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Influence of Sensory Biofeedback on Fes Assisted Walking

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Abstract. A paraplegic person can walk with a minimum of four channels of functional electrical stimulation (FES) and crutch support. While visual feedback can provide information for taking appropriate voluntary control actions, the patient's preserved sensory capabilities can additionally be utilized by introducing artificial sensory feedback in the form of electrical stimuli to the non- paralyzed upper body. This sensory feedback information has been related to two important walking tasks: continuation into the next walking phase after successfully accomplishing the previous movement of the lower limb (reward) and prevention of falling (warning). The sensory feedback system described here consists of lower limb transducers with processing devices providing appropriate input signals for a personal computer. The patient's gait parameters are recorded by lightweight strain gauge goniometers attached to the knees and foot-switches positioned under the toes and heels. The computer controls a two channel sensory stimulator providing an electrotactile stimulation signal of 5 Hz (warning) or 50 Hz (reward). The lower limb sensory feedback stimulation system was tested in three completely paralyzed spinal cord injured subjects with thoracic lesions to the spinal cord. The recorded gait parameters were assessed for a period of one week prior to and three weeks after the introduction of the sensory biofeedback system. Cadence and duration of double limb support phase were recorded at the end of each experiment and compared with the initial measurements. The average improvement in walking performance while using the sensory biofeedback system was 15% for the T-3,4 subject, 30% for T-7,8 and over 100% for T12 subject.

Key words: SCI Patients, Paraplegic Patients, Paraplegia, Paraplegic Walking, Functional Electrical Stimulation, FES, FES walking, Sensory Biofeedback Systems, Sensory Integration, Experiments

Vpliv senzorne povratne zanke na hojo paraplegikov s funkcionalno električno stimulacijo

Povzetek. Paraplegiki lahko z oporo bergel hodijo z minimalno štirikanalno funkcionalno električno stimulacijo (FES). Običajna hoja pacientov je omejena na gibanje z vidno povratno zanko. Obstoječe senzorne sposobnosti paraplegikov pri hoji s funkcionalno električno stimulacijo lahko izboljšamo z dodatnim sistemom za generiranje nadomestnih senzornih informacij. V našem primeru posredujemo te informacije z električno stimulacijo na zgornjem neparaliziranem delu telesa. Izhodni senzorni signali so povezani z gibanjem pacienta v vseh pomembnih fazah koraka in posredujejo pacietnu informacijo o možnosti nadaljevanja v naslednjo fazo hoje potem, ko je uspešno zaključil prehodnji gib s spodnjo okončino (nagrada) in opozorilo pred padcem (kazen). Opisani senzorni sistem se sestoji iz senzorjev pritrjenih na spodnjih okončinah paraplegika, ki so opremljeni s posebnimi elementi za prilagajanje vhodnega signala v osebni računalnik. Parametre hoje paraplegika merimo s sodobnimi goniometri z uporovnimi lističi, pritrjenimi na kolenih in nožnimi stikali nameščenimi na prstih in peti. Osebni računalnik krmili preko svojih izhodov dvokanalni senzorni stimulator, ki generira dva frekvenčno različna stimulacijska signala 5 Hz (kazen) in 50 Hz (nagrada). Senzorni povratnozančni sistem smo testirali na treh popolnoma paraliziranih pacientih z zelo različnimi poškodbami hrbtenice. Opravili smo enotedenske meritve normalne hoje paraplegikov brez senzornega povratnozančnega sistema in tri tedne meritev z omenjenim sistemom. Ob koncu vsakega eksperimenta smo analizirali spreminjanje kadence in časa trajanja faze dvojne opore v posameznem koraku, v primerjavi izhodiščnimi meritvami. Zabeležili smo povprečno izboljšanje hoje z uporabo senzorne povratne zanke za 15% pri T-3,4, 30% pri T-7,8 in 100% pri T-12 paraplegikih.

Ključne besede: pacienti s poškodbo hrbtenice, paraplegiki, paraplegija, hoja paraplegikov, funkcionalna električna stimulacija, FES, hoja s funkcionalno električno stimulacijo, senzorni povratnozančni sistemi, senzorna integracija, eksperimenti

1 Introduction

In the normal individual, peripheral nerve sensory signals are utilized either in a reflex loop, evaluated at low hierarchical levels, or processed in the central nervous system. The control of motor functions as well as reception of sensory signals of the distal extremities are impaired after spinal cord injury. As a result the patient

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must rely primarily upon visual information during artificially augmented motor task performance. Central posture stability centers are also impaired due to insufficient sensory information from the lower part of the patients body. Limb movements can only partially be restored by applying functional electrical stimulation [1,2], even more difficult is to restore the flow of sensory information received form the periphery [3].

Vodovnik, Chrochetiere, and Reswick [4] in 1967 developed an elbow joint controller while investigating closed loop FES. Evaluating the dynamic muscle model, they defined a relation between the output stimulation amplitude and the joint torque. Based on experimental studies of muscle properties, a positional joint controller following an EMG reference signal was developed. Stanič and Trnkoczy (1974) [5] designed a PID hierarchical ankle joint controller. At the top level were defined the most important control parameters which were further processed at the next stage including an algorithm for calculating the corresponding output stimulation parameters. The bottom of the hierarchical control structure was represented by the muscles as actuators driven by FES. By presenting ankle joint control in hierarchical fashion, they exposed the problem of developing sensory integration similar to the processing of the human nervous system.

In 1991 Lan, Crago and Chizeck [6] compared two pulse width controllers (first-order PW controller and adaptive controller) with a third controller where both stimulus pulse width and period were varied simultaneously for muscle force modulation. The comparative evaluation was carried out in an intact cat ankle joint through the control of isometric joint torque, unloaded position tracking and load transitions between isometric and unloaded conditions. The simplest pulse width controller demonstrated adequate robust control. This study provided guidelines for future development of control algorithms in neural prostheses.

Petrofsky and Phillips [7,8] reported a complex walking system incorporating a closed loop controller. Functional electrical stimulation of lower extremities represented an output signal which was controlled by shoulder movement. The movement control was based on sensory integration of foot pressure sensors, ankle, knee and hip joint goniometers attached to a mechanical orthosis and ultrasound proximity sensors on the shoes. Independence of the control system was the main reason why the authors started developing cognitive sensory biofeedback system using vibrotactile interface on the patient.

Our sensory biofeedback system [14,15] for controlling the movements in SCI patients is based on completely voluntary control. The intent of the developed sensory stimulation system is to give to the patient simple and efficient information based on simple sensory integration. Information provided to the patient's non-paralyzed upper body is used for rewarding the patient for successful progression into the next phase of walking or warning him if he is in danger of falling. The reward signal is presented by 50 Hz sensory stimulation, while the warning signal is in the form of 5 Hz stimulation. The stimulation parameters were chosen with regard to past experiments made by other researchers [13], simplicity of selecting the stimulation frequency and the complexity of the control unit used for sensory stimulation.

2 Instrumentation

The laboratory version of the sensory feedback system (Fig. 1) runs on a personal computer containing a Burr Brown data acquisition module, model PCI-20000. This PC board is able to process 16 analog signals and up to 16 digital channels either as input or output signals. An eight channel analog bus is used as an interface with the following transducers on the patient being evaluated:

- two hand pushbuttons,
- two goniometers (left and right knee),
- four foot-switches (left and right toe and heel switches).

The computer controls a special stimulator providing 5 Hz or 50 Hz sensory stimulation to electrodes placed over the upper arm. The analog foot switch signals require two level digital presentation realized by software Schmitt triggers. The rule based control algorithm uses the knee angle limits estimated for each phase of walking for generating appropriate sensory information to the patient.

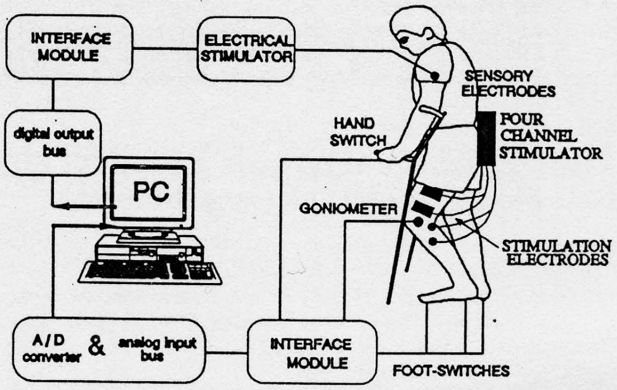

Figure 1. Sensory feedback system and input/output signals

Knee angles were measured by applying Penny and Giles goniometers. These devices consist of a spring-protected measuring element and two small endblocks for mounting the device across the joint. In knee flexion/extension measurements the proximal telescopic endblock was attached laterally to the leg so that the axes of the leg and the endblock were parallel. The distal endblock was positioned so that the axes of the thigh and the endblock were also parallel. These goniometers are easy to attach and cause only small errors due to the skin movement. The foot-switches produced an analog signal which required further computer processing, and attached under the toes and heels of both feet.

Hand pushbuttons were fixed into the handles of a walker or crutches and were used for voluntary control of a simple four-channel FES unit. They were also connected to the PC interface board providing the input signals and were assessed by the control algorithm and used for recognition of the current phase of walking.

All transducers were connected to the interface module attached with a belt to the patient's waist. This module contained a two-channel stimulator providing sensory stimulation signal on the electrodes positioned over the patient's upper left and right arms. Both stimulation channels could produce output voltages of up to 50 V at either 5 Hz or 50 Hz. Audio sensory signals were generated by the PC audio module.

3 Methods

3.1 Determination of Stimulated Muscle and Voluntary Control Events

Using the four channel functional electrical stimulation gait pattern, knee extensors were stimulated during the stance phase while the flexion reflex was elicited in the swing phase of gait. FES was controlled when the ipsilateral hand pushbutton was pressed "SC" (Switch Closed) and released "SO" (Switch Open). The control event "SC" was characterized by unilateral electrical stimulation of peroneal nerve eliciting the flexion reflex in the ipsilateral lower extremity while the contralateral knee extensors stimulation remained present. The control event "SO" returned the patient to the double support phase characterized by bilateral knee extensor stimulation. The subject remained in the swing phase of walking as long as he pressed the corresponding switch. These switches represent the sole control over the movements in the ipsilateral lower extremity.

At gait initiation the SCI subject is supported by both legs and crutches. The knees are locked in the fully extended position by the help of bilateral knee extensors stimulation. Pressing the control pushbutton "SC" brings the walking subject into the swing phase characterized by peroneal nerve stimulation provoking the flexion reflex and resulting in simultaneous hip and knee flexion and ankle dorsiflexion. The foot is completely lifted from the ground. At this point the delay and rise time of polysynaptic flexion reflexes must be taken into account. As the subject is leaning slightly forward, the stimulated leg swings forward in the sagittal plane. The contralateral extremity remains in the fully extended position. When the walking subject releases the pushbutton, corresponding to the control event "SO", the controlled leg makes full contact with the ground while both knees are in extended position. This state considered in the sensory biofeedback system as foot-contact phase, is followed by crutch transfer in double support phase, where both legs are extended and both feet are firmly on the ground.

3.2 Selection of Biomechanical Variables and Appropriate Sensors

The described states of FES assisted walking can be assessed by the following sensors: bilateral strain-gauge knee goniometers and foot-switches or pressure shoe insoles. Small, light-weight, reliable strain gauge Penny and Giles goniometers were used for bilateral knee measurements because they can be very easily attached and adequately measure position in the joint. In the swing and stance phases ON-OFF information is needed about the foot contact state. The corresponding input basograms were obtained by simple foot switch sensors with level detection determined by software Schmitt trigger.

The selected sensors provided information about the following biomechanical variables:

Φ_k	knee angle (180 degrees corresponding to the fully extended lower limb)
SH	binary heel switch function (SH=ON heel switch is in contact with the ground, SH=OFF heel is lifted from the ground)
ST	binary toes and metatarsal switch function (ST=ON toe switch is in contact with the ground, ST=OFF toes are lifted from the ground)

3.3 Selection of Sensory Stimulation Parameters

Sensory stimulation was delivered to the patient through two pairs of electrodes positioned over the skin of patient's left and right arm. The stimulation frequency was 5 Hz or 50 Hz, with pulse duration of 0,3 ms and amplitude of 30 V - 40 V. When the leg was in the support phase the quality of knee extension was determined by the knee goniometer. In case of inadequate knee extension a warning sensory signal was delivered to the ipsilateral sensory electrodes. The warning signal remained present as long as the patient did not correct the situation by unloading the limb in the stance phase or by increasing the stimulation of knee extensors. Low frequency sensory stimulation (5 Hz) was used as the warning.

When the planned movement was satisfactorily accomplished and a new voluntary control event could be started by the patient, a corresponding reward sensory signal occurred. This signal lasts for a predetermined time interval (0.2 s). The reward sensory signal is generated twice in each gait cycle, first in the swing phase of walking and second just at the beginning of the double support phase when the controlled leg makes contact with the ground.

3.4 Design of the Control Algorithm

The determination of reward or warning states depended upon identifying the various states of the gait cycle. The swing phase was started by the control signal "SC" and was assessed by the knee goniometer:

- ($\Phi_k > \Phi_{1k}$) where Φ_{1k} describes the minimal knee flexion parameter providing smooth swinging of the leg. During the swing phase the foot-switches are expected not to be in contact with the ground:
- SH = OFF,
- ST = OFF.

After accomplishing the state described the patient receives the reward sensory signal.

The foot-contact phase occurs after the voluntary control event "SO". During this phase the patient has to make an appropriate contact with the ground with both legs extended. This state can be characterized by the following ipsilateral conditions:

- $(\Phi_k < \Phi_{0k})$,
- SH = ON,
- ST = ON or OFF,

where Φ_{0k} describes maximal allowed knee flexion in the support phase. The contralateral extremity is supposed to remain in extended position during both swing and foot-contact phase. For this situation a reward sensory signal with a duration of 0.2 s is generated.

The warning signal was provided to the patient when bilateral observations during the double support phase and unilateral measurements of the supporting leg indicated an impending problem. The leg in the support phase should remain extended within the following knee condition defined with respect to knee goniometer variables:

- $(\Phi_k < \Phi_{0k})$.

The warning signal is delivered to the patient independently for each leg when the allowed knee flexion parameter is exceeded.

The basic control rules are in Fig. 2 represented as a part of a gait cycle with the corresponding variables defined as:

- "SC", "SO" - changes in hand pushbutton states,
- A - knee flexion of the supporting leg exceeded,
- B - posture corrected by unloading the limb or changing the stimulation amplitude,
- C - appropriate knee flexion and foot switches OFF,
- D - contact with the ground with the leg fully extended.

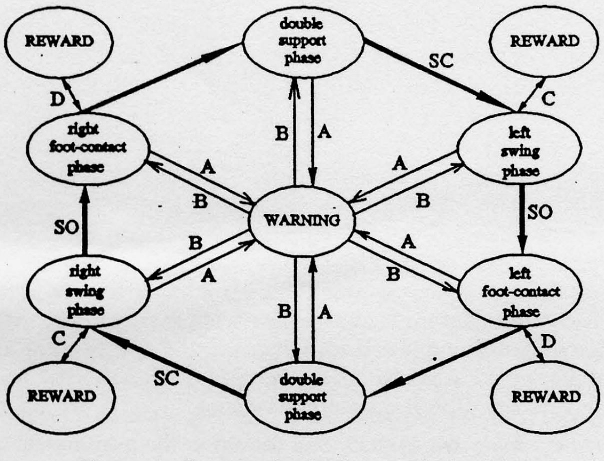

Figure 2. Sensory feedback control algorithm

As shown in the state diagram in Fig. 2, the warning signal can be generated unilaterally in the swing and foot contact phases of walking and bilaterally in the double support phase with no limitations regarding the number of warning signals in the gait cycle. The reward signal, however, can be generated unilaterally on the side of the controlled leg only once in the swing phase and in the foot contact phase.

The voluntary transfer of the crutch results mainly in the change of upper body position. As proprioception and exteroception of the trunk is to some extent preserved in paraplegic subjects, the states occurring after the crutch transfer were not considered in our preliminary experimental studies.

4 Results

4.1 Testing procedure

Measurements with the sensory biofeedback system were performed in three spinal cord injured patients over a period of one month each. These patients had thoracic lesions: T3-4 (A.K., female, 26 years), T7-8 (V.H., male, 24 years) and T12 (B.T., male, 30 years). The purpose of the experiment was to show that improvements in walking would occur as a consequence of applying the sensory biofeedback system. During the first week the average cadence and the variability of patient's gait pattern was assessed when walking without the sensory biofeedback system. In the next three week period the gait parameters while training the patient to walk with the sensory biofeedback system were measured. Average gait parameters were measured each day and then compared for both measuring periods without and with sensory biofeedback system.

During the experiment the transducer signals were measured on the patient along with the sensory information signals delivered to the nonparalyzed upper part of the body. Fig. 3 presents both hand-switch signals, goniograms, basograms and sensory stimulation signals resulting from the biofeedback system during four-channel FES assisted walking. Sensory information delivered to the right and left side of the body is represented by the following levels on vertical axis:

- level 4 - reward sensory stimulation delivered to the right sensory electrodes,
- level 5 - reward sensory stimulation representing reward signal delivered to the left sensory electrodes.

In a single gait cycle two reward signals are supposed to be generated on each side, first providing the patient with information about satisfactory knee flexion while the leg is lifted from the ground and second after completing the swing phase representing the information that the leg is fully extended and in contact with the ground.

The sensory feedback system can provide three more types of information signals representing unilateral or bilateral warning functions. They occur during inadequate right or left or both knee extensions when the leg is supporting the body.

In analyzing the patient's walking pattern, two time intervals related to the sensory signals were expected to be influenced by the sensory biofeedback system (Fig. 3):

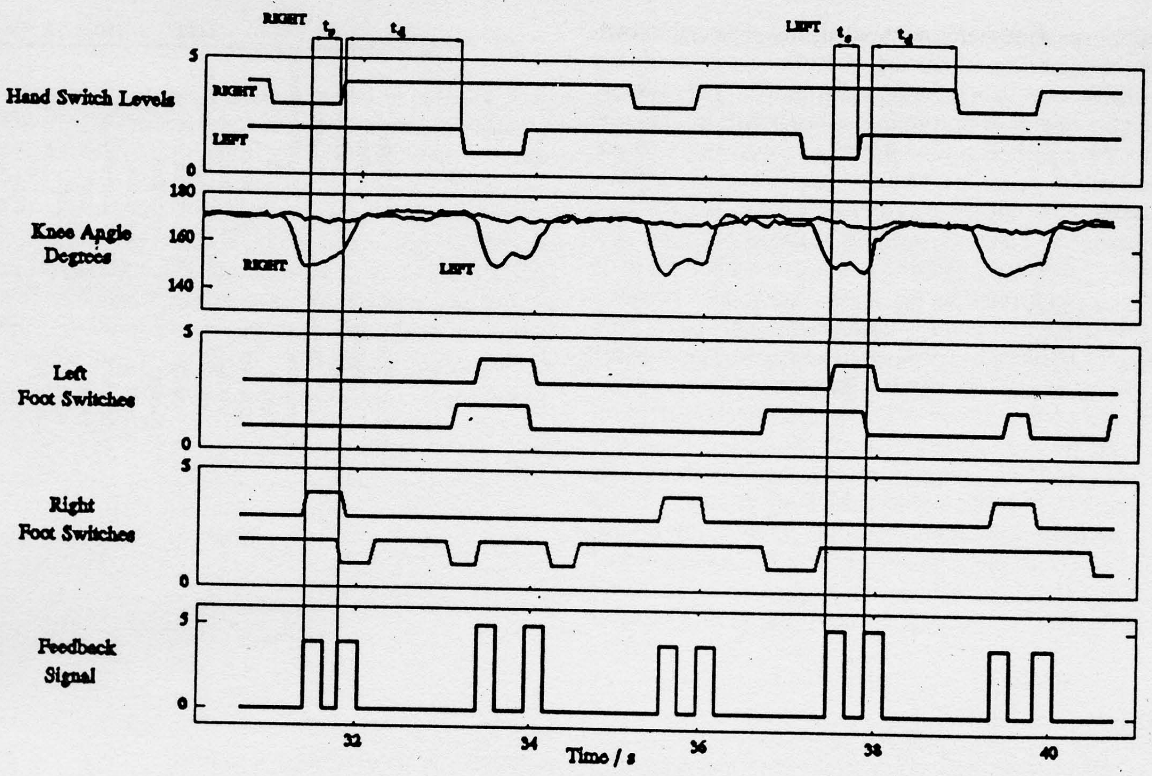

Figure 3. Sensory signals as measured during the experiment

- t_s is the time delay between the first sensory signal occurrence and the ipsilateral hand switch release. The duration of this interval is rather short.
- t_d is the time delay from the second reward sensory signal to the beginning of the contralateral step. This period represents duration of the double support phase when muscle fatigue in both knee extensors is the most crucial problem. It is therefore of utmost importance to make this period as short as possible.

Our aim was to find the differences in the patients' walking pattern after daily use of the sensory biofeedback system. Before the experiment each patient was extensively trained by the physiotherapist without using sensory biofeedback system, so his walking capabilities at the beginning of our experiment were considered to be stable (A.K., T3-4 patient, 25 months past injury, 22 months walking with FES, V.H., T7-8 patient, 45 months past injury, 30 months walking with FES, B.T., T12, 15 months past injury, 14 months walking with FES). We evaluated the patient's walking pattern during the first five days without using the developed feedback system and then during the following three weeks while using the sensory information biofeedback system. The time intervals t_s and t_d and gait cadence (number of steps per minute) were assessed and average values and standard deviations of all data collected during each day were calculated. During the experiment there were some problems with displacement of stimulation electrodes, sensory biofeedback initial condition variability and technical problems with the prototype stimulation unit that forced the patient to stop for a moment, causing some long time intervals. Inaccurate data, occurring because of the unexpected problems, were eliminated by considering only the measurements within the range of three standard deviations with respect to the computed average values. The presentation of the data was separated for the right and left leg with the purpose to include as much information as possible. When a problem occurred in a particular gait cycle, the whole gait cycle was not lost, but at most only half of it. Taking this approach for presentation of walking parameters the difference between right and left gait parameters is obvious.

4.2 Assessment Results

Information on cadence and intervals t_s and t_d in all three patients was collected. During the first days of experiment the patient with the highest level of injury made only a few steps in each run and walked very inefficiently. Cadence was almost constant during the first week and it increased as the patient started using the sensory biofeedback system. However, it did not reach the expected level of improvement in the last week of experiment. The cadence improved only 15% while using sensory biofeedback system. The second patient with an injury at T7-8 was already a highly trained person, which was confirmed during the first week of initial measurements. This patient's walking cadence increased about 30% during one month of measurements.

The most promising results were obtained with the last patient (Fig. 4). His walking was very stable during the initial measurements without using sensory biofeedback system and he improved considerably immediately when he started using the sensory biofeedback system. During the first days of training both sensory information signals were considered to be very important. Towards the end of the experiment he started walking so fast that the first reward signal was hard for him to recognize. Comparing the patient's walking at the beginning and at the end of the investigation, it was concluded that with the sensory information the patient adopted a new and faster technique for swing phase performance. The same effect was observed in the double support phase which was almost for 100% shorter than at the beginning of the investigation. Stable walking parameters during the initial period of five days can be observed in the beginning of Fig. 4. After this period the paraplegic subject started using the sensory biofeedback system and his walking improved immediately. During the following days he was getting used to the sensory information signals which helped him to achieve even faster walking during the last days of experiment. The results assessed during the thirteenth day of experiment can be ascribed to malfunction of the stimulator system.

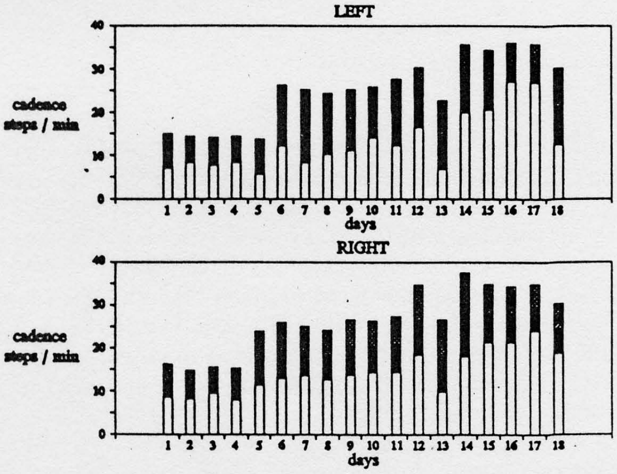

Figure 4. Average cadence measurements for the patient with SCI lesion T12

Before making any conclusions about gait improvements, it is important to consider the two time periods t_d and t_s assessed during the walking cycle. The interval t_d is the most important time period representing in fact the double limb support phase. This phase is characterized by a very high rate of fatigue of the patient's knee extensor muscles. The duration of interval t_d is very long (practically half of the step time) during simple four-channel FES assisted gait. In order to reduce the double limb stance phase and thus fatigue, the developed system generates a second reward signal which informs the patient that he has accomplished stable contact with the ground and that he can proceed into the next phase of walking. The average time delays (Fig. 5) displayed through the experiment are in agreement with the cadence presentation.

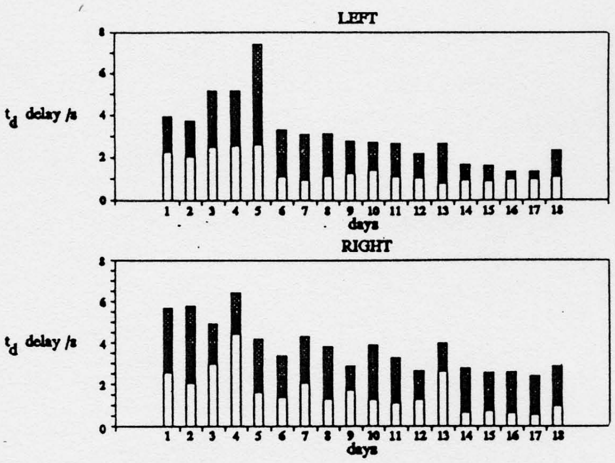

Figure 5. Time delays measured in double support phase

The duration of the first reward signal (t_s) is rather short and as such is not very significant. Statistical results of estimating the time delay t_s are quite consistent in the right leg and less so in the left leg (Fig. 6). During the first days of walking with the sensory biofeedback system, the patient used this reward signal as information that the controlled leg was sufficiently flexed and that the foot was off the ground. With the help of this signal the last patient was able to move the body's center in the forward direction voluntarily. Reduction of the duration t_s in the right extremity may be considered a result of daily training. The time interval t_s is very short, so there is the question as to the patient's ability to recognize and use the first reward signal appropriately. It is our opinion that during the first days of using the sensory biofeedback system, the paraplegic subject had already learned how and when to start the swing phase and there was no further need to produce this reward signal during the last days of experiment.

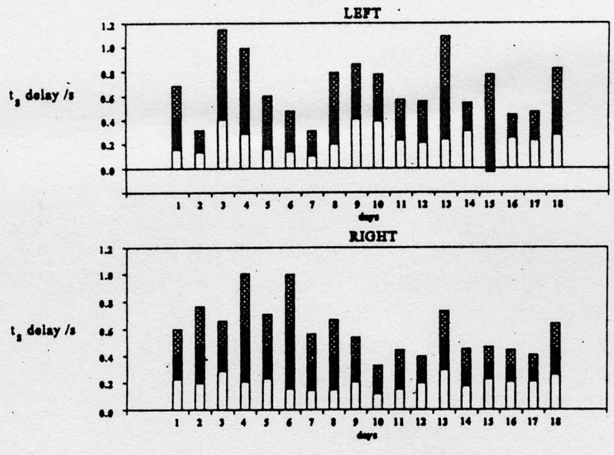

Figure 6. Time interval measured in swing phase

5 Discussion

The sensory biofeedback system tested in three SCI patients is a result of simple sensory integration aimed to improve paraplegic walking abilities. Two different sensory signals were generated: a REWARD signal suggesting to the patient to continue into the next phase of walking and a WARNING signal preventing the person from falling due to increased muscle fatigue. The patient was provided with sensory information through an electrotactile interface realized by stimulation signals of 5 Hz and 50 Hz.

Examples of feedback stimuli have been demonstrated by Szeto and Lyman [10,11] who investigated the electrocutaneous sensory interface using frequency and pulse width modulation techniques and an auditory displaced array of sensory electrodes. Improved estimation of different feedback approaches was proposed by recording the patient's ability to follow a reference signal with regard to a sensory information signal. Statistically estimated results of these experiments suggested, for control of joint position, the use of an array of sensory electrodes as the most favorable electrotactile system. A different approach was undertaken by Solomonow [12] who investigated two point stimulation while changing the stimulation parameters and the distance between the pair of sensory electrodes. The closest distance when the patient still recognized the two signals was tested in three different experiments with different stimulation parameters on two pairs of sensory electrodes. Combinations were tested with both signals in phase, one signal delayed with respect to another and different stimulation frequencies on both electrode pairs. Riso and Van Doren [13] reported the implementation of an electrocutaneous interface for the control of an upper extremity prosthesis. Some of the lost sensory information in the hands of C5 and C6 tetraplegic patients was replaced by implementing electrocutaneous sensory information for position tracking and object grasping tasks using an array of sensory electrodes for shoulder position information in combination with frequency modulation. In these experiments sensory information was primarily used only as supplemental information for impaired sensitivity. Sensory information directly representing the magnitude of a particular angle between limb segments or any other mechanical variable can only be applied in a single limb control. In our approach the patient was provided with more complex sensory information suggesting when to take the next locomotor action. Our system provides the patient with simple sensory information as a result of a complex decision process based on many input sensory signals. This may be important for defining appropriate input and output interfaces and control strategies in future complex sensory integration systems.

By increasing the number of sensors implemented for replacement of a patient's impaired sensory capabilities, the concept of sensory integration in a complete neural prosthesis becomes of utmost importance. Considering the previous contributions of other authors, Crago [9] proposed the idea of developing a neural prosthesis estimating position, velocity and acceleration of the center of mass of the body. Different combinations of level sensors, foot-force transducers, joint angle measurements, gravity vector direction detection and probably inertial navigation devices will be required in a future FNS assisted walking without supplemental support from crutches or walkers. In contrast to artificial sensors there are also signals provided by receptors from the paralyzed body. An important contribution in this area was made by Hoffer and Haugland [3] who suggest that sensory signals recovered from peripheral nerves present a feasible option to restore hand as well as gait functions in spinal cord injured patients. By automatically correcting the muscle activation levels provided by FES, tactile feedback would assist the user in the demanding task of activating paralyzed muscles when joint angle and load distribution change or when fatigue develops. When permanently implanted, a neurally interfaced system is available for use at all times, is reliable and without need for frequent recalibration and could be expected to be more cosmetically acceptable to the user than external devices.

Our approach was only a preliminary step toward the use of integrated sensory environment in a neural prosthesis. We believe that structured integrated environment of natural and artificial sensors is the future objective of research experiments dealing with control of FES assisted walking based on sensory signals.

6 Acknowledgement

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7 References

[1] A. Kralj, T Bajd, *Functional Electrical Stimulation: Standing and Walking after Spinal Cord Injury*, Boca Raton, Florida: CRC Press, 1989.

[2] L. Vodovnik, T. Bajd, F. Gračanin, A. Kralj, P. Strojnik, Functional Electrical Stimulation for Control of Locomotor Systems, *CRC Critical Rev. Bioeng.*, vol. 6, no. 9, pp. 63-131, 1981.

[3] J.A. Hoffer and M.K. Haugland, *Signals from Tactile Sensors in Glabrous Skin Suitable for Restoring Motor Functions in Paralyzed Humans*, Neural Prostheses, Replacing Motor Function After Disease or Disability, New York: Oxford University Press, 1992.

[4] L. Vodovnik, W.J. Crochetiere and J.B. Reswick, Control of a Skeletal Joint by Electrical Stimulation of Antagonists, *Med. Biol. Eng.*, vol. 5, no. 2, pp. 97-109, 1967.

[5] U. Stanič and A. Trnkoczy, Closed-Loop Positioning of Hemiplegic Patient's Joint by Means of Functional Electrical Stimulation, *IEEE Trans. Biomed. Eng.*, vol. 21, no. 5, 1974.

[6] N. Lan, P.E. Crago and H.J. Chizeck, Feedback Control Methods for Task Regulation by Electrical Stimulation of Muscles, *IEEE Trans. Biomed. Eng.*, vol. 38, no. 12, pp. 1213-1223, 1991.

[7] J.S. Petrofsky, C.A. Phillips, Computer Controlled Walking in The Paralyzed Individual, *The J. Neuro. Ortho.*

Med. Surg.*, vol. 4, no. 2, pp. 153-165, 1983.

[8] C.A. Phillips, J.S. Petrofsky, A Total Neural Prosthesis for Spinal Cord Injury Rehabilitation: The Cognitive Feedback System With a Functional Electric Stimulation Orthosis, *The J. Neuro. Ortho. Med. Surg.*, vol. 7, no. 3, pp. 225-234, 1986.

[9] Crago, H.J. Chizeck, M.R. Neuman, F.T. Hambrecht, Sensor for Use with Functional Neuromuscular Stimulation, *IEEE Trans. Biomed. Eng.*, vol. 33, no. 1, pp. 256-268, 1986.

[10] A.Y.J. Szeto and F.A. Saunders, Electocutaneous Stimulation for Sensory Communication in Rehabilitation Engineering, *IEEE Trans. Biomed. Eng.*, vol. 29, no. 4, 1992.

[11] A.Y.J. Szeto and Y. Chung, Effects of Training on Human Tracking of Electrocutaneous Signals, *Ann. Biomed. Eng.*, vol. 14, pp. 369-381, 1986.

[12] M. Solomonow, J. Lyman and A. Freedy, Electrotactile Two-Point Discrimination as a Function of Frequency, Body Site, Laterality and Stimulation Codes, *Ann. Biomed. Eng.*, vol. 5, pp. 47-60, 1977.

[13] C.L. Van Doren, R. Riso, K. Milchus, Sensory Feedback for Enhancing Upper Extremity Neuromuscular Prostheses, *J. Neuro. Rehab.*, vol. 5, no. 1, pp. 63-74, 1991.

[14] R. Erzin, T. Bajd, A. Kralj, R. Turk, H. Benko, Sensory Feedback in Voluntary Controlled FES Assisted Walking, *Proceedings of 4th Vienna International Workshop on Functional Electrostimulation*, Vienna, pp. 116-119, 1992.

[15] R. Erzin, T. Bajd, A. Kralj, R. Turk, H. Benko, Influence of Sensory Biofeedback on FES Assisted Walking, *The Ljubljana FES Conference*, Ljubljana, pp. 89-92, 1993.

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Recenzija

Y. Eliashberg, V. Milman, L. Polterovich, R. Schoen (editorji): **Geometries in Interaction - Special Issue in Honor of Mikhail Gromov**

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Knjiga je ponatis 14 člankov, ki so prvotno izšli v zborniku Geometric And Functional Analysis, vol.5.2.

V zadnjem času je bil dosežen zelo velik napredek na področju geometrije. Odkrite so bile nove povezave med geometrijo in številnimi drugimi smermi matematike, kot so algebra, analiza, topologija.

V knjigi je zbranih 14 člankov, ki obravnavajo široko paleto osnovnih raziskav moderne geometrije in z njo povezanih področij. Zanimiva bo za raziskovalce in študente tematike, povezane z geometrijo in njeno uporabo v funkcionalni analizi, pri parcialnih diferencialnih enačbah, v analitični teoriji števil in fiziki.

T. Slivnik