A METHOD FOR DYNAMIC BALANCE TRAINING COMBINING PERTURBED STANDING WITH SENSORY ELECTRICAL STIMULATION

DINAMIČNO URJENJE RAVNOTEŽJA MED STOJO Z UPORABO KOMBINACIJE MOTILNIH SUNKOV IN ELEKTRIČNE STIMULACIJE

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Abstract

Background:

Dynamic balance training is an important treatment modality after stroke. We propose a novel method for balance training that utilises sensory electrical stimulation during perturbed stance in subjects with neurological impairment. The feasibility of this methodology is investigated in a case study with one chronic stroke patient.

Methods:

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.

Results:

The subject improved his ability to balance throughout the training, with the largest improvements occurring

Izvleček

Izhodišča:

Dinamično urjenje ravnotežja je pomembna terapevtska metoda za bolnike po možganski kapi. V članku predlagamo novo metodo za urjenje ravnotežja, ki vključuje senzorično električno stimulacijo, aplicirano sočasno s posturalnimi odzivi med stojo. Uporabnost predlagane metode smo preizkusili v študiji primera z osebo po preboleli možganski kapi v kronični fazi.

Metode:

Napravo za dinamično vzdrževanje ravnotežja smo izpopolnili tako, da smo vanjo vgradili električne motorje, ki omogočajo izvajanje mehanskih sunkov med stojo. Oseba, ki je v študiji sodelovala, je vadila posturalne odzive med dvema različnima, deset dni trajajočima obdobjema. V prvem obdobju je naprava izvajala motilne sunke v osmih različnih smereh transverzalne ravnine. V drugem obdobju pa smo dodali še senzorično električno stimulacijo, ki smo jo aplicirali na kožo, ki pokriva naslednje mišice okvarjenega spodnjega uda: soleus (SOL), tibialis anterior (TA), tensor fascia latae (TFL) in vastus (VAS). Po vsakem vadbenem obdobju smo merili posturalne odzive z dvema pritiskovnima ploščama ter z EMG odzivi mišic SOL, TA, TFL in VAS.

Rezultati:

Oseba, ki je v študiji sodelovala, je svoje sposobnosti za vzdrževanje ravnotežja izboljšala med celotnim obdobjem urjenja, največje izboljšanje pa smo ugotovili v drugem obdobju, ko smo aplicirali še senzorično električno stimulacijo.

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during the final period when sensory electrical stimulation was used.

Conclusion:
These observations verify the feasibility of the approach and suggest that sensory electrical stimulation may have beneficial effects on balance training.

Key words:
sensory electrical stimulation, dynamic balance training, perturbed stance

Zaključki:
Ugotovitve potrjujejo uporabnost predlaganega pristopa in kažejo, da ima lahko senzorična električna stimulacija pozitiven učinek na urjenje vzdrževanja ravnotežja.

Ključne besede:
senzorična električna stimulacija, dinamično urjenje ravnotežja, posturalni odzivi

INTRODUCTION

Stroke is a world-wide leading cause of disability. Within EU approximatelly 500.000 new cases emerge every year. 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 were developed in order to reduce the physical effort of the therapist as well as the need for human attendants (3), for example, apparatuses like 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), and the Lokomat (8), a robotic orthosis supporting spinal cord injured and chronic stroke patients during treadmill training rehabilitation. Initial results with these devices showed an improvement in rehabilitation outcome (5), (9)–(11).

According to the findings of Field-Fote (12), the spinal and cortical neural circuitry are modified by applied electrical stimulation as the neural circuitry underlying motor performance on a short- and long-term basis is modulated. Studies which combined robotic rehabilitation approaches with functional electrical stimulation (FES) also showed an improvement in rehabilitation outcome (13), (14). However, Tong *et al.* (15) 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 have shown that stroke patients can regain independence in activities of daily life using transcutaneous electrical nerve stimulation (TENS) (16)–(20). 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 (21). Matjačić *et al.* (22) developed a mechanical apparatus called the BalanceTrainer (Medica Medizintechnik, Hochdorf, Germany) which assists physiotherapy personnel in their rehabilitation work with neurologically impaired patients. This device has mainly been used with stroke patients. It is similar to a normal standing frame but in addition allows dynamic balance training and step like movements. Recently Matjačić *et al.* (23) presented a novel training regime for exercising the balance and upright posture of the upper body during standing and stepping, where the subject had to perform several tasks while standing in the BalanceTrainer.

Based on the reported potential benefits of employing assistive devices, we wished to investigate the feasibility of combining BalanceTrainer therapy with sensory transcutaneous electrical nerve stimulation in stroke rehabilitation. 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 only.

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.

METHODS

The modified BalanceTrainer

The BalanceTrainer (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. 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. 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.

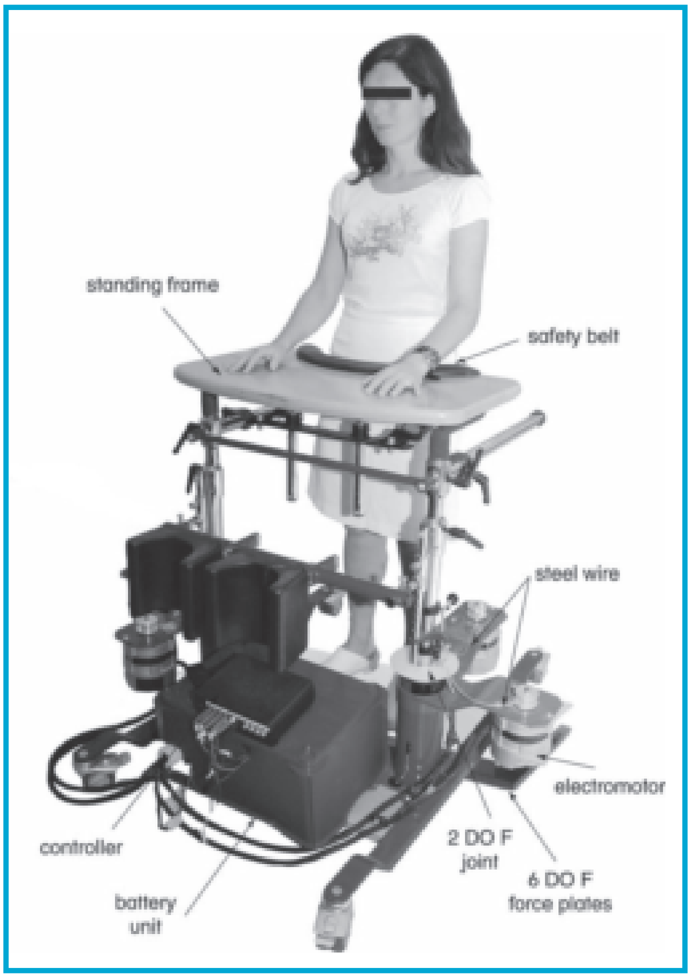


Fig. 1: *The modified BalanceTrainer with electric motors which are used to apply perturbations.*

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 as shown in figure 2. The magnitude of the perturbation depends on the duration for which the motors are active. It was chosen to be 0.6s 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.

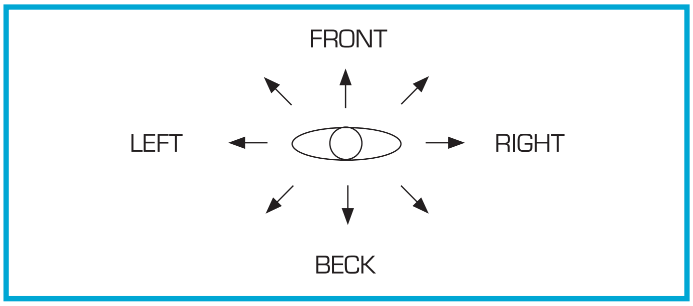


Fig. 2: *Perturbation directions.*

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). He was 19 months post stroke, with impairment affecting his right side, and no longer received physiotherapy treatment at the time of the study. The subject needed no support during quiet standing. He was using an orthosis to prevent foot-drop during gait, which was removed for the training and assessment sessions. The experimental procedures were approved by the Slovenian National Ethics Committee and the subject provided written, informed consent prior to participation.

Measurements

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

$$CoPx = -My/Fz$$
$$CoPy = Mx/Fz\ ,$$

with Mx and My denoting the moments in x- and y-direction and Fz 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™) were used. The data were amplified using a MyoSystem 2000 Amplifier (Noraxon Inc., USA), sampling the data at 1 kHz. EMG data were processed using an anti-aliasing filter and a 4th-order high pass Butterworth filter with a cut-off frequency of 7 Hz.

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. Depending on the direction of perturbation, the muscles which are mainly involved for the recovery of the perturbation were stimulated (see table I). As the subject's right side is 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 (25).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 initiates 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.The most appropriate pulse width was found to be 250μs and was kept constant whereas the current value changed.The starting and finishing times of the stimulation are shown in table II.

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
SOL	0.25	1

To compensate for variations in the placement of the electrodes between training sessions, the current levels of the stimulation signal were adjusted for each muscle group separately. For this, 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 20–40mA was used, while for TA the current level was 40–50mA.

Experimental Protocol

The experimental protocol is summarised in figure 3. 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 re assessed (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 was perturbed in eightdifferent directions (see figure 2) and was asked to react to the perturbations in the way he thought most appropriate.

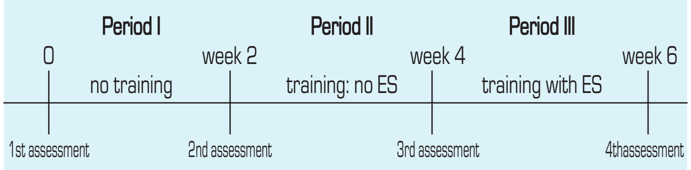


Fig. 3: *The time scale of training using electrical stimulation (ES) in the last training period.*

A *round* of perturbations was 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 approximately 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 peroid III, sensory electrical stimulation was applied using the procedure outlined in previous subsection. 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.

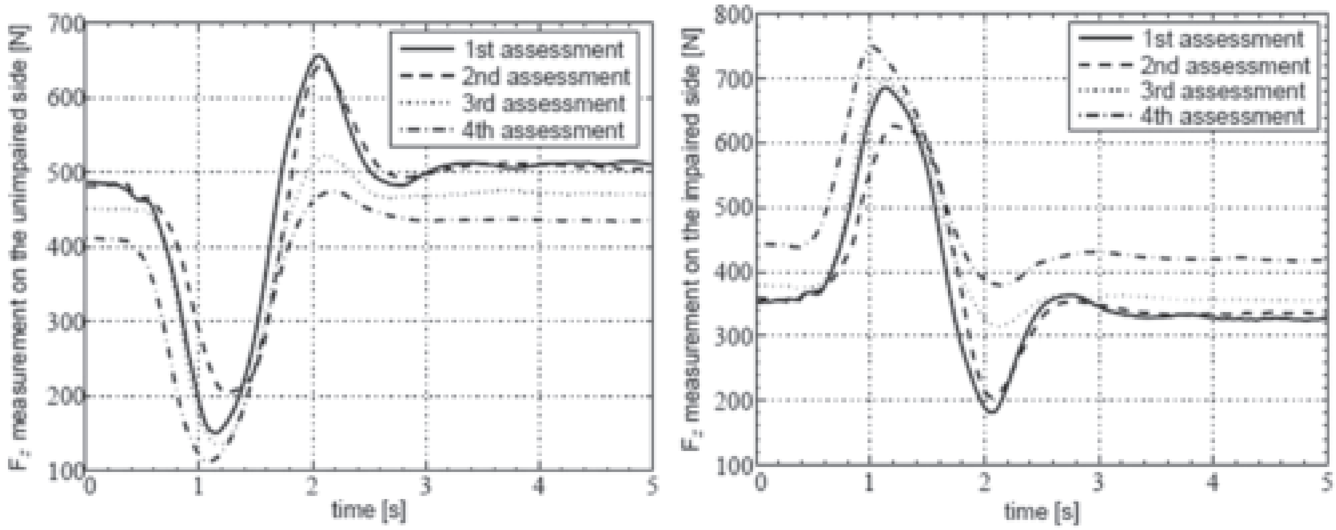
RESULTS

Measurement results reported here were obtained during the four assessment sessions. Corresponding data were averaged over the 16 rounds which constituted one assessment.

Force data

Although the subject was perturbed in eight directions in each assessment (as shown in figure 2), 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.

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 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 Fz 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. On the impaired side, the initial period of constant force is followed by an increase in Fz 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.



(a) Vertical force F_z on the unimpaired (left) side.

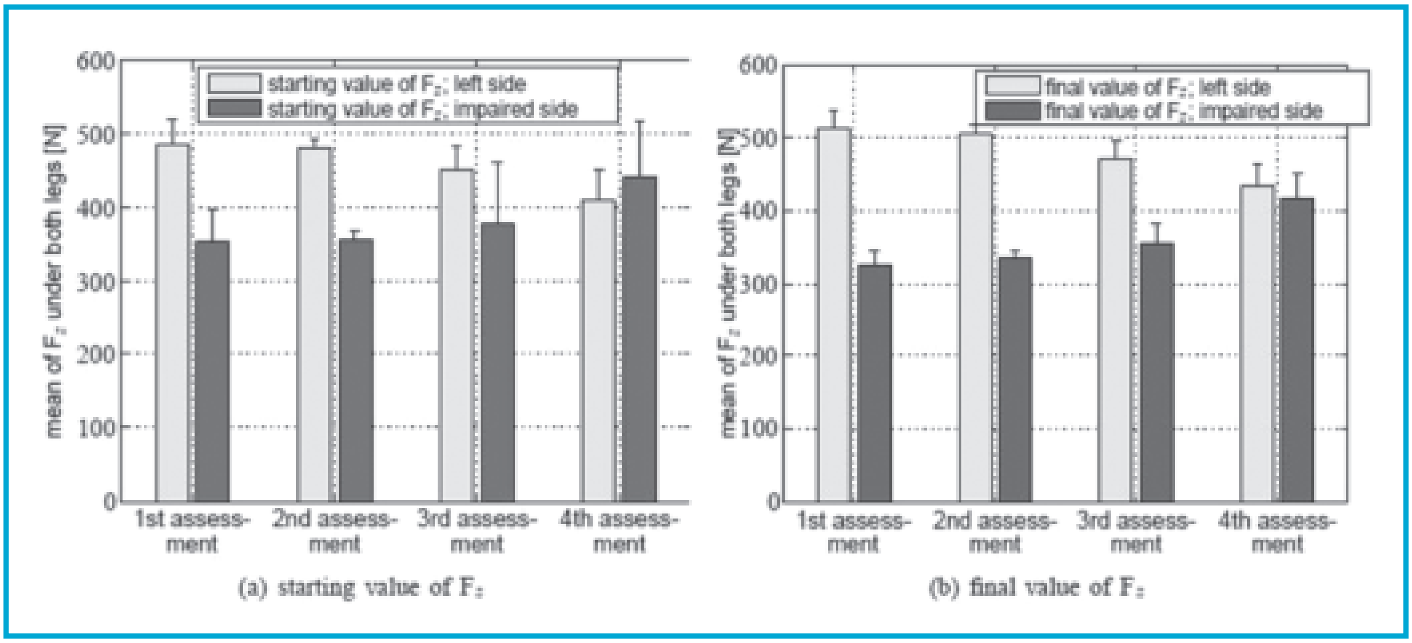
(b) Vertical force F_z on the impaired (right) side.

Fig. 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 0s.*

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 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(a)) 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.

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 Fz 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 5(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 slighly larger force under the impaired leg.

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 shape of the CoP distribution during the 1st and 2nd assessments (solid and dashed lines) is similar, with a relatively large foreward 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



(a) starting value of F_z

(b) final value of F_z

Fig. 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.*

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.

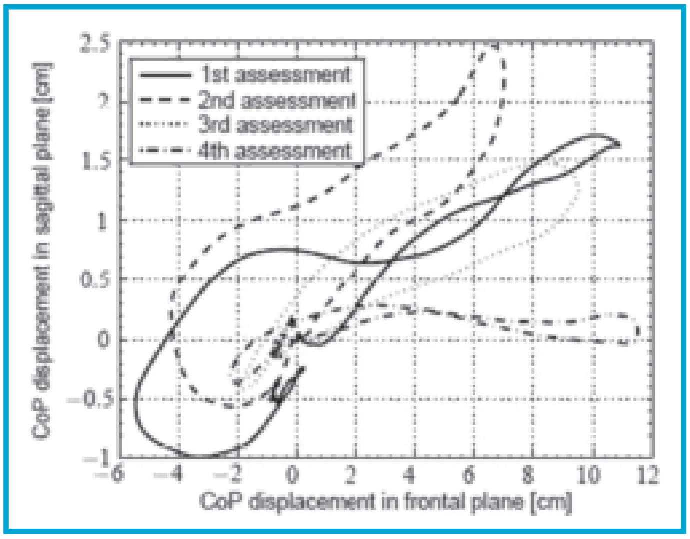


Fig. 6: *Change in the centre of pressure (CoP) after the subject had been perturbed to the right; measured during all four assessments.*

EMG measurements

In order to evaluate to which extent training influences the recruitment of the muscle groups of the impaired leg, EMG data recorded from the right leg during perturbations to the right were analysed. 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 comprise each assessment. Note that, the offset in the EMG measurements originates from the fact that the muscles could not be totally inactive as the subject is maintaining his posture. Furthermore, the EMG electrodes could not be placed each time at exactly the same positions and the conductivity of the body tissue changes from assessment to assessment (26). As a consequence, the measurements of the activity of the same muscle group show different offsets at different assessments.

Figure 7 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 7 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 7, as the EMG signals of the soleus muscle group (SOL), which stabilises the movement to the front, indicate activity whereas during the final assessment no activation of this muscle group is seen. The activation peak in the EMG data of the VAS muscle during the third assessment indicates that the subject tended to lock his knee. As this was a perturbation to the right the tibialis anterior (TA) was, as expected, not active.

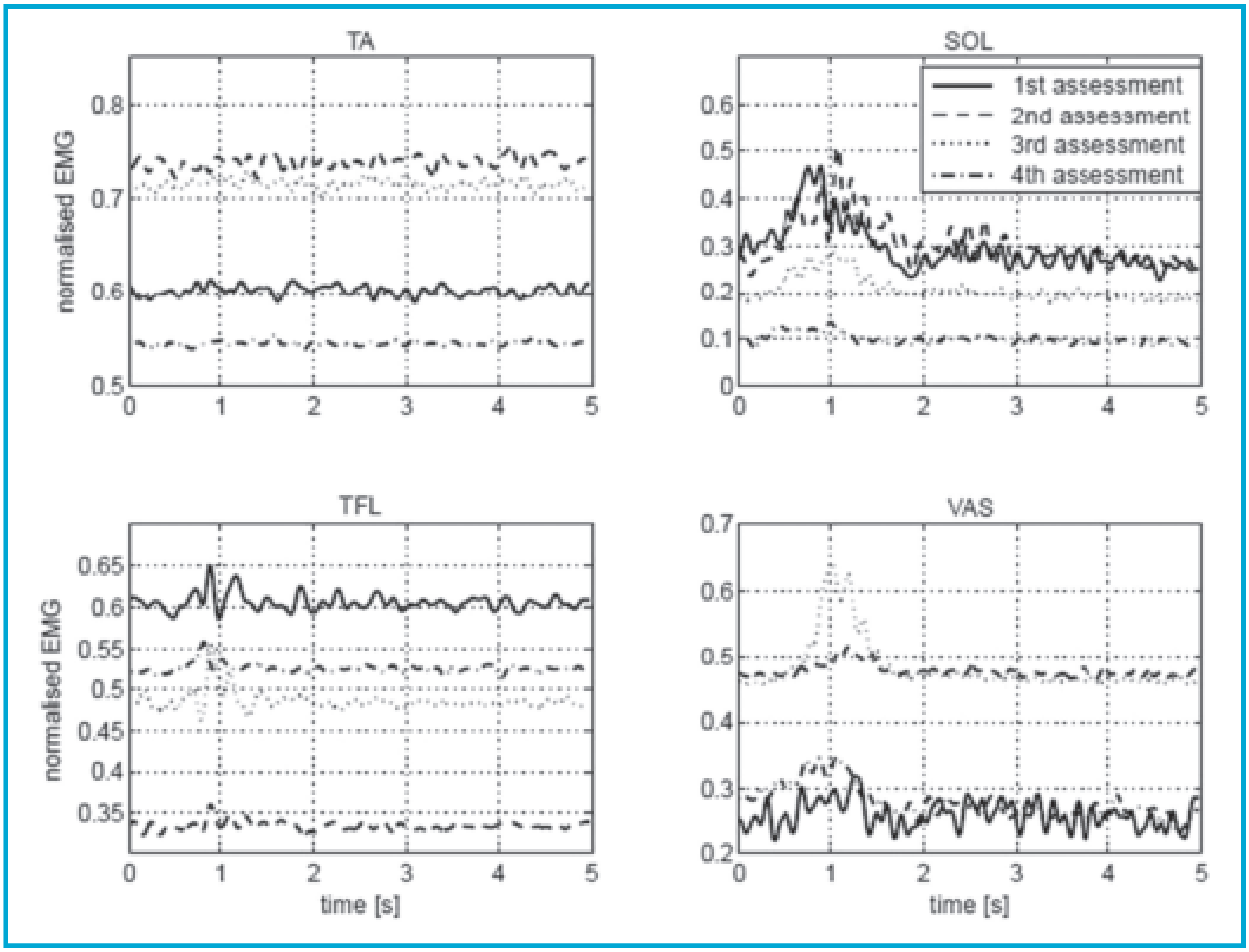


Fig. 7: *Average normalised measurements of the EMG signal measuring the activities of TA, SOL, TFL, and VAS muscle groups of the right leg during all the assessments. The subject was perturbed to the right.*

DISCUSSION

The result show that throughout the training programme, changes in ground reaction forces and in the muscle activation did occur, with effects on the subject's ability to balance. The force trajectory data shown in Reults section indicate that the vertical forces during the recovery from the perturbation were reduced throughout the training period. As figure 5(a) shows, 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. 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.

The EMG data show that during the course of training the subject develops a strategy of muscle activation in order to react to the perturbation in a more efficient way. The responses in the SOL muscle group in figure 7 show that during the course of training the subject developed a way to respond to perturbations in such a way that the effort of this muscle group is reduced. As figure 7 indicates, 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.

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 figure 4b). 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. In addition, the CoP displacement (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. While this study illustrates the feasibility of combining active balance training with sensory electrical stimulation, the limitation to a single subject case does not allow 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 programme.

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 Balance Trainer. 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 improves 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 randomises the order of training with or without electrical stimulation are needed to verify this hypothesis.

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