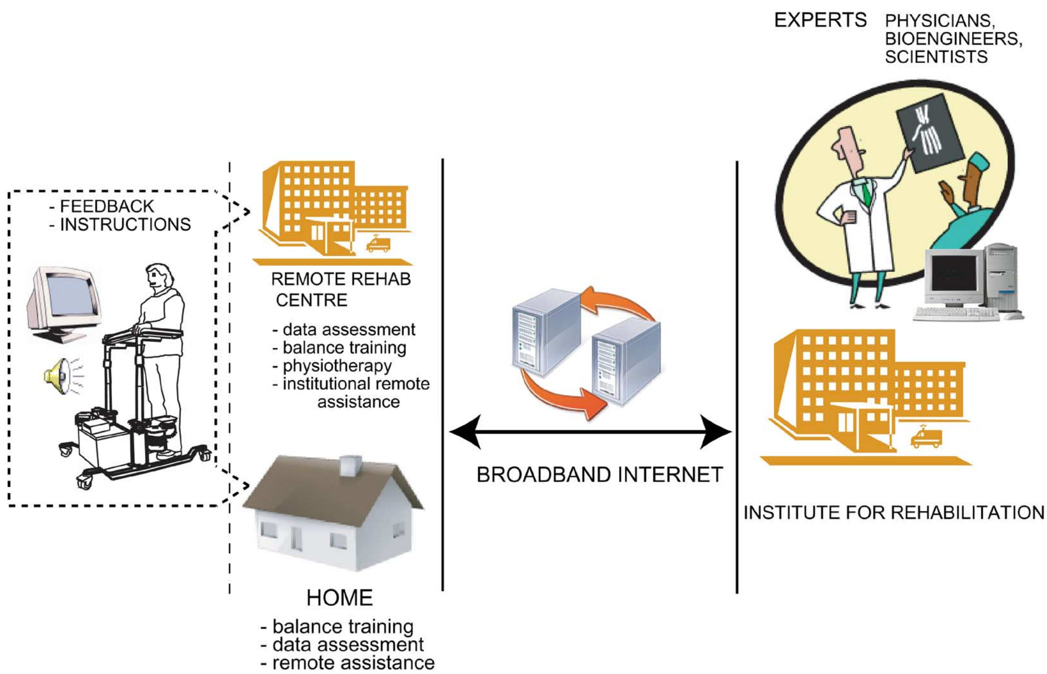

Fig. 9. Proposed apparatus can be located at the patient's home or in remote rehabilitation center where balance training is performed. Additional instructions are provided through the broadband internet video conference connection with medical experts. Periodically the postural responses are evaluated and data are sent over the internet to the expert center.

there has been reported that the force plate measurements and the BBS quantify similar aspects of the postural stability [26].

The results of our study demonstrate that the overall BBS has increased after the rehabilitation treatment. Moreover, the BBS has increased in each individual subject. In clinical terms the subjects' balance capabilities have improved, but the mean BBS value was still less than 45, the value that stands for the fall risk [21]. Therefore, we may expect that subjects after the treatment still have some postural difficulties. The overall mean load ratio [Fig. 4(b)] between the affected and unaffected lower extremity revealed similarly the positive effects of the rehabilitation treatment. The load ratio moved towards the neurologically intact subjects' value (in neurologically intact volunteers the load ratio tends towards 1) meaning that after the recovery from the perturbation the subjects had more confidence and put more load on their affected lower extremity. Both outcome measures demonstrated statistically significant progress in rehabilitation treatment and showed good linear correlation (Fig. 6). Therefore, our results suggest that the same information on rehabilitation progress obtained by the BBS can also be reliably determined through mean load ratio measurements. Additionally, the objective postural response evaluation tool provided information on progress for each perturbation direction separately. Thus, to take the advantage of such tool the load ratio was presented for each perturbation direction demonstrating progress for particular perturbation directions. Namely the BBS and the mean load ratio can demonstrate an overall progress as the insight into postural responses in each particular direction can reveal directionally-specific deficiencies in postural control of an individual. For each perturbation also the COP AP/ML ratio demonstrated progress, especially in medial–lateral (LT, RT) and backward directions, indicating that the majority of balance improvement for the entire group can be attributed to more reliable postural control in ML and BW directions. Slightly less significant with high standard deviation results appeared in BL, FR, and BR directions, predominantly due to the subjects with low rehabilitation entry BBS (< 5). Those subjects showed improvement in terms of the BBS, but had still difficulties with balance and recovery from the perturbation in diagonal directions. The later also resulted in lower linear correlation with the BBS. Directionally specific evaluation of postural control demonstrated that differences in performance of various subjects can be expected. While the BBS and the mean load ratio outcome measures correlate well and can provide a reliable information on the current state of the postural control, directionally specific outcome measures proposed in our study may indicate critical perturbation directions that may have remained after the treatment (Table I). Additionally the GRF undershoots were explored for each perturbation direction. Results showed decreased undershoot for critical directions (right-side stroke subjects—BR, FR, RT) of transverse plane and overall GRF undershoot decrease after the rehabilitation treatment, which all show towards postural response improvement. We could not confirm statistical correlation between the GRF undershoot and the BBS, most likely due to the limited number of participating subjects and the fact that some subjects with low BBS have improved their BBS but their postural response abilities remained weak. Similar findings were reported during quiet standing [27].

The outcomes suggest that the assessed mean load ration and the COP in anterior–posterior and medial–lateral directions and their corresponding peak quotient during perturbed posture can objectively demonstrate the rehabilitation treatment progress. According to the data assessed it would be also possible to predict the BBS from mean load ratio measurements. Likewise the information on directionality may offer the physiotherapist the option to provide the patient specific direction oriented training tasks and therefore increase the efficiency of the rehabilitation.

The proposed "evidence-based rehabilitation" may also gain further interests in the field of telerehabilitation/teletherapy research and development, particularly if a replacement of standing platform and fixed force plates with portable force plates is considered and monitored data are regularly send over the network to the specialized rehabilitation center from where expertise and further instructions can be provided as remote feedback (Fig. 9).

V. Conclusion

A development of novel instruments in balance and postural response training and evaluation usually rises several questions, asking whether the computerized posturography is really needed [28]. Most of the healthcare professionals use only the subjectively oriented and questionnaire based tools that are clinically well accepted and widely in use. But when such information is used in conjunction with computerized objective oriented posturography, the rehabilitation outcome evaluation may gain reliability. Especially, if combined with the proposed methodology, providing directional postural control and balance capabilities evaluation.

Such objective computerized tool may be well suited for home-based intervention program. In this program the stroke patient may be released from the rehabilitation center earlier and continue with the balance training at home and occasionally accomplish the postural response assessment. The data assessed may be sent over the internet to the rehabilitation center where the experts decide on further treatment and notify the user to report at the outpatient department. The results presented may gradually lead to the realization of such home-base service. Nevertheless, a larger group of participating subjects is needed to confirm the applicability of the presented outcomes.

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