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BalanceReTrainer: A new standing-balance training apparatus and methods applied to a chronic hemiparetic subject with a neglect syndrome

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Abstract. In this paper we present a mechanical apparatus and methods named BalanceReTrainer for standing-balance training in neurologically impaired individuals. BalanceReTrainer provides an impaired individual with a fall-safe balancing environment, where the balancing efforts of a standing individual are augmented by stabilizing forces acting at the level of pelvis in the sagittal and frontal planes of motion, assisting the balancing activity ankle and hip muscles and at the level of shanks, assisting the knee extensor muscles. A range of different levels of supporting forces is generated by passive, compliant means. Additionally, movement in the sagittal and frontal planes, acquired by transducers is fed to an electronic interface which transforms the current inclinations into a computer mouse signals, which are interfaced to a personal computer (PC) where balance training and evaluation program is running. The level of stiffness support and level of difficulty of computer task can be selected according to current balancing abilities of the impaired individual. We further present results of a case study where an ambulatory chronic hemiparetic subject with neglect syndrome received ten days of balance training on BalanceReTrainer. Biomechanical evaluation of weight-shifting activity before and after treatment shows a substantial functional improvement.

Keywords: Standing-balance training, neurological rehabilitation, stroke

1. Introduction

Every year approximately one million people in Europe and North America suffer from a cerebrovascular incident or stroke. The effects of stroke can be devastating, resulting in deficits of cognitive, sensory and motor functions. Motor deficits persist chronically in about one-half of stroke survivors [5]. Stroke patients commonly experience some spontaneous recovery, but are also treated with extensive physical and occupational therapy. Stroke rehabilitation is labor-intensive, in most cases relying on one-on-one, manual interactions with therapists. Falls are very common in stroke survivors and falling is one of the most frequent complications among stroke patients [17,19]. Injuries and other consequences resulting from falls, e.g. restricted activity as a result of the fear of new falls, are likely to have a negative effect on the rehabilitation outcome and quality of life in general. Thus, one of the major challenges and goals of stroke rehabilitation is to improve postural stability, motor performance, and the patient's self-perception and awareness of the risk of falls. Since adequate postural control and balance is an essential component of a variety of activities of daily living such as standing up, reaching when standing,

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manipulating objects, walking and stair climbing, the standing-balance training is a crucial therapeutic procedure in the rehabilitation of stroke patients [23].

Conventional balance training therapy is mostly done through instructions and assistance of therapists, which is time consuming and labor intensive. It is often inefficient due to lack of patients' active involvement, which holds also for force-platform biofeedback devices designed for training stance steadiness and symmetry [16]. During conventional balance training therapy and during force-platform biofeedback sessions, the subjects are exposed to possible unwanted destabilization and potential fall. Current therapeutic techniques are therefore rather static and often the patients use their arms for stability, which significantly limits the outcome of the training process [22]. When using hands, holding on stable support like parallel bars, standing becomes quadripedal. In this case the task of maintenance of selected posture significantly differ from bipedal standing where the task of balancing requires much more refined sensory-motor activity. Therefore, we hypothesize that when balance-training activity is exercised in bipedal stance we can expect improved functional skills that would transfer in activities of daily living. Additionally, it has been recognized that weight-shifting activities that challenge the limits of stability and require accuracy and speed should be incorporated within the balance re-training therapy [16].

Modern concepts of neurological rehabilitation favor task specific training [7]. Recent studies have demonstrated that intensive and repeated practice modify neural organization and effect recovery of functional motor skills [3,6,9,11]. Adopting this approach to standing-balance training requires methodology enabling the impaired subjects to practice balance skills in a fall-safe environment providing repeatable sensory inflow and an appropriate level of mechanical support substituting for missing motor output. It is important that the mechanical support is such that renders the use of the arms for stabilization unnecessary thus facilitating the use of the involved lower extremity and development of alternative sensory-motor programs needed for efficient postural control. At present there is no available technique giving a fall-safe, dynamic balance-training environment in clinical practice.

Our recent studies have examined the biomechanical principles underlying the regulation of balance in neurologically intact humans. The results have shown that the functional postural activity in the ankles and hips can adequately be described as regulation of a selected level of stiffness, which has strong implications for neurological rehabilitation of balance [12,15]. A mechanical apparatus, having two degrees of freedom, enabling physiological range of movement in the ankles and hips and preventing movement in the knees, was developed [13]. The apparatus was called the Multipurpose Rehabilitation Frame (MRF) and has two hydraulic servo-controlled actuators, which can provide supporting forces acting upon the pelvis of a standing subject as well as accurate and repeatable perturbing forces. The MRF was used as a balance-training device in a group of spinal cord injured individuals where, following the principles of postural activity in neurologically intact individuals, the MRF assisted by providing stiffness-like forces to the pelvis of the standing subjects. Nine days of training (half of an hour per day) resulted in significant improvement of balancing abilities of all the subjects as measured by a decrease in the level of supporting stiffness. Also, the subjects significantly improved their abilities to perform functional manipulation tasks while standing outside the MRF [13]. The study clearly indicated that the proposed balance training approach is viable. However, it also exposed important deficiencies. Firstly, the hydraulic equipment is too heavy, noisy and expensive to be used in clinical practice or at home. Secondly, the task of the standing subjects was only to maintain vertical posture for the duration of the training session. Thus, after a few sessions of this activity the interest of the subjects decreased, which calls for a task that requires sufficient cognitive involvement and provides a challenge to training subjects. Lastly, we noticed that locking the knees limits the scope of neurorehabilitation as in this case an important postural degree of freedom, namely the vertical postural axis, controlled by the extent of knee flexion/extension is left out.

In this paper we present a mechanical apparatus and methods, collectively named BalanceReTrainer, developed to enable task-oriented balance training to neurologically impaired individuals in a fall-safe environment. The mechanical apparatus is based upon the MRF device and extended by enabling controlled knee flexion/extension which enables unhindered mobility of the lower extremities during standing while at the same time providing adjustable level of support to muscles of lower extremities. We further report on the case study of a patient with chronic hemiparesis and with neglect syndrome who received 2-week standing-balance training on BalanceReTrainer.

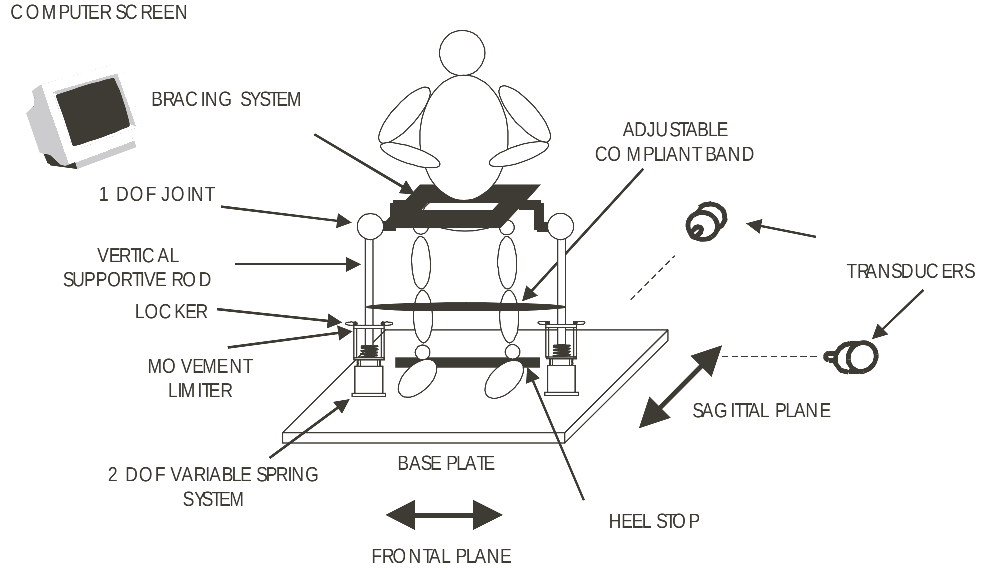

Fig. 1. Schematic presentation of BalanceReTrainer. The apparatus consists of two 2-DOF variable spring systems mounted with vertical supportive rods that end with 1-DOF hinge joints. Both 1-DOF joints are connected through bracing system. A subject is standing on the base plate supported by the bracing system and adjustable compliant band. Movement is limited by movement limiters while by the aid of lockers the movement can be inhibited. Inclinations of the subject in the sagittal and frontal planes is acquired by the transducers and interfaced to the PC where balance-training and evaluation program is running.

2. BalanceReTrainer

BalanceReTrainer is a mechanical apparatus that provides an impaired individual with a fall-safe balancing environment, where the balancing efforts of a standing individual are augmented by stabilizing forces acting at the level of pelvis in the sagittal and frontal planes of motion, assisting the balancing activity of ankle muscles (sagittal plane) and ankle and hip muscles (frontal plane) and at the level of shanks, assisting the knee extensor muscles. In this way the apparatus enables full physiological range of movement in all three principal postural degrees of freedom (sagittal plane, frontal plane and vertical axis) [14]. Figure 1 shows the mechanical apparatus, which consists of a rigid base plate upon which two 2-DOF (degrees of freedom) variable spring system joints are mounted. Each 2-DOF joint complex is connected to a plain 1-DOF hinge joint by vertical supportive rod. Both 1-DOF joints are connected together by a rigid bracing frame. The subject stands on the base plate, having knees supported by the adjustable compliant band and pelvis braced by the bracing system.

The apparatus has three DOF, i.e. enables inclination in the ankles in the sagittal plane, inclination in the ankles and hips in the frontal plane and knee flexion as shown in Fig. 2. The range of motion of the apparatus is limited to $\pm$ 15 degrees in all three DOFs by means of mechanical limiters. The supporting forces are generated entirely by passive, compliant materials. Figure 3 shows the construction of a 2-DOF variable spring system joint complex, which serves two purposes. Firstly, it enables movement in sagittal and frontal planes and secondly, it opposes this movement by means of helical spring. This spring is centered within two cylinders that are connected in a threaded arrangement, thereby allowing displacement of the inner cylinder relatively to the base plate mounted outer cylinder. In this way the active length of the spring (as shown in Fig. 3) is varied, which determines the level of opposing force and determines stiffness of the whole complex.

The level of supporting forces can be varied from zero up to the level where no balancing activity is needed from the standing subject. The level of supporting force applied by the adjustable compliant band to the shanks can be varied by engaging/disengaging a number of rubber rings (six in total; as shown in Fig. 4). Additionally, movement in the sagittal and frontal planes, acquired by transducers (potentiometer arrangements located in within springs), is fed to an electronic interface which transforms the current inclinations into computer mouse signals, which are interfaced to a personal computer (PC). Thus, a standing subject, by voluntarily changing the posture in the

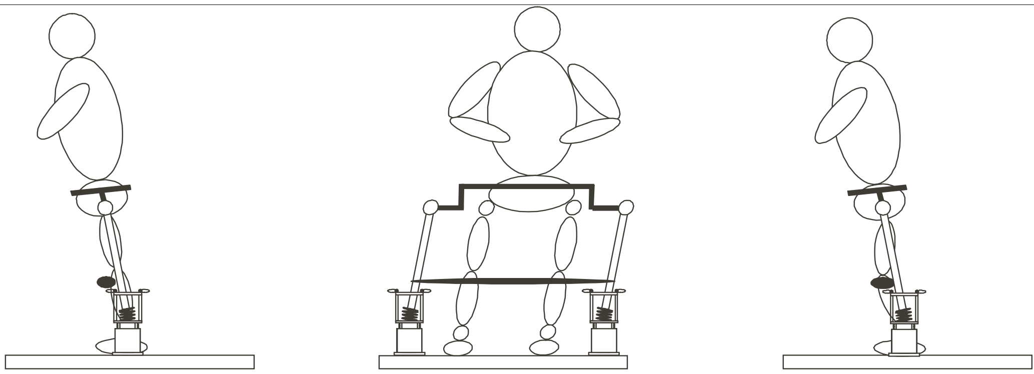

Fig. 2. Schematic presentation of the three DOF of the apparatus (inclination in the sagittal plane, inclination in the frontal plane and movement along the vertical postural axis – knee flexion/extension).

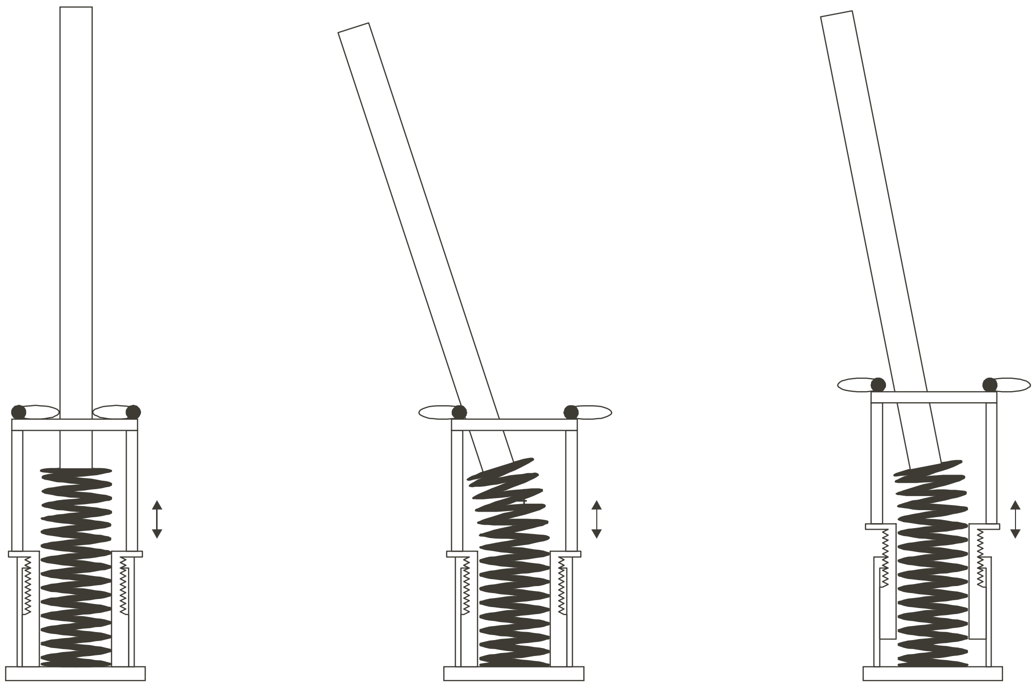

Fig. 3. Detailed presentation of the 2-DOF variable spring joint, which consists of helical spring, two housing cylinders, circular movement limiter and lockers. When lockers are disengaged circular movement of the supportive rod is possible up to the limits imposed by the circular movement limiter. Stiffness of the 2-DOF variable spring joint depends on the position of the inner housing cylinder, which can be easily displaced via threaded arrangement, relatively to the base plate mounted outer housing cylinder.

sagittal and frontal planes, can control various software applications running on the PC.

A balance training and evaluation program was developed to facilitate and test balancing in the whole range of anterior-posterior and medio-lateral postural space in a gradual and systematic way, thus enabling a uniform neurorehabilitation program and objective evaluation of balancing abilities of a standing subject. The succession of scenes appearing at the computer display is shown in Fig. 5. The opening scene (Fig. 5(A)) consists of eight symmetrically placed target circles and the tracker circle, which appear in the middle of the screen. The task imposed on the standing subject is first to move the mouse cursor (by changing posture in sagittal and frontal planes) into the tracker (step 1, Fig. 5(B)), which becomes locked to the cursor. A further objective is then to move the tracker into the illuminated target (step 2, Fig. 5(C)) and keep it in the target for a given period of time (step 3, Fig. 5(D)). The total time window given for completion of the task is limited and can be varied as well as the sizes of target and tracker circles. In this way the difficulty of the task can be varied. Successful task completion is signaled by auditory feedback – a short low-frequency beep. A short high-frequency beep signals failure. One training session consists of tracking each target for at least three times where the order of appearance of the targets is randomized. At the end of training session the performance is displayed in form of percentage of successful attempts for each of the targets separately and as a grand total of all attempted targets regardless of direction. This evaluation is mostly intended for training subject as it gives an objective measure of performance, which is thought to be an important source of motivation for subjects to improve their performance and thus exercise high quality self-therapy.

3. Case report

A 40-year old woman was affected by a first-time ischemic stroke in the territory of the right middle cerebral artery with a consecutive left-sided hemiparesis one and a half year before admission. Upon the admission she could sit unsupported, ambulate with the aid of a cane (FAC level 5, Rivermead MAS 10 – gross function, 4 – leg and trunk) and stand unassisted with eyes open at least for 10 seconds. A strong visual neglect was confirmed by clinical observation and a pathological line cancellation test within a neuropsychological interview. German version of a test battery for the assessment of attention (TAP – Testbatterie zur Aufmerksamkeitsprufung) was used [4]. The subject was sitting in front of a screen with a central fixation point. Moveable digits were presented in both visual fields and the evaluation parameter was the reaction time needed to detect the digits in both fields. Time differences between the left and right side were calculated and given as z-values. The pre-treatment score was 17. She had difficulties while standing manifested in pronounced asymmetrical weight bearing and limited ability to bear weight on the affected limb. Particularly, this subject had difficulties with shifting body weight to paretic side resulting in altered posture, impaired balance and gait function. This disorder represents one of the most demanding challenges in the physiotherapy of the hemiparetic subjects with neglect syndrome. A 10-m walking test was also performed and the subject needed 24 seconds to cover the distance before treatment.

Fig. 4. A photograph of the BalanceReTrainer prototype and a neurologically intact individual exercising computer based balance-training task.

For two weeks she received therapy on BalanceReTrainer, five times a week, each of the ten sessions lasting for approximately 20 minutes. During one session a therapist instructed the patient to incline forward, backward, left and right in each direction ten times and in oblique directions 20 times. The level of stiffness support at the pelvis and at the knees was set to appropriate levels (i.e. to such a level that enabled subject to perform the required task), which were reduced in the course of treatment program according to subject's needs and at physiotherapist's discretion. In addition the subject accomplished one computerized balance-training task per session where the difficulty of the task was progressively increased during the treatment period. The outcome of the treatment program was evaluated by the assessment of the ground reaction forces distribution under the soles of feet (Ultraflex CDG, Infotronic) during the task of shifting weight distribution. The following maneuver was performed: first the subject was instructed to bear even weight on both limbs, then to incline the body anteriorly and toward the unaffected limb, followed by diagonal transfer of

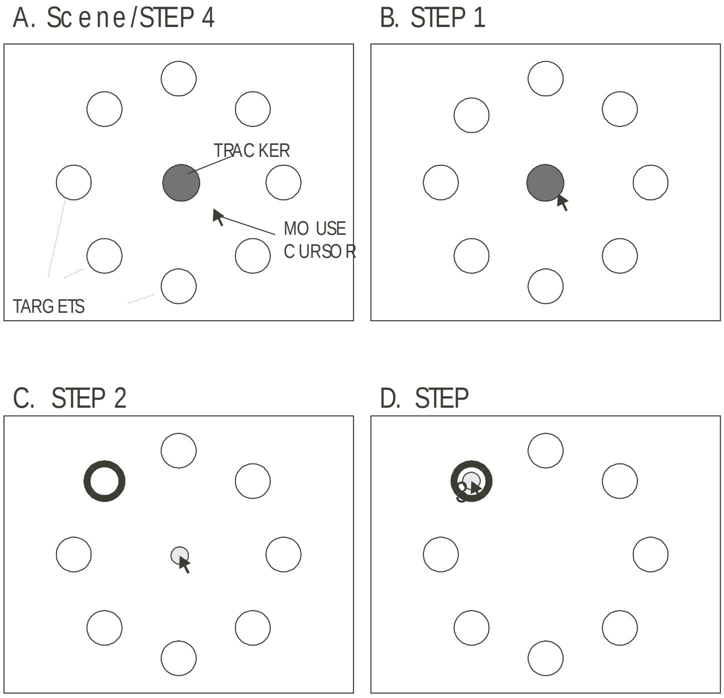

Fig. 5. Computer based balance-training and evaluation task. A. The initial scene consists of eight symmetrically placed target circles, the tracker circle and the mouse cursor, which is linked to BalanceReTrainer movement. B. Standing subject approaches the tracker. C. The tracker becomes attached to mouse cursor and thereafter moves together with the mouse cursor; one of the target circles becomes bolded. D. The subject steers the tracker into the bolded target.

weight posteriorly and toward the affected side. While performing the described maneuver the subject stood on BalanceReTrainer for safety reasons. The level of support was minimized, therefore, the apparatus did not provide any physical assistance. This assessment was done prior to commencement and at the end of the treatment program.

The results of the evaluation is shown if Fig. 6. Figure 6(A) shows the trajectories of centre of pressure (COP), which in quasi-static conditions equals to center of mass (COM) of the whole body. One can see that before the treatment the subject kept COM close to unaffected limb and she was not able to perform the required maneuver. While after the treatment one can clearly observe the required movement. A more detailed picture of the performance is seen in Fig. 6(B) where the partial limb loading and pressure distribution is displayed for both limbs separately and at successive time instants of the execution of the required maneuver. At the beginning of the maneuver (time: 0 s) one can see that before the treatment the weight ratio between the left and right limb respectively was 35%:65% while after the treatment this ratio substantially improved (44%:56%). The second sample (time: 5 s) also shows marked difference as after the treatment practically all the weight is born by the unaffected leg as contrasted to situation before treatment (only 86%). Then, the diagonal weight shift is initiated and in the next two samples (time: 7 s and 11 s) we can observe similar weight distribution before and after treatment. However, at the end of this diagonal weight shift segment of the evaluation task we can observe a major difference in performances before and after treatment (time: 13 s). Before treatment the subject returned the majority of weight on the unaffected limb. The required weight shift toward the affected leg was accomplished dynamically (as can be also seen from Fig. 6(A)). The subject was not able to sustain weight on the affected limb. In contrast, the recording after the treatment shows that as much as 95% of the body weight was born on the affected limb. The final sample (time: 15 s) shows that the subject successfully maintained the majority of weight on the affected limb after the treatment, which was not the case before the treatment. At the end of the treatment the FAC and RMAS scores did not change in comparison to values obtained before treatment while the z-value, measuring visual neglect, was decreased to 8. After the treatment the subject needed 20 seconds to accomplish 10-m walking without use of cane.

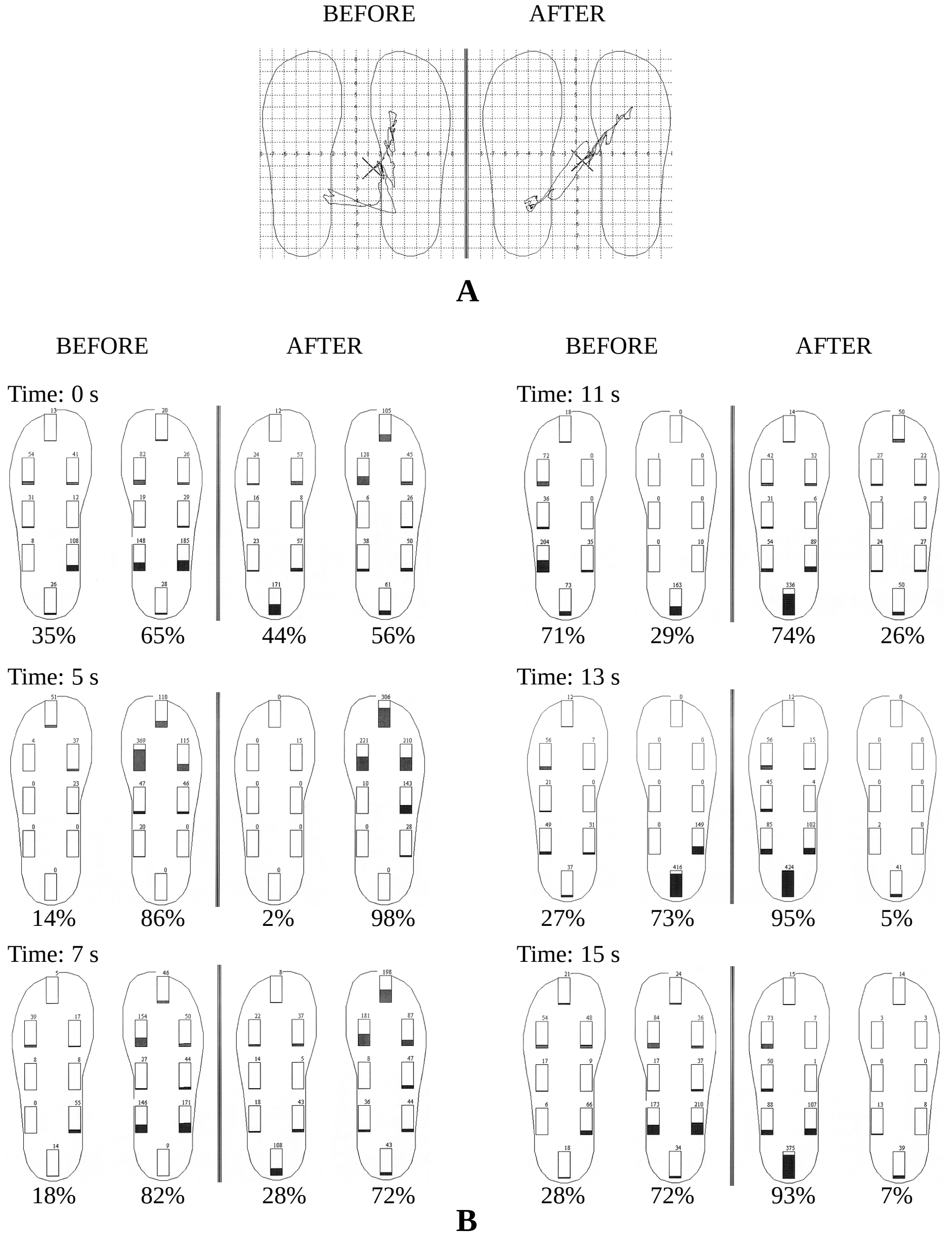

Fig. 6. Biomechanical recordings of COP and reaction force distribution under feet soles during the execution of the evaluation maneuver. A. COP trajectories before and after the treatment. B. Successive samples of reaction forces distribution and relative loading under feet soles.

4. Discussion

The results of the case study presented in this paper provide additional evidence on the appropriateness and efficacy of the developed mechanical apparatus for rehabilitation of neurologically impaired population, which has been initially used in incomplete spinal cord injured subjects [13]. Our case study indicates that BalanceReTrainer might be an effective tool for purposes of balance re-training during standing of stroke victims. The biomechanical outcome measures used for evaluation of the treatment effects objectively show the improved postural abilities in our subject. Since the subject was well beyond the period where the observed changes could be attributed to spontaneous recovery, there is little doubt that the observed improvement is due to our therapeutic intervention. Unfortunately, our results do not enable an insight into possible mechanism to which the functional improvement could be linked. There are several possible factors contributing to improved postural control of our subject after the treatment period. The first explanation is that BalanceReTrainer provided the subject with an environment that is fall-safe, thereby allowing the subject to explore her limits of stability and performance, which is not the case with any other balance-training technique. Therefore, it could be that our subject already possessed the sensory-motor ability required for execution of the evaluating maneuver, however before the treatment was not able to utilize it due to fear of falling and lack of internal presentation on the limits of the presumed preserved sensory-motor ability. A second possibility explaining significant improvement in performance before and after the treatment could be in plastic changes occurring in the brain, which is a known phenomenon [11]. Presumably these plastic changes occurred as a consequence of repeatable practice in dynamic postural environment, providing repeatable afferent input and motor augmentation, leading to re-organization and establishment of new brain regions that projected onto the sensory-motor systems of the affected lower limb. Leipert et al. [10] have demonstrated by means of fMRI that such plastic changes indeed take place following repeated mass-practiced activity both in sub-acute and chronic stroke subjects. They further demonstrated that plastic changes due to the efficient therapeutic technique exist and persist for long-term periods following the end of treatment. Most likely the combination of the two above described mechanisms, enabled by a fall-safe training environment in which the amount of motor support can be adjusted to a level which just enables a subject to be successful in the given task, are equally important.

There exist several treatment approaches for reducing the visual neglect. Standard clinical treatment enhances visual exploration by training the patient to make saccadic eye movements to the impaired field, however the long-term effectiveness remains unproven [2]. More recent studies, demonstrating amelioration of neglect following the immediate applications, have focused on sustained attention training [18], which can be combined with various techniques of basic sensory stimulation, i.e. vestibular stimulation [20] and neck muscle vibration [21]. These approaches are based on model derived from anatomical studies in humans and neurophysiological work on the primate brain, which suggest that the posterior parietal lobe is a multimodal association area that forms a distributed representation of space [1]. According to this model the peripheral sensory representation systems are intact whereas the highest level of supramodal representation is erroneous, leading to extreme rightward orientation bias of patients with left sided neglect. This influences also postural control mechanisms and symmetry in limb loading, which is nicely demonstrated by application of caloric stimulation and neck vibration, where the sensory information contribution to postural regulation is manipulated. The treatment on BalanceReTrainer attracts patient's attention to the neglected side with the dynamically moving symbols, which provides task-dependent differences in the neglected visual field. Karnath and Niemeier [8] have shown that such differences reinforce compensation and improve scaning and utilization of compensatory search strategies. Additionally, postural movement of the body during the training on BalanceReTrainer, providing meaningful and repeatable sensory inflow from the vestibular and proprioceptive systems, accompanies this task, which all may contribute to reduced neglect as well as improved postural control. This explanation is in line with findings of other studies [8,21]. The fact that the selected subject exhibited a strong neglect prior to treatment intervention, which was noticeably decreased after the end of the treatment period, indicates that a cognitive task in the form of a computerized balance training task, which requires attention in both visual fields is an important subpart of the therapy that enhances subjects' motivation and provides suitable neglect treatment modality.

The results of this case study are encouraging and call for controlled clinical studies in which individuals should be subjected to the described treatment program and evaluated. It will be also interesting to investigate whether the treatment effects are sustained in the period following treatment and also whether the quality of life has improved.

In recent years the potential of biomechatronic devices delivering semi-automated neurological rehabilitation has been recognized. This potential relates not only to the possibility of improved therapeutic procedures and recovery of neurological patients but may also reduce costs associated with treatment and social re-integration of disabled people in society. Biomechatronic, robotic technology for neurological rehabilitation has been developed for goal-directed movement (walking and reaching) [3,6,9]. Several clinical studies have shown the benefits of robot-delivered neurorehabilitation, however, prohibitive costs of the equipment, high demands on operation training and safety aspects impede transfer to clinical practice. This in turn prevents widespread clinical use and consequently sustained use and evaluation of such technologies. Biomechatronic technology aimed at neurological rehabilitation of balance have important advantage over the above described devices for neurorehabilitation of reaching and walking – BalanceReTrainer is made of inexpensive passive mechanical elements, which makes it a low-cost, easy to use and safe piece of equipment. Furthermore, it offers a physiological way of balance training, by providing physiologically and biomechanicaly sound afferent and motor augmentation in bipedal standing conditions. Most importantly it is an economically viable technological solution for effective balance-training exercise in the clinical environment and at home where little or no assistance is needed from the side of caregivers or family members.

Even though the application of the developed technology and methodology in this paper was focused on stroke it is not difficult to see the potential of the proposed method and apparatus in neurological rehabilitation of other etiologies (spinal cord injury, multiple sclerosis, traumatic brain injuries, cerebral palsy). Another huge field of application is in the population of elderly, where the incidence of falls and fall-related injuries is significant and represent a serious socioeconomic burden to any society.

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