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Dynamic balance training with sensory electrical stimulation in chronic stroke patients

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Abstract— **A case study investigating the impact of sensory electrical stimulation during perturbed stance in one chronic stroke patient is presented.**

A special apparatus called the BalanceTrainer was used. It allows the application of 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, tibialis anterior, tensor fascia latae, and vastus muscles 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. The subject improved his ability to balance throughout the training, with the largest improvements during the final period when electrical stimulation was used.

I. INTRODUCTION

A. Background

In Scotland approximately 15,000 people suffer strokes for the first time with approximately 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.

A common problem stroke survivors face is falls due to balance impairment [2], [3]. As a consequence, patients reduce their activity level which again has a negative effect on the rehabilitation outcome and the quality of life in general. To overcome this problem, the major task is to improve the ability to balance and to increase confidence in being able to perform everyday activities. The traditional method of rehabilitation combines different neuro-therapeutic techniques and methods with strength training using occupational therapy and physiotherapy. These approaches focus mainly on the strengthening of the legs and neglect the fact that the ability to balance using the upper body is just as important. Matjačić *et al.* [4] presented a novel approach to train the balance and upright posture of the upper body during standing and stepping, where the subject had to perform several tasks during standing using the “BalanceReTrainer” [5].

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In this paper we investigate whether a chronic stroke patient improves his ability to balance as he is being perturbed while additional sensory electrical stimulation is applied.

II. METHODS

A. The Standing Frame

Matjačić *et al.* [6], [7] developed a device known as the **M**ultipurpose **R**ehabilitation **F**rame (MRF). This frame was designed for experiments with spinal cord injured subjects using hydraulic actuators to support them during standing. The hydraulic actuators also allowed the application of perturbations. The use of hydraulic actuators gave very precise adjustment of the supporting stiffness, which was important for research purposes but is not really necessary for everyday rehabilitation. The use of electrical stimulation of the paralysed lower limbs in combination with the MRF was investigated by Jaime *et al.* [8].

Clinicians showed interest in the potential of the MRF in rehabilitation not only for paraplegic patients, but also for stroke patients. However, the hydraulic components make the machine difficult to handle for nontechnical staff, it is bound to one fixed location close to a hydraulic pump, and the noise level of the hydraulic pump makes it difficult to use for long periods of time.

In order to make the standing frame mobile and easier to use, the MRF was modified and tailored for the purposes of physiotherapy personnel. The hydraulic system was replaced by springs providing the required supporting stiffness which can be adjusted continuously. The outcome of the mechanical changes resulted in a device called the BalanceTrainer (Medica Medizintechnik, Germany), as described in [5].

In order to apply perturbations, we modified the BalanceTrainer by fitting four electric motors (two at each side) which are connected via ropes to the frame (see figure 1). To perturb the frame in a certain direction the appropriate electric motor winds up the rope and pulls the frame out of its upright position.

The subject is secured by a belt attached to the frame. When the frame is perturbed from its upright position the subject standing in the frame is pulled from his/her neutral upright position. While the applied perturbing torque magnitude is constant, the perturbation level can be varied by altering the duration for which the electric motors are active. Three different perturbation levels were used: weak, middle, and strong with the electric motors being active for 0.4, 0.6, and 0.8 s, respectively.

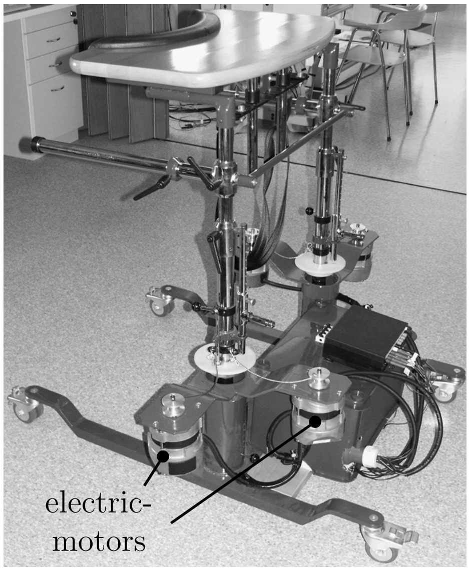

Fig. 1: The BalanceTrainer with electric motors which are used to apply perturbations.

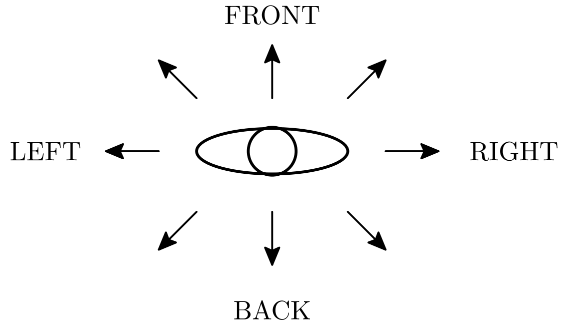

Fig. 2: Perturbation directions.

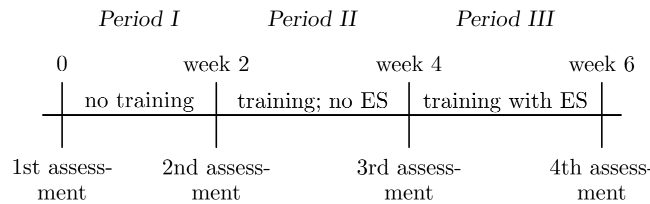

Fig. 3: The time scale of training. Electrical stimulation (ES) was used in the last training session.

B. Measurements

In order to assess changes in ground reaction forces the subject stands on two force plates (AMTI, Massachusetts, USA). Using the measurement of ground reaction forces the force distribution between the two legs as well as changes in the centre of pressure (CoP) can be assessed.

C. Experimental Protocol

The experiments were performed with one chronic stroke patient who no longer receives physiotherapy treatment. The experiments were divided into three different periods (see also figure 3):

- no testing (*Period I*)
- tests *without* electrical stimulation (*Period II*)
- tests *with* electrical stimulation (*Period III*)

The subject was perturbed in eight different directions (see figure 2). The subject was asked to react to the perturbations in a way he thinks is most appropriate. Each experimental session lasted approximately 20 minutes. In this time the subject performed 16 "rounds". A round is completed when the subject has been perturbed in all eight directions. The order of perturbation direction was changed randomly from round to round. The time between the single perturbations varied randomly allowing 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. The tests were performed on a daily basis during periods II and III in addition to the subject's normal daily activities.

The time scale of the overall experimental procedure is shown in figure 3. The experiments start off with an assessment of the subject's baseline balancing performance.

After two weeks without training the performance of the subject was re-assessed. A two-week training session followed, with the subject standing daily for approximately twenty minutes in the frame while being perturbed. After a third assessment the subject underwent a final period of two week's training where this time the soleus (SOL), tibialis anterior (TA), tensor fascia latae (TFL), and vastus (QUAD) muscle groups in the impaired leg were stimulated. The stimulation intensity was adjusted so that the subject could locate which muscle group was being stimulated without having the muscle contracting due to stimulation. At the end of this training period the performance was assessed again. No stimulation was applied during this final test to show the extent to which stimulation throughout the training period helped the subject to improve balance in the absence of supporting stimulation.

direction	TFL	QUAD	TA	SOL
front				✓
back		✓	✓	
right	✓			
front/right	✓			✓
back/right	✓	✓	✓	

TABLE I: Direction of perturbation and stimulated muscle groups for impairment on the right side. The ticks indicate which muscle groups are stimulated. Note that stimulation was only applied to the affected right leg.

Depending on the direction of perturbation, different muscles are stimulated. If the subject's right side is impaired the stimulation is applied only for perturbations in the sagittal and right directions (as shown in table I).

D. Stimulation Parameters

For training Period III starting at week 4 (see figure 3), stimulation was applied using surface electrodes placed on the TA, the SOL, the TFL and the QUAD muscles of the impaired leg. The stimulation was current controlled, monophasic, and charge balanced using the Stanmore Stimulator [9]. The aim was to stimulate for the period of time the subject was trying to return to the starting position after he has been perturbed. The intensity of stimulation was regulated by the pulse width of the stimulation pulses and the current level.

Preliminary tests were used to determine that an appropriate pulse width for stimulation was 250 μs, and to find the optimal duration of stimulation during a trial.

To compensate for variations in the placement of the electrodes between training sessions, the current values of the stimulation signal were adjusted. For this the subject had to feel the stimulation clearly without having the stimulated muscles contracting due to the stimulation. The current values used ranged from 20 to 50 mA.

E. Subject

The participating subject was male, aged 43, 19 months post stroke, with impairment affecting his right side. He was using a prosthesis to prevent the foot dropping during gait. The subject needed no support during quiet standing. For the training sessions the prosthesis was removed.

III. RESULTS

The results shown here are averages of 16 measurements. For clarity only reactions to perturbations towards the right are shown. As this is the subject's impaired side these results will make improvements in the performance most obvious.

A. Comparison of vertical force results

Figure 4 shows a plot comparing the vertical force F_z measured during the four assessments. Comparing the performance of the subject during the first two assessments (see solid and dashed line in figure 4), the plot shows that the starting value, the undershoot value, and the final value are very similar. The only difference is the peak value as the subject is perturbed to the right.

After two weeks of training without electrical stimulation (3rd assessment, dotted line in figure 4), the results do not differ very much from the results measured during the first assessment (solid line), as the starting values, the peak values and final values are nearly the same. The main difference lies in the different undershoot values. When compared to the second assessment (dashed line), however, a higher peak value can also be observed which indicates that the subject was now putting more weight onto his impaired leg.

After another two weeks of balance training, with electrical stimulation, (4th assessment, dashed-dotted line), an increase in starting, peak and final values and a decrease in the undershoot value can be observed when compared to the first three assessments. This indicates that the subject now has more confidence in putting additional weight onto his impaired leg.

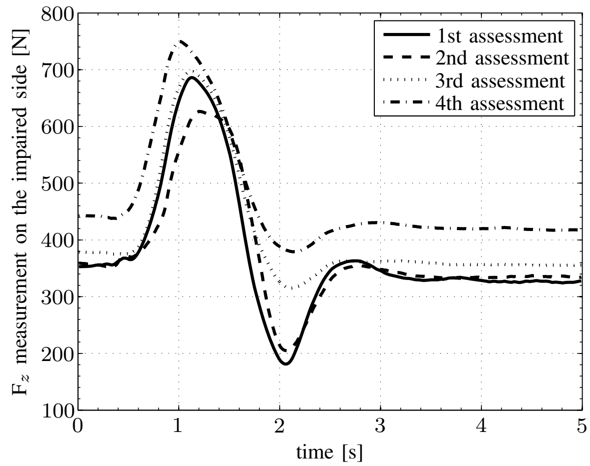

Fig. 4: Vertical force F_z on the impaired side after the subject has been perturbed to the right, measured during the four assessments.

B. Comparison of CoP results

Figure 5 shows the position of the centre of pressure (CoP) obtained from averaged measurements during the four assessments.

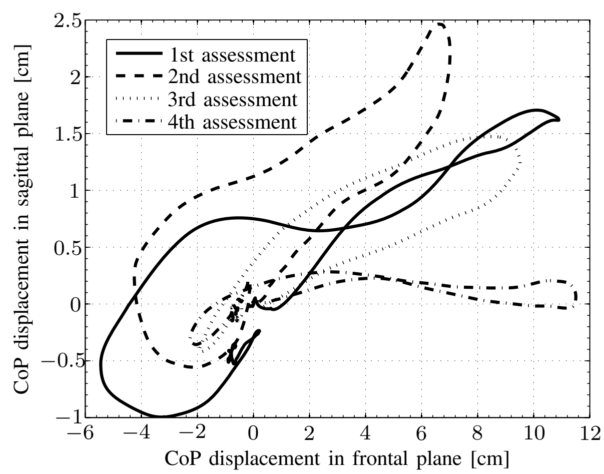

Fig. 5: Change in the centre of pressure (CoP) after the subject has been perturbed to the right, measured during the four assessments

This plot shows that during the first three assessments the subject moved not only to the side but also to the front (see solid, dashed, and dotted lines in figure 5).

Comparing the results of the first two assessments, one can see that the subject moved more to the front during the second assessment than he did during the first assessment. This is also the reason why the peak value during the second assessment (see figure 4) was smaller than during the first assessment.

Figure 5 shows that after two weeks of training (3rd assessment, dotted line) the subject was still moving slightly to the front as he is perturbed to the right. During the return to the starting position, however, the movement backwards is much smaller than it was during the first and second assessment which is also expressed through the reduced undershoot value in figure 4.

The final assessment (dash-dotted line) shows a clear movement to the right with only a small movement to the back as the subject returns to the original position. This is also represented by the reduced undershoot shown for the fourth assessment in figure 4 and indicates increased confidence in shifting the body weight onto the impaired leg.

C. Changes in weight distribution

The bar plot in figure 6 shows the average vertical force F_Z measured under each foot as the subject was perturbed to the right during the four assessments.

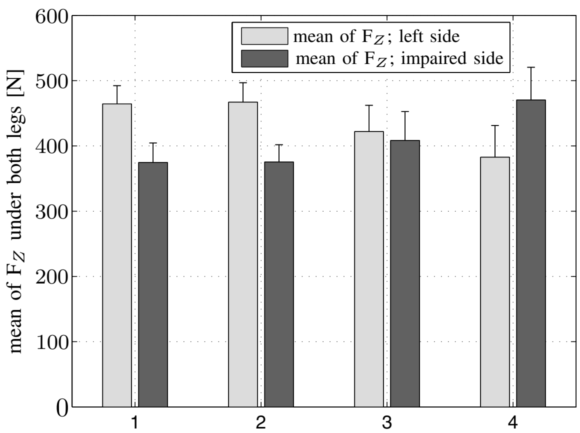

Fig. 6: Mean values (top of bars) and standard deviations (whiskers) of the vertical forces measured under both feet during the four assessments with the perturbation applied to the right.

This plot confirms that during the first and second assessments the subject was imbalanced and put more weight onto his left leg than onto his impaired right leg. After two weeks of training without stimulation the subject distributed his body weight more equally between the two legs (see bars at "3rd assessment" in figure 6). After an additional two weeks of training combined with electrical stimulation the subject shifted his body weight more onto his impaired leg as he is perturbed to the right which corresponds to the behaviour expected from a non-impaired subject.

IV. DISCUSSION

The results presented show a clear improvement in balance over the course of training with the BalanceTrainer. Comparing to the results measured during the first assessment, the amount of body weight the subject shifted onto the impaired leg during the last assessment increased by 25%. This suggests that using balance training for rehabilitation in chronic stroke could improve confidence during standing and walking and reduce the risk of falling.

The largest improvement in balance ability was observed during the final training period, when electrical stimulation was used. However, from this single subject study it is not possible to conclude whether this improvement was due to the applied stimulation or whether these results would be similar if the subject had trained during the last period without stimulation. Additional tests with a larger subject group will be needed to give an answer to the question of whether additional stimulation consistently affects balancing performance in this population.

V. ACKNOWLEDGMENTS

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