

Sensory Electrical Nerve Stimulation for Training Dynamic Balance Responses in a Chronic Stroke Patient

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Abstract

We propose a novel method for applying sensory electrical stimulation during perturbed stance in subjects with neurological impairment. The feasibility of this methodology was investigated in a case study with one chronic stroke patient. A dynamic standing frame was modified with electrical actuators which allow the application of unexpected perturbations to neurologically impaired people during standing, while protecting the subject from falling. The subject underwent two different periods of perturbation training, each lasting ten days. During the first period, the subject was perturbed in eight different directions. During the second period, the subject was also perturbed, but was assisted by sensory electrical stimulation of the soleus (SOL), tibialis anterior (TA), tensor fascia latae (TFL), and vastus muscles (VAS) in the impaired leg. After each period of training, an assessment was carried out to measure the forces the subject applied on the ground via two force plates and the EMG responses of the SOL, TA, TFL, and VAS muscles. The subject improved his ability to balance throughout the training, with the largest improvements occurring during the final period when sensory electrical stimulation was used. These observations verify the feasibility of the approach and suggest that sensory electrical stimulation may have a beneficial effect on balance training. Recommendations for further studies to verify the method in larger subject groups are given.

Keywords: Sensory electrical stimulation, Balance control, Stroke rehabilitation

1. Introduction

In Scotland, with a population of 5 million people, annually approximately 15,000 people suffer strokes for the first time, with circa 80% surviving beyond 30 days. Of all surviving stroke patients who start with a rehabilitation programme, around 50% will remain impaired on their affected side [1]. For the rehabilitation of stroke patients, a therapist can usually work with only one patient at a time, and therefore, the rehabilitation is very labour-intensive. Additionally, the physical effort required by the therapist can be very high in assisting the patient during rehabilitation [2]. Therefore, assistive devices have been developed in order to reduce the physical effort of the therapist as well as the need for human attendants [3]. Examples include the MIT-Manus [4-6], which assists the rehabilitation of elbow and shoulder movement in stroke patients, the gait trainer, which allows chronic stroke and

paraplegic patients to train gait-like movement [2,7]. Also, the Lokomat [8], a robotic orthosis supporting spinal cord injured and chronic stroke patients during treadmill training rehabilitation. Devices specific for balance retraining include balance platforms (such as the BalanceMaster and the Biodex Balance System), which are based on a moving standing platform combined with biofeedback, and the BalanceTrainer [9], which is a dynamic standing frame allowing balance training and step-like movements. Initial results with these devices showed improvements in rehabilitation outcome [5,10-13].

According to the findings of Field-Fote [14], the spinal and cortical neural circuitry are modified by applied electrical stimulation as the neural circuitry underlying motor performance is modulated on a short- and long-term basis. Studies which combined robotic rehabilitation approaches with functional electrical stimulation (FES) also showed an improvement in rehabilitation outcome [15,16]. However, Tong et al. [17] stated that there was no significant difference in performance achieved after using a combination of rehabilitation robot and FES compared to the performance achieved after using a rehabilitation robot alone. Other studies

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have shown that stroke patients can regain independence in activities of daily life using transcutaneous electrical nerve stimulation [18-22]. This type of stimulation uses only a small electrical current applied to the skin which can usually be felt and will, at normal strength, only stimulate sensory nerves [23].

Based on the reported potential benefits of employing assistive devices, we wished to investigate the feasibility of combining such therapy with sensory transcutaneous electrical nerve stimulation in stroke rehabilitation, using a modified BalanceTrainer. Based on an alternating training protocol, we aimed to investigate whether this combined approach would have the potential to lead to a significant change in performance compared to rehabilitation using the modified BalanceTrainer alone. In this paper, we present a control method and apparatus for applying sensory electrical stimulation during perturbed stance in a modified BalanceTrainer. We show the outcome of a case study where we investigated the change in balance performance in a chronic stroke patient during perturbed standing while applying transcutaneous electrical nerve stimulation. Force plate measurements and EMG data were used to evaluate the balance performance at assessment points throughout the training. The results are discussed and the feasibility of this approach evaluated.

2. Methods

2.1 The modified BalanceTrainer

The BalanceTrainer (Medica Medizintechnik, Hochdorf, Germany, see Figure 1) is based on the concept of an ordinary standing frame: A table at pelvis height is placed on two vertical bars which are connected to the base of the frame, providing balance support to the user through direct contact at the pelvis while allowing free voluntary movement of the trunk. In contrast to a static standing frame, the connection to the base is dynamic, consisting of two-degrees-of-freedom mechanical joints which contain helical springs placed in steel cylinders with one end mounted firmly to the base and the other connected to the vertical bar. These springs provide dynamic support to the subject using the frame which can be adjusted by varying the active length of the springs, allowing dynamic balance training and step-like movements. In order to allow the subjects to get into the frame securely, a locking mechanism prevents the frame from tilting. A belt, wrapped around the subject's pelvis, is attached to the table and secures the subject during exercise.

In order to apply active perturbations, the BalanceTrainer was modified by fitting four electric motors (two at each side) which are connected via ropes to the frame. The setup is shown in Figure 1 and described in detail in [24]. To perturb the frame in a certain direction, the appropriate electric motor winds up the rope and pulls the frame away from its upright position. This leads to a corresponding perturbation being applied to the subject standing in the frame. Simultaneous activation of two motors allows a total of eight directions of perturbation.

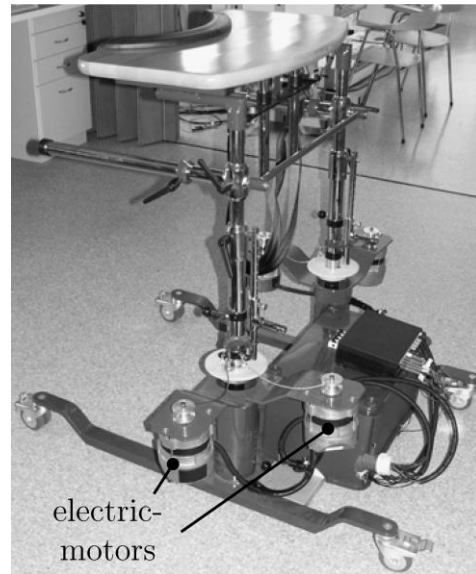


Figure 1. The modified BalanceTrainer with electric motors which are used to apply perturbations.

The magnitude of the perturbation depends on the duration for which the motors are active. It was chosen to be 0.6 s for this study as that provided sufficient disturbance for the participating subject, but the value can be adjusted depending on the size and weight of the user.

2.2 Subject

The experiments were performed with one chronic stroke patient (male, 45 years old, with a height of 1.85 m and a weight of 85 kg which remained unchanged throughout participation in the study). He was 19 months post stroke, had completed the stroke rehabilitation program and no longer received physiotherapy treatment at the time of the study. The impairment affected his right side. The subject needed no support during quiet standing, but was using an orthosis to prevent foot-drop during gait, due to inactive tibialis anterior muscle on the affected side. The orthosis was removed for the training and assessment sessions. All experimental procedures were approved by the Slovenian National Ethics Committee, and the subject provided written, informed consent prior to participation.

2.3 Measurements

In order to evaluate changes in ground reaction forces, the subject stood on two force plates (AMTI, Massachusetts, USA). The force distribution between the two legs, as well as changes in the center of pressure (CoP) were assessed. The CoP components in x- and y-direction were calculated as,

$$CoP_x = -M_y/F_z,$$

$$CoP_y = M_x/F_z,$$

with M_x and M_y denoting the moments in x- and y-direction and F_z being the vertical force. The sample time of the force measurements was 1 kHz. Before every session, the force plates were reset.

For the acquisition of the EMG data, repositionable surface electrodes (3M™ Red Dot™ Monitoring Electrodes with Foam Tape, 3M™, USA) were used. The signals were amplified (MyoSystem 2000 Amplifier, Noraxon Inc., USA) and recorded with a sample rate of 1 kHz, after appropriate anti-aliasing filtering. The raw EMG signals were inspected to ensure that the electric fields from the motors or other environmental disturbances did not interfere with the recordings. EMG data were rectified and the linear envelop extracted by applying a 4th-order low-pass Butterworth filter with a cut-off frequency of 7 Hz [25].

2.4 Sensory electrical stimulation

Sensory electrical stimulation was applied to the skin areas over the soleus (SOL), tibialis anterior (TA), tensor fascia latae (TFL), and vastus (VAS) muscle groups in the impaired leg as the subject was perturbed. These stimulation sites were selected as the corresponding muscle groups are important for ankle stabilization (SOL, TA), knee extension (VAS) and medial-lateral movement (TFL), and therefore affect balance control [26]. Depending on the direction of perturbation, the muscles which are mainly involved in the recovery of the perturbation were stimulated (see Table 1). As the subject's right side was impaired, the stimulation was applied only for perturbations in the sagittal plane (front, back) and towards the right (right, front/right, back/right).

Table 1. Directions of perturbation and stimulated muscle groups for impairment on the right side. The ticks indicate which muscle groups were stimulated. Note that stimulation was only applied to the affected right leg.

Direction	TFL	VAS	TA	SOL
Front				✓
Back		✓	✓	
Right	✓			
Front/right	✓			✓
Back/right	✓	✓	✓	

The stimulation was current-controlled, monophasic, and charge-balanced using the Stanmore Stimulator [27] and delivered via self-adhesive surface electrodes (PALS, 50-mm round, Axelgaard Mfg. Co., Ltd., Denmark). The aim was to stimulate during the time when the subject was trying to return to the starting position after he had been perturbed. The intensity of stimulation was regulated by the current level of the stimulation pulses.

The start of stimulation was triggered by a signal which initiated the perturbation of the frame. The timing of the stimulation as well as the triggering of the perturbation were controlled by PCs running Matlab/Simulink. A preliminary test with an able-bodied person was carried out to determine an

appropriate pulse width and the duration of the stimulation of the different muscle groups. The aim was to determine the precise on-set for the stimulation and to make sure that the stimulation was active only during the time the subject was reacting to the perturbation. Note that these stimulation times were not obtained from measurements of muscle activity, but were based on observations of the recovery pattern following perturbation. The same starting and finishing times of the stimulation were used for all directions of perturbations and are summarized in Table 2.

Table 2. Start and finishing time of stimulation for each muscle group after the initiation of perturbation.

Muscle group	Start [s]	Finish [s]
TFL	0.25	1.5
VAS	0.5	1.5
TA	0.25	1.0
SOL	0.25	1.0

A stimulation frequency of 20 Hz and a constant pulse width of 250 μ s were chosen, while the stimulation currents were adjusted individually at the start of each session to compensate for variations in the placement of the electrodes. The current levels were selected for each muscle group separately in such a way that the subject had to feel the stimulation clearly without having the stimulated muscles contracting due to the stimulation. For TFL, VAS and SOL, a current range of 20-40 mA was used, while for TA, the current level was 40-50 mA.

2.5 Experimental protocol

The experimental protocol is summarized in Figure 2. At the beginning of period I, a baseline assessment of the subject's balancing performance was carried out (1st assessment). After two weeks without training (period I) the performance of the subject was reassessed (2nd assessment). A two-week session with training in the BalanceTrainer (period II) followed. After a 3rd assessment, the subject underwent a final period (period III) of training which was identical to training period II, except that this time, sensory electrical stimulation was applied. At the end of this training period, the performance was assessed again (4th assessment).

During periods II and III, the subject trained five days a week. While training, the subject stood in the standing frame with close contact at the pelvis and the feet in a normal parallel quiet standing position. He was perturbed in eight different directions and was asked to react to the perturbations in the way he thought most appropriate without moving his feet. To recover from the perturbation, a combination of ankle and hip strategy was typically required. A round of perturbations was

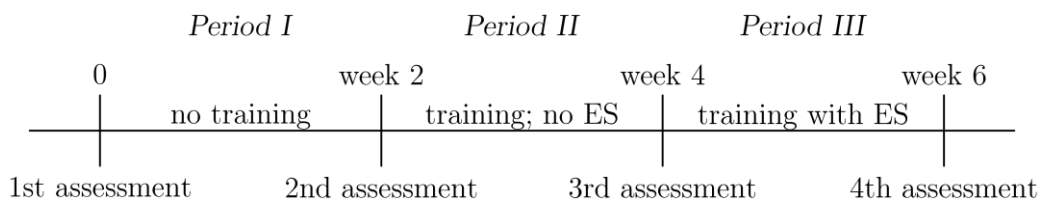


Figure 2. The time scale of training using electrical stimulation (ES) in the last training period.

completed when the subject had been perturbed once in all eight directions. The order of perturbation direction changed randomly from round to round. The time between perturbations also varied randomly, but was chosen large enough to allow the subject to return to the initial upright position before the next perturbation was applied. It took the subject less than five seconds to react to the perturbation and to return to the initial position. At each training session, the subject performed 16 rounds, resulting in a total duration of approximately 20 minutes per session. During period III, sensory electrical stimulation was applied using the procedure outlined in section 2.4.

For the assessments, the subject carried out the same exercises as during normal training days, but surface EMG data of the SOL, TA, TFL and VAS muscle groups in the impaired leg as well as force plate measurements were recorded. No stimulation was applied during the assessments sessions.

2.6 Data analysis

2.6.1 Statistical analysis of force data characteristics

To allow a more detailed statistical analysis of the changes in the force data between assessments, a number of key characteristic values were extracted from the vertical force response, F_z , of the impaired leg to the perturbations during the assessment sessions. These values, which are summarized in Figure 3, include: the starting value of F_z , the peak value (i.e. the difference between maximum and starting value of F_z), the peak time (i.e. the time at which the peak has been reached), the undershoot value (i.e. the difference between the minimum and the starting value of F_z), the undershoot time (i.e. the time at which the minimum has been reached), and the final value of F_z .

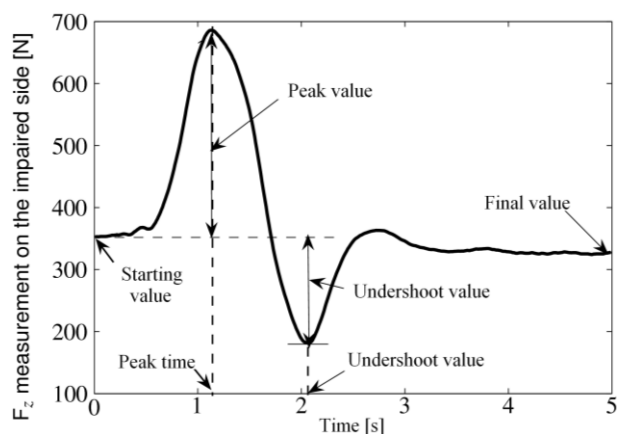


Figure 3. Characteristic values used for the evaluation of the ground force measured under the impaired foot during the perturbation to the right.

The characteristic values are based on the 16 sets of data for each direction obtained during one assessment. A one-way analysis of variance (ANOVA) was used to analyze these, giving a statistical test of whether the means of the characteristic values obtained at the four assessments were equal. To obtain further details about which pairs of means were significantly different, a multiple comparison algorithm

was applied using the Dunn-Šidák procedure [28]. The confidence interval was set to 95% ($p < 0.05$). The Matlab Statistics Toolbox (The Mathworks, USA) was used for the statistical analysis.

2.6.2 Analysis of EMG data

To enable the analysis of the relative changes in EMG following a disturbance, the EMG data were normalized and their offsets removed. Since the maximal contraction the subject was able to produce with the impaired limb could not be established directly, we used the maximal value of the existing EMG measurements over the 4 assessments for each muscle group for normalisation. The EMG data were averaged over the 16 rounds of perturbation which comprised each assessment.

3. Results

Measurement results reported here were obtained during the four assessment sessions. Corresponding data were averaged over the 16 rounds which constituted one assessment. The results showed the voluntary response of the subject to the perturbations since no sensory electrical stimulation was applied in the assessment sessions.

3.1 Force data

Although the subject was perturbed in eight directions in each assessment, changes in the force data were most apparent for perturbations in the direction of the subject's impaired side, i.e. to the right. For this reason, the presentation of the force data focuses on the reactions to perturbations to the right. The trajectory of vertical force data is presented, followed by the weight distribution between the two legs and the displacement of the CoP.

3.1.1 Vertical force

The trajectories of the vertical force data following the initiation of the perturbation at time 0 are shown in Figure 4 for the unimpaired and impaired side for all four assessments. The corresponding upper limits for the standard deviation values are summarized in Table 3 (the trajectories of the standard deviations were omitted from Figure 4 for clarity).

The generic shape of the response is similar for all assessments: On the unimpaired side, the initial period of constant force is followed by a reduction in F_z as the subject is pushed away from this side. As he regains balance, an overshoot in the force on this side can be observed, which is followed by a period of relatively constant force as he has recovered from the perturbation. On the impaired side, the initial period of constant force is followed by an increase in F_z as the subject is pushed towards this side. As he regains balance, an undershoot in the force on this side can be observed which is followed by a period of relatively constant force. The results show that it took the subject approximately 3.5 sec to fully recover from the perturbation.

The performance during the 1st and 2nd assessments (solid and dashed lines in Figure 4) shows a very similar pattern of behaviour. Following two weeks of training without

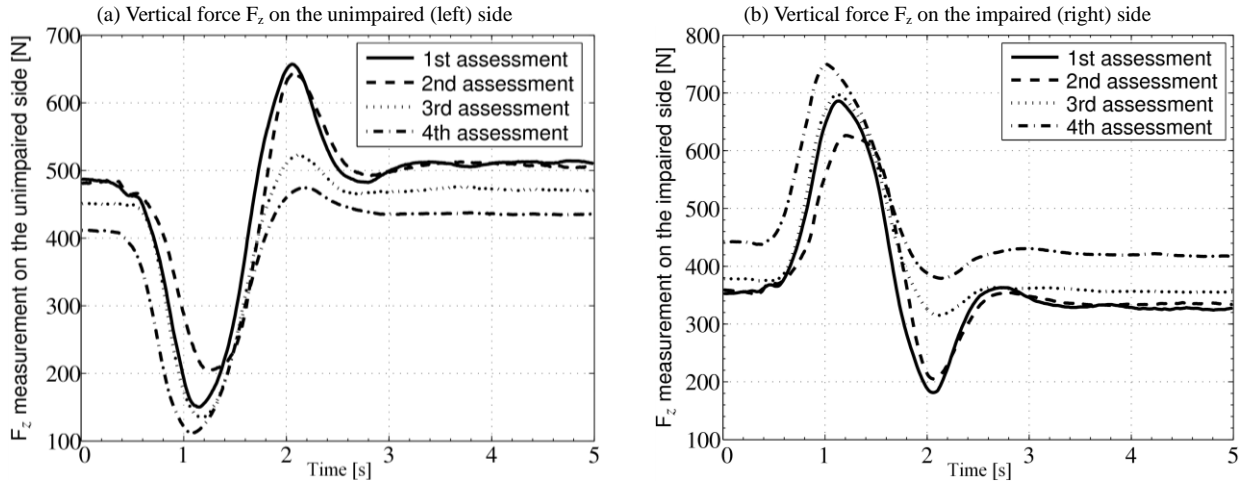


Figure 4. The change in the vertical force F_z on the impaired and unimpaired side after the subject was perturbed to the right; measured during all four assessments. Perturbation was initiated at 0 s.

Table 3. Upper limits of standard deviation values of the vertical force F_z on the unimpaired (left) and impaired (right) side for each assessment, as shown in Figure 5.

Assessment	Standard deviation for F_z left [N]	Standard deviation for F_z right [N]
1	<77.3	<77.6
2	<72.3	<68.7
3	<59.1	<57.7
4	<43.6	<45.5

sensory electrical stimulation (period II) the most obvious change in performance during assessment 3 (dotted lines) can be observed during the recovery from the perturbation: On the unimpaired side (see Figure 4) the overshoot is reduced, while on the unimpaired side, the corresponding undershoot is smaller. After another two weeks of balance training (assessment 4, dash-dotted lines in Figure 4), this time with sensory electrical stimulation (period III), a marked increase in starting and final values on the impaired side can be observed when compared to the third assessment, while the corresponding values are reduced under the unimpaired leg. In addition, a further reduction in overshoot on the unimpaired side and undershoot on the impaired side can be noted. The peak standard deviations reported in Table 3 show that their values decreased throughout the program, with the largest decrease when the subject was participating in the training program. This indicates that the balance performance is becoming more consistent throughout participation in the intervention.

3.1.2 Weight distribution between the two legs

The results shown in Figure 5 give an indication of the weight distribution between the unimpaired and the impaired legs by comparing the vertical forces at the start (Figure 5(a)) and at the end (Figure 5(b)) of the perturbation trial. Values were averaged for each assessment and are shown together with the respective standard deviations.

Figures 5(a) and (b) show that before and after the perturbation is applied, the subject puts more weight on his unimpaired (left) side during assessments 1, 2 and 3. Only during the final assessment is the weight distribution more balanced, with a slightly larger force under the impaired leg.

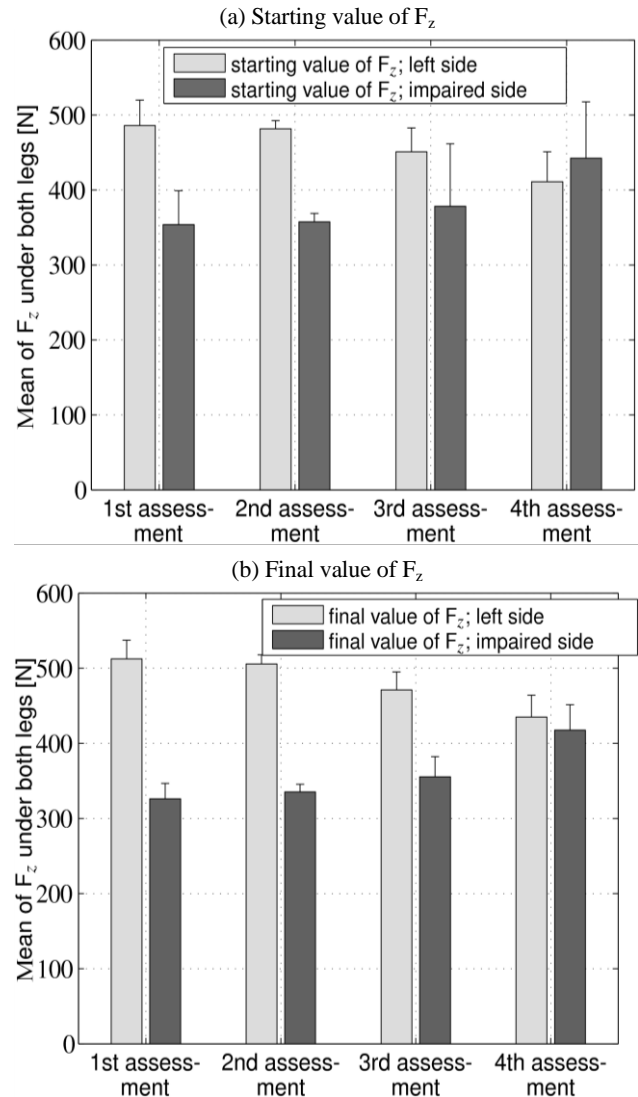


Figure 5. Bar plots of the starting and the final values of the vertical force F_z with the corresponding standard deviations (whiskers) regarding the 16 repetitions of the vertical forces measured under both feet during the four assessments. The subject was perturbed to the right.

3.1.3 Centre of pressure

Figure 6 shows the position of the centre of pressure (CoP) obtained from averaged measurements during each of the four assessments. The corresponding upper limits for the standard deviation values are summarized in Table 4.

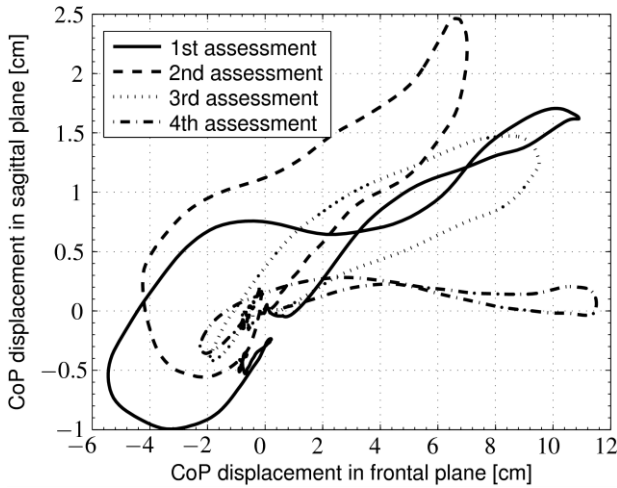


Figure 6. Change in the CoP after the subject had been perturbed to the right; measured during all four assessments.

Table 4. Upper limits of deviation values of the CoP in frontal (CoP_x) and sagittal (CoP_y) plane for every assessment, as shown in Figure 7.

Assessment	Standard deviation CoP _x [cm]	Standard deviation CoP _y [cm]
1	<0.91	<1.6
2	<0.86	<2.1
3	<0.57	<1.9
4	<0.52	<1.9

The shape of the CoP distribution during the 1st and 2nd assessments (solid and dashed lines) is similar, with a relatively large forward movement and a significant overshoot in the direction opposite to the perturbation.

After two weeks of training (3rd assessment, dotted line in Figure 6) the subject was still moving slightly to the front as he was perturbed to the right. During the return to the starting position, however, the movement backwards and to the left is reduced. The final assessment (dash-dotted line in Figure 6) shows a straight movement to the right, with only a small movement to the front and back as the subject reacts to the perturbation.

The results reported in Table 4 show that the peak standard deviations of the CoP in the frontal plane decrease after assessment 2. This confirms that the balancing performance becomes more consistent throughout the training programme which starts following the 2nd assessment. The standard deviations of the CoP in the sagittal plane remain unaffected throughout the programme.

The characteristic values defined in section 2.6.1 were analysed using the methods described previously. Figure 7 shows the means (marked with a circle) of the characteristic values, together with their standard deviations (marked by the whiskers). The groups of measurements which are not significantly different from other groups are presented as thin lines, whereas those which are statistically significantly different are marked bold.

3.2 EMG measurements

In order to evaluate the extent to which training influences the recruitment of the muscle groups of the impaired leg, EMG data recorded from the right leg during

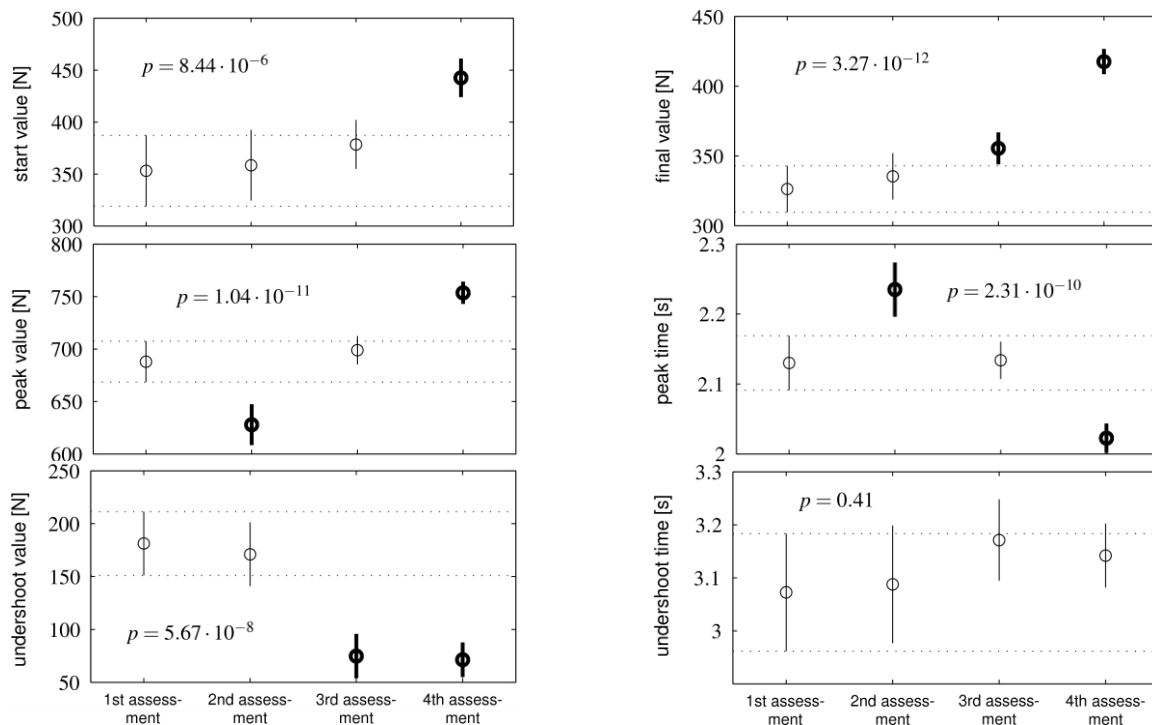


Figure 7. Statistical evaluation of the various characteristic values measured on the impaired side. Variables which are statistically significantly different are marked bold. Significance indicated when $p < 0.05$.

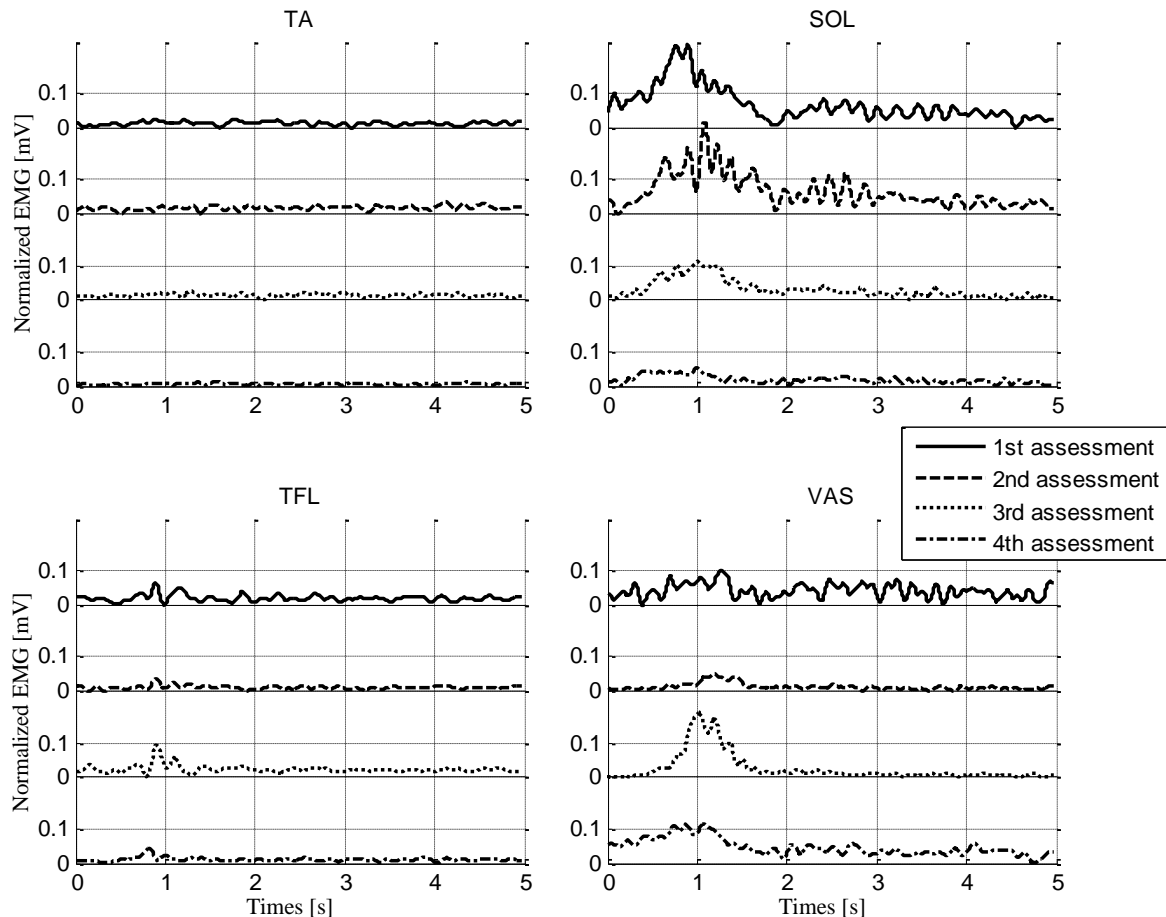


Figure 8. Average normalized EMG signals measuring the activities of TA, SOL, TFL, and VAS muscle groups of the right leg during all the assessments. The subject was perturbed to the right.

perturbations to the front, back and right were analysed. During perturbations to the front and back, we expect that the shank muscles will be used, while during perturbations to the right, mainly the hip muscles will be involved in helping the subject to recover from a perturbation. The knee joint was slightly flexed (ie. not hyper-extended) throughout the experiments.

No signs of interference from environmental disturbances or the electric motors could be observed in the recorded EMG signals. Data shown are averaged over the 16 rounds of perturbations which constituted one assessment.

3.2.1 Perturbation to the right

Figure 8 shows the EMG data recorded during the four assessments as the subject was perturbed to the right. The main muscle group involved in counterbalancing the perturbation to the right is the TFL muscle group. Figure 8 shows a slight activation during the first, third and fourth assessments in this muscle group.

As shown in Figure 6, the subject moved slightly to the front during the first three assessments as he was perturbed to the right. This can be clearly seen in Figure 8, as the EMG signals of the soleus muscle group (SOL), which stabilizes the movement to the front, indicate activity. As the subject is successfully able to avoid movement to the front during the final assessment, no activation of SOL can be observed. This

also coincides with a more even distribution of the subject's weight between left and right leg during this assessment (see Figure 5).

The activation peak in the EMG data of the VAS muscle during the third assessment indicates that the subject tended to extend his knee in response to the perturbation. As the perturbation was directed towards the right, the tibialis anterior (TA) was, as expected, not active.

3.2.2 Perturbation to the front

Figure 9 shows the EMG data measured during all four assessments as the subject was perturbed to the front.

Stabilization of the body during perturbations to the front mainly involves the SOL muscle group, while the TA muscle group is not activated. Activation of the VAS muscle group during the 1st assessment indicates that the subject extended his knee. During the subsequent assessments the VAS muscle group remained inactive. In Figure 9, a distinct activation of the SOL muscle group during the first three assessments can be seen which might correspond to knee flexion in response to the perturbation. This is reduced during the last assessment. The activation of the TFL muscle group indicates that the subject moved not only to the front but to the right as well.

3.2.3 Perturbation to the back

Figure 10 shows the EMG data obtained during the assessments as the subject was perturbed to the back.

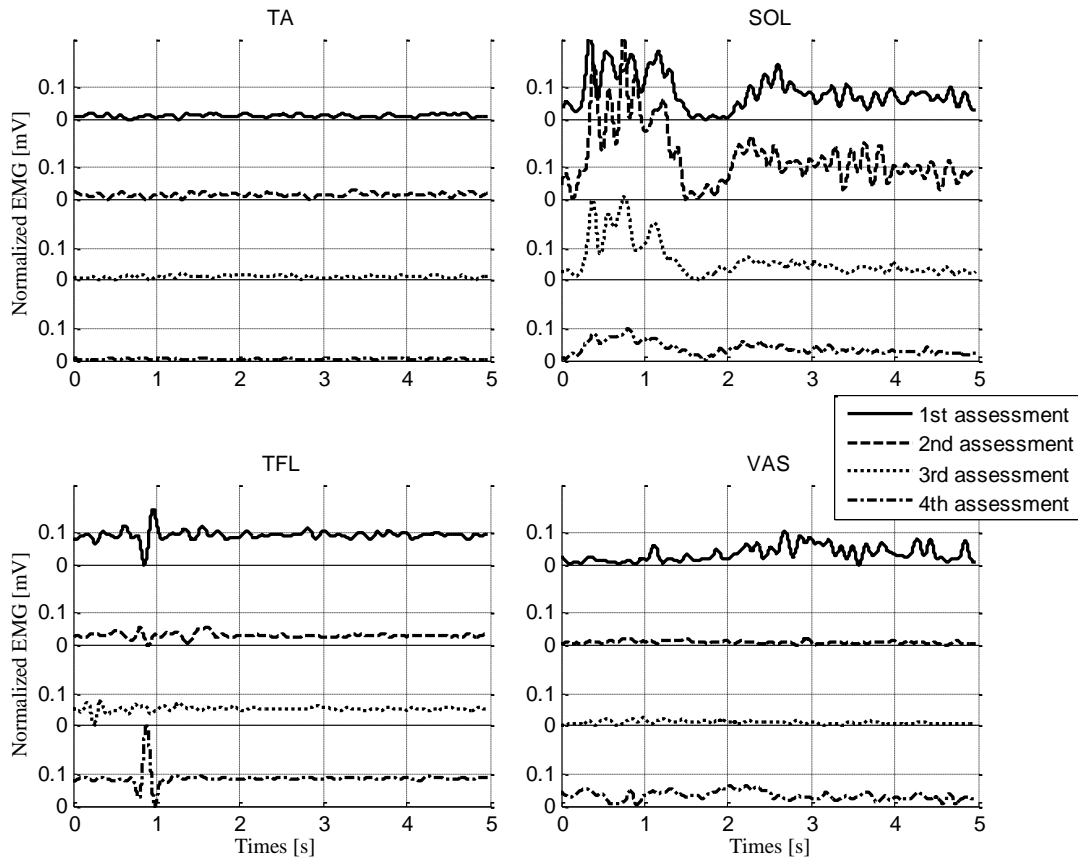


Figure 9. Average normalised EMG signals measuring the activities of TA, SOL, TFL, and VAS muscle groups of the right leg of all the assessments. The subject was perturbed to the front.

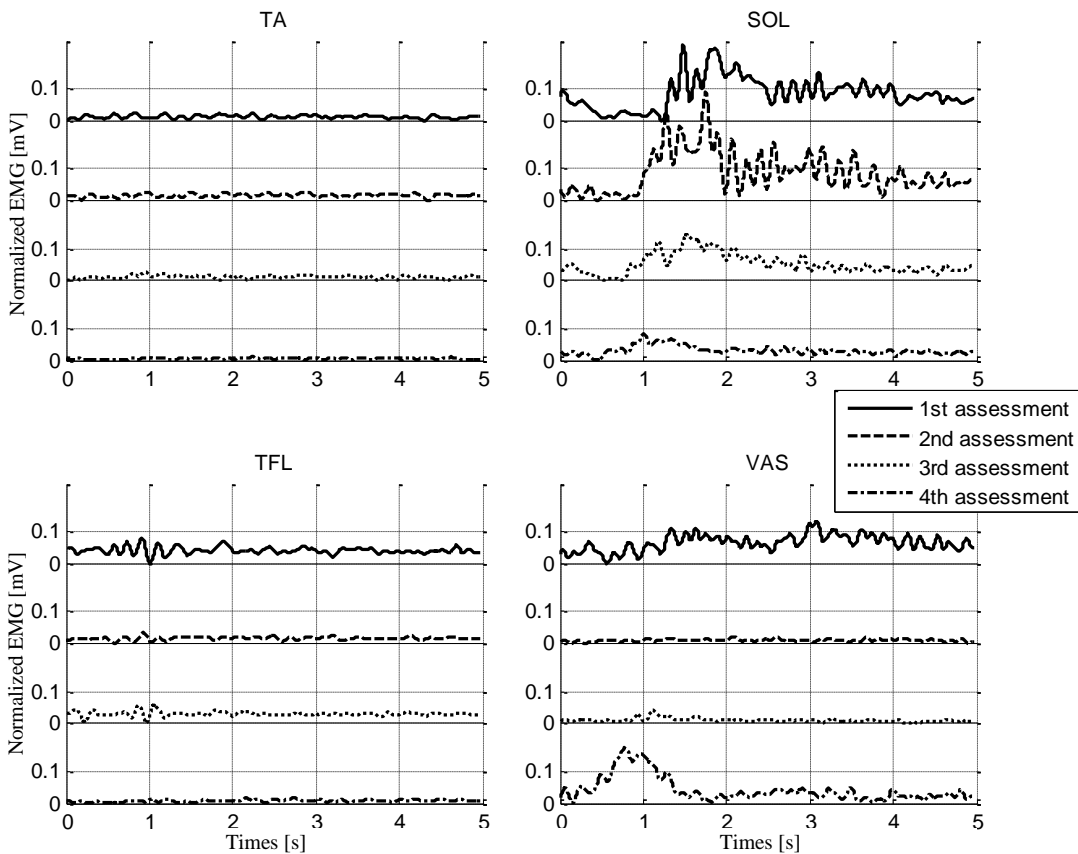


Figure 10. Average normalized EMG signals measuring the activities of TA, SOL, TFL, and VAS muscle groups of the right leg of all the assessments. The subject was perturbed to the back.

During perturbations to the back, the TA and VAS muscle groups should be activated. Figure 10 shows a clear activation of the VAS only during the last assessment, while the subject did not activate the TA muscle group during any of the four assessments.

The results recorded during the first two assessments give a clear sign of SOL activity, which shows that the subject moved not only to the back due to the perturbation but later to the front as he returned to the upright position. The TFL muscle group was active during the first assessment but was no longer in use during later assessments. In the 4th assessment, the VAS is active before the SOL which indicates that the subject extended his knee in response to the perturbation before recovering.

4. Discussion

The result show that throughout the training program, changes in ground reaction forces and in the muscle activation did occur, with effects on the subject's ability to balance.

4.1 Statistical analysis of force data

The force trajectory data shown in Figure 4 indicate that the vertical forces during the recovery from the perturbation were reduced throughout the training period. Analysis of the characteristic values (cf. Figure 7) shows that all characteristic values, except for the undershoot time, had changed significantly during the final assessment.

The start value (top left plot in Figure 7) indicates how much weight is initially placed on the impaired leg. As confirmed in Figure 5, the subject shifted more weight onto the unimpaired side during the first 3 assessments. The significant increase in this value during the final assessment shows that the subject was confident to distribute his weight more evenly between the two legs. Note, that although the data shown here focus on perturbations to the right, the subject was perturbed randomly and could therefore not anticipate the direction of a perturbation.

Similarly to the start value, the final values of the vertical force (F_z) measured under the right foot (top right plot in Figure 7) show a significant change during the last two assessments which show that the subject used his impaired leg more than at the beginning of the experiments. Changes in peak value and times (middle plots in Figure 7) are inconclusive and cannot be attributed to the training progress, as they are mainly a direct result of the perturbation application. However, a significant reduction in peak time during the final assessment indicates that the subject was able to counteract the perturbation faster, probably as a result of the more favourable initial weight distribution. While the undershoot time (bottom right plot in Figure 7) did not change significantly throughout the assessments, the undershoot value (bottom left plot) decreased significantly during the last two assessments. This shows that the subject put less weight onto the left (unimpaired) leg as he was returning to the initial position, which indicates that the perturbation was counteracted more accurately and that his balance improved.

This analysis indicates that the subject's ability to balance improved significantly over the course of training, together with the confidence to put more weight onto the impaired leg. The improved balance ability is a result of a combination of improved ability in the affected leg, together with better coordination and integration with upper body movement. Observation of the subject during the assessments gave the impression that he was more at ease at the very end of the experimental period than during the first sessions.

4.2 Analysis of EMG Data

The EMG data presented in Figures 8-10 show a tendency of reduction in muscle activity in response to the perturbation following the intervention period. It appears that during the course of training, the subject develops a strategy of muscle activation which allows him to react to the perturbation in a more efficient way. This might be due to the fact that better coordination between leg muscle groups and with the upper body may allow the subject to reduce the contribution from the leg muscles. The change in CoP trajectory shown in Figure 6 also indicates that the improved balancing skills lead to a decreased movement of the CoP and, consequently, decreased EMG activity.

The responses in the SOL muscle group indicate that over the intervention period a strategy is developed in response to perturbations to the front which reduces the effort of this muscle group (cf. Figure 9). As Figure 10 shows, the subject is not able to activate his TA muscles as there is no sign of contraction in the EMG data. This also can be seen in the fact that the subject's foot still dropped after the experiments were concluded. Although the EMG data presented here give some indications of neuromuscular adaptations following the training period, the results remain overall inconclusive. It may be necessary to include activity at the hip in the analysis to obtain a more complete picture of the activity following perturbations.

4.3 Balance training and sensory electrical stimulation

After the first two weeks of training, the subject showed more confidence in shifting his body weight onto the impaired leg as the vertical force measured under the right foot increased significantly compared to the values measured during the first two assessments (see Figures 4(b) and 7). This suggests that using balance training for rehabilitation in chronic stroke could improve confidence during standing and walking and reduce the risk of falling.

Our findings show the largest improvements in balance ability during the final training period, when sensory electrical stimulation combined with the use of a rehabilitation assisting device, the modified BalanceTrainer, was applied. While the value of the undershoot remained unchanged during the final training period, the start and final value of the vertical force continued to improve and were significantly different from the results using the rehabilitation assisting device only (see Figure 7). In addition, the CoP displacement (cf. Figure 6) illustrates that the subject was able to counteract the

perturbation after the final training period in a more confident and precise way, without significant movement to the front which was still present at the 3rd assessment.

This study shows that the active balance training is a rehabilitation technique which may be combined with sensory stimulation. While it illustrates the feasibility of combining active balance training with sensory electrical stimulation, the limitation to a single subject case does not allow us to attribute the improvements during the final training period to the added electrical stimulation. It indicates, however, that adding electrical stimulation may benefit the outcome of the rehabilitation program.

The primary aim of the electrical stimulation used in this study was to provide sensory input to aid neurological rehabilitation. Transcutaneous electrical stimulation will, however, affect both sensory and motor neurons. While the stimulation level was chosen in such a way that no superficial muscle contraction could be observed, the stimulation may still have activated motor units and therefore acted not solely as sensory stimulation. More detailed neurophysiological assessments would need to be conducted to ascertain the precise effect of the stimulation on the different sensory and motor pathways.

While our stimulation procedure as described in Section 2.4 requires the subject to be able to feel the sensation in order to set the stimulation intensity, sensory electrical stimulation may also be applicable in subjects without sensation, but in whom lower sensory pathways are intact. In these subjects, our approach may still lead to peripheral or central neural adaptations as a result of afferent inputs elicited by stimulation [29].

5. Conclusions

In this case study, a new training approach for chronic stroke patients was introduced combining sensory electrical stimulation with active balance training using the modified BalanceTrainer. Before the training started, the balance performance of the subject was assessed.

Measurements of vertical forces under the subject's feet show that the subject improved balance over the course of training, with the biggest change seen during the final assessment following a training period with applied sensory stimulation. This may suggest that this type of stimulation can enhance the outcome of dynamic balance training. Further investigations with a larger subject group together with a training regime which randomizes the order of training with or without electrical stimulation are needed to verify this hypothesis. A further suggestion for future studies would be to record the kinematics of the subject's lower and upper limbs as well as of the upper body and the movement of the pelvis, in addition to the force data. While making the experimental setup more complex, these measurements would give a more detailed picture of the changes in performance, allowing to analyze the changes in the upper body movement. The EMG responses did not show whether the stimulation had an effect on neural adaptations leading to a reactivation of the paralysed muscles.

While conclusions drawn from the results in this case study are limited and at this stage cannot be generalized, evidence in the literature suggests that sensory electrical stimulation can modulate the neural motor circuitry after neurological impairment [29] and appears to be a valuable addition to training programs [30]. Future experiments performed in a clinical setting with a larger subject group, using the methods and techniques introduced here, might give an answer to the question of whether balance training with sensory stimulation consistently improves balance performance in this population, while additional neurophysiological assessments would be necessary to verify the source of any adaptation observed.

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References

- [1] Scottish Intercollegiate Guidelines Network, *Management of Patients with Stroke: Rehabilitation, Prevention and Management of Complications, and Discharge Planning*, 2002.
- [2] S. Hesse and D. Uhlenbrock, "A mechanized gait trainer for restoration of gait," *J. Rehabil. Res. Dev.*, 37: 701-708, 2000.
- [3] R. Mahoney, "Robotic products for rehabilitation: status and strategy", *Proc. of ICORR*, 12-22, 1997.
- [4] N. Hogan, H. I. Krebs, J. Charnmarong, P. Srikrishna and A. Sharon, "MIT-MANUS: a workstation for manual therapy and training. I," *Proc. IEEE Int. Workshop Robot Human Communication*, 161-165, 1992.
- [5] M. L. Aisen, H. I. Krebs, N. Hogan, F. McDowell and B. T. Volpe, "The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke," *Arch. Neurol.*, 54: 443-446, 1997.
- [6] H. I. Krebs, N. Hogan, M. L. Aisen and B. T. Volpe "Robot-aided neurorehabilitation," *IEEE Trans. Rehab. Eng.*, 6: 75-87, 1998.
- [7] S. Hesse, D. Uhlenbrock, C. Werner and A. Bardeleben, "A mechanized gait trainer for restoring gait in nonambulatory subjects," *Arch. Phys. Med. Rehabil.*, 81: 1158-1161, 2000.
- [8] S. Jezernik, G. Colombo, T. Keller, H. Frueh and M. Morari, "Robotic orthosis lokomat: a rehabilitation and research tool," *Neuromodulation*, 6: 108-115, 2003.
- [9] Z. Matjačić, S. Hesse and T. Sinkjær, "BalanceReTrainer: a new standing-balance training apparatus and methods applied to a chronic hemiparetic subject with a neglect syndrome," *NeuroRehabilitation*, 18: 251-259, 2003.
- [10] B. T. Volpe, H. I. Krebs, N. Hogan, L. Edelstein, C. Diels and M. Aisen, "A novel approach to stroke rehabilitation: robot-aided sensorimotor stimulation," *Neurology*, 54: 1938-1944, 2000.
- [11] M. Ferraro, J. J. Palazzolo, J. Krol, H. I. Krebs, N. Hogan and B. T. Volpe, "Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke," *Neurology*, 61: 1604-1607, 2003.
- [12] H. Krebs, M. Ferraro, S. Buerger, M. Newbery, A. Makiyama, M. Sandmann, D. Lynch, B. Volpe and N. Hogan, "Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus," *J. NeuroEng. Rehabil.*, 1: 5, 2004.
- [13] Z. Matjačić, Š. Rusjan, I. Stanonik, N. Goljar and A. Olenšek, "Methods for dynamic balance training during standing and stepping," *Artif. Organs*, 29: 462-466, 2005.
- [14] E. C. Field-Fote, "Electrical stimulation modifies spinal and cortical neural circuitry," *Exerc. Sport Sci. Rev.*, 32: 155-160,

- 2004.
- [15] S. Hesse, C. Werner and A. Bardeleben, "Electromechanical gait training with functional electrical stimulation: case studies in spinal cord injury," *Spinal Cord*, 42: 346-352, 2004.
- [16] R. K. Tong, M. F. Ng, L. S. Li and E. F. M. So, "Gait training of patients after stroke using an electromechanical gait trainer combined with simultaneous functional electrical stimulation," *Phys. Ther.*, 86: 1282-1294, 2006.
- [17] R. K. Tong, M. F. Ng and L. S. Li, "Effectiveness of gait training using an electromechanical gait trainer, with and without functional electric stimulation, in subacute stroke: a randomized controlled trial," *Arch. Phys. Med. Rehabil.*, 87: 1298-1304, 2006.
- [18] L. Nyberg and Y. Gustafson, "Patient falls in stroke rehabilitation: a challenge to rehabilitation strategies," *Stroke*, 26: 838-842, 1995.
- [19] A. Forster and J. Young, "Incidence and consequences of falls due to stroke: a systematic inquiry," *Br. Med. J.*, 311: 83-86, 1995.
- [20] Y. Tekeoğlu, B. Adak and T. Göksoy, "Effect of transcutaneous electrical nerve stimulation (TENS) on Barthel Activities of Daily Living (ADL) index score following stroke," *Clin. Rehabil.*, 12: 277-280, 1998.
- [21] L. Sonde, C. Gip, S. E. Fernaeus, C. G. Nilsson and M. Viitanen, "Stimulation with low-frequency (1.7 Hz) Transcutaneous Electric Nerve Stimulation (low-TENS) increases motor function of the post-stroke paretic arm," *Scand. J. Rehabil. Med.*, 30: 95-99, 1998.
- [22] L. Sonde, H. Kalimo, S. E. Fernaeus and M. Viitanen, "Low TENS treatment on post-stroke paretic arm: a three-year follow-up," *Clin. Rehabil.*, 14: 14-19, 2000.
- [23] D. Skeil and A. C. Thorpe, "Transcutaneous electrical nerve stimulation in the treatment of neurological patients with urinary symptoms," *BJU Int.*, 88: 899-908, 2001.
- [24] I. Cikajlo and Z. Matjačić, "A novel approach in objective assessment of functional postural responses during fall-free perturbed standing in clinical environment," *Technol. Health Care*, 15: 181-193, 2007.
- [25] P. Konrad (Ed.), *The ABC of EMG: A Practical Introduction to Kinesiological Electromyography*, Scottsdale, AZ: Noraxon Inc., 2005.
- [26] D. A. Winter, "Human balance and posture control during standing and walking," *Gait Posture*, 3: 193-214, 1995.
- [27] G. F. Phillips, J. R. Adler and S. J. G. Taylor, "A portable programmable eight-channel surface stimulator," *Proc. Ljubljana FES Conf.*, 166-168, 1993.
- [28] Y. Hochberg and A. C. Tamhane (Eds.), *Multiple Comparison Procedures*, New York: Wiley, 1987.
- [29] E. C. Field-Fote, "Electrical stimulation modifies spinal and cortical neural circuitry," *Exerc. Sport Sci. Rev.*, 32: 155-160, 2004.
- [30] K. S. Beekhuizen and E. C. Field-Fote, "Sensory stimulation augments the effects of massed practice training in persons with tetraplegia," *Arch. Phys. Med. Rehabil.*, 89: 602-608, 2008.
- [31] G. Worms, Z. Matjačić, H. Gollee, I. Cikajlo, N. Goljar and K. J. Hunt, "Dynamic balance training with sensory electrical stimulation in chronic stroke patients," *28th Ann. Int. Conf. of the IEEE Engineering in Medicine and Biology Society*, 2150-2153, 2006.
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