Journal of Medical Engineering & Technology, Volume 24, Number 5, (September/ October 2000), pages 215–226

Development and evaluation of a two-dimensional electrocutaneous cognitive feedback system for use in paraplegic standing

Z. Matjačić†*, P. L. Jensen†, R. R. Riso†, M. Voigt†, T. Bajd‡ and T. Sinkjaer†

†Center for Sensory–Motor Interaction, Aalborg University, Aalborg, Denmark
‡Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia

Fatigue of electrically activated paralysed muscles is a major factor limiting the duration of functional electrical stimulation (FES) supported paraplegic standing. Fatigue can be significantly delayed by changing the posture. Since paralysed individuals are deprived of proprio- and exteroception from the lower limbs they are not aware of the posture and loading of their paralysed legs. If suitable cognitive feedback (CF) information about posture in the sagittal and frontal planes is provided, they might be able to successfully exercise posture switching. A two-dimensional electrocutaneous CF system was developed. Relative limb loading and the location of the weighted centre of pressure were selected as informational variables. Discrete encoding schemes in the form of spatial and frequency codes were employed and the informational signals were divided into three sub-regions. The ability to correctly interpret the CF was investigated using one- and two-dimension tracking tests in three paralysed subjects, each of whom were studied over five consecutive days. All three subjects were able to use the CF in one-dimension tests. Two subjects could do the same also in two-dimension tests. The encoding scheme which was developed to communicate the selected biomechanical variables proved to be easily understood and thus appropriate for use in paraplegic standing.

Introduction

Functional electrical stimulation (FES) supported standing after complete spinal cord injury (SCI) is an important therapeutic modality in the rehabilitation of paralysed individuals [1]. The dominant problem in FES supported standing which prevents a person with SCI to stand for prolonged periods is fatigue of the artificially activated muscles. An appealing approach to reduce muscle fatigue is to switch between different postures such that different muscle groups are cyclically engaged and relaxed [2]. This concept was successfully undertaken in the laboratory setting but was never widely used. One of the major reasons for this is the relation between the user and the orthotic device where a standing subject must follow the action of a preprogrammed stimulation, which is uncomfortable and can also cause a fall.

It would be much easier and safer if a standing person could voluntarily change the posture followed by an appropriate action of the orthotic system [3, 4]. However, since the paralysed subjects are deprived of proprio- and exteroception from the lower limbs they are not aware of the posture and loading of their lower extremities. If we were able to adequately substitute for the missing proprioception by means of cognitive feedback (CF), paralysed individuals might be able to voluntarily switch between postures, instead of having to adapt to preprogrammed FES driven patterns.

To date only a few simple CF systems providing sensory substitution for the lost sensory modalities have been introduced in paraplegic standing. Phillips and Petrofsky [5] developed a system that communicated the distribution of the vertical force under the foot sole (measured in the sagittal plane) via a vibrotactile display to the chest of a standing paralysed subject. Turk *et al.* [6] used auditory CF to communicate the angle of inclination of the body in the sagittal plane in standing subjects. Matjačić and Bajd [7] used similar single channel auditory feedback in unsupported paraplegic standing. Andrews *et al.* [8] studied the use of an electrocutaneous display to warn a patient whenever inclination in the sagittal plane exceeded a predetermined angle and also when the limb-loading ratio exceeded predetermined boundaries. In all four studies, the authors reported that the provision of CF led to improved balance, usually reflected as a reduction in body sway. The aim of the described CF schemes was to provide subjects with information on how much they have deviated from a preferred posture, which was in most cases upright. An important aspect in designing these schemes was the simplicity of the CF system because excessive cognitive load on subjects should be avoided since maintenance of standing requires substantial physical and mental effort for a person with paralysis.

However, neither of the presented CF systems can provide a standing subject with comprehensive information on posture, which is needed to control standing and voluntary switching between postures in the sagittal and frontal plane. To provide adequate information about current posture, a CF system should communicate selected biomechanical variables or combinations of them reflecting the current state of the

---

**Author for correspondence; email: zm@smi.auc.dk*

ISSN 0309-1902 print/ ISSN 1464-522X online
http://www.tandf.co.uk/journals

paralysed extremities in the sagittal and frontal planes. An important question exists whether a paralysed individual standing by means of FES can understand and make use of a complex CF system, which carries posture information in two dimensions.

The objective of the present investigation was to develop and evaluate a two-dimensional electrocutaneous CF display suitable for use in paraplegic standing. To address the latter objective, the abilities of three paralysed persons to correctly interpret sensory signals provided by the proposed two-dimensional CF display were evaluated in tracking studies performed during standing.

Cognitive feedback system

Figure 1 illustrates the elements of the CF system, which provides a paralysed subject, standing in parallel bars, with information about his current posture derived from the centre of pressure (COP) under the feet. The CF system and test apparatus consists of the following four units: (1) a sensory system to assess the pressure distribution under the feet and perform feature extraction, (2) an encoding algorithm, (3) an electrotactile display and (4) a visual display.

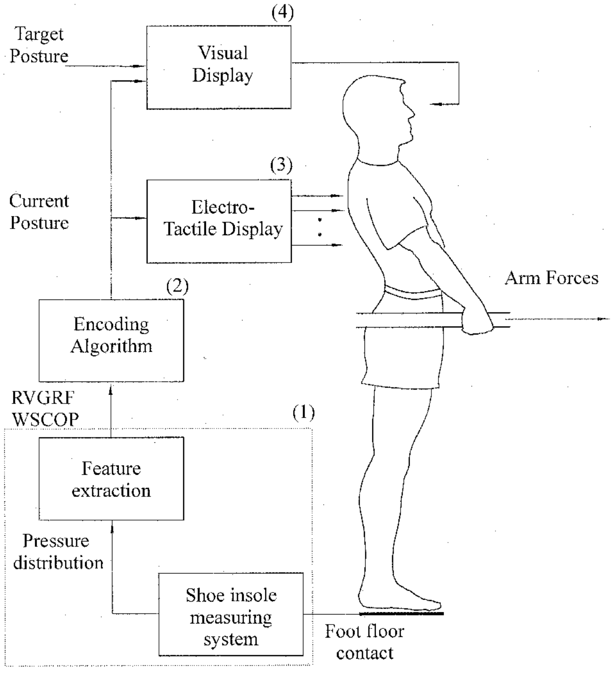


Figure 1. The elements of the CF system. The pressure distribution under the standing subject's feet is acquired using a shoe insole measuring system. After filtering, the relative vertical ground reaction forces and weighted sagittal centre of pressure are calculated and describe the Current posture *of the standing subject (1). The encoding algorithm (2) transforms the acquired signals into stimulation parameters that are displayed to the standing subject via an electrotactile display (3). A visual display (4) is used to provide the subject with information about the* Current *and* Target postures.

Assessment of pressure distribution under the feet and feature extraction

During quiet standing an intact person maintains the knees in an extended position. Ankle flexion and extension muscles control postural sway in the sagittal plane, while posture in the frontal plane is controlled by the hip adductors and abductors [9]. The COP and the relative vertical ground reaction forces (RVGRF) under both feet predominantly vary according to the change of torque in the ankle and hip joints. RVGRF is expressed as a fraction of the total sum of vertical ground reaction forces (GRF) under the left and right legs. The C-posture utilized by the paralysed individuals is, from a biomechanical point of view, similar to the quiet standing of an intact subject with the exception of the added arm support needed in paraplegic standing. In the absence of contractures in plegic joints of a paralysed individual, shear forces under the feet (resulting from arm forces) are small compared to the body weight. Therefore, the RVGRF changes mainly due to passive stiffness of the plegic hip joints and reflects relative limb loading. The weighted sagittal COP (WSCOP), which changes due to passive stiffness of the plegic ankle joints, reflects the position of the centre of mass (COM) of the body in the sagittal plane. The RVGRF and WSCOP signals were selected as informational input to the CF system since they adequately reflect the current posture.

Pressure distribution under the feet of a standing subject was measured by a Pedar® (NOVEL, GmbH) shoe insole measuring system, modified for use in real time and connected to a personal computer (PC). Using the pressure distribution we were able to calculate the vertical GRF (VGRF) and COP under each foot. VGRF and COP signals were low-pass filtered (Butterworth, 4 order, 2.5 Hz) and subsequently used to calculate the WSCOP and RVGRF signals as described in Winter *et al.* [9]. It should be noted that two RVGRF signals exist, one for each limb. However, they both carry the same information. If the RVGRF under the left leg is increased above 50% by some value, then the RVGRF under the right leg is decreased by the same value. From this point onward when referring to the RVGRF signal, we have in mind the RVGRF under the left leg. The WSCOP signal was expressed as the percentage of the shoe insole length, where 0% corresponds to the position of WSCOP at the toes, and 100% corresponds to the position of the WSCOP at the heel. However, the WSCOP was usually confined to a much narrower range (*ca.* 55–75%).

Encoding algorithm and electrotactile display

Tactile input of sensory information requires the information signals to be encoded into stimulation signals, which should be clear, comfortable and easily understood [10]. Based on experiences from prior work of Szeto and Saunders [10], Kaczmarek *et al.* [11], Riso *et al.* [12] and Szeto and Riso [13] we designed an encoding algorithm to convert the WSCOP and RVGRF signals into stimulation parameters for use with an electrotactile display.

Three pairs of skin stimulation sites, symmetrically placed with respect to both sides of the upper body as shown in figure 2, were used to spatially encode the WSCOP. The range of the WSCOP signal was divided into the *Anterior*, *Middle* and *Posterior* regions of the foot and mapped onto the skin stimulation locations. The location of the WSCOP in the *Anterior*, *Middle* and *Posterior* region corresponded to stimulation of the electrode pair at the shoulders, lateral back skin and medial back skin, respectively. Only one pair of electrodes was activated at any given time. If the WSCOP was located outside the bounds defined by the three regions, no electrode pair was active. The coding of the WSCOP relates sway in the sagittal plane to stimulation of a particular electrode pair by means of the spatial mapping between the information signal and the electrodes' locations. The use of a position code to convey a positional signal should minimize the mental processing load on a standing subject [12].

The encoding scheme for the RVGRF signal is shown in figure 3. This encoding scheme is implemented through the same three pairs of electrodes used for the spatial encoding of the WSCOP signal. The information about the current value of the RVGRF is coded by frequency modulation of the stimulus train delivered to the active pair of electrodes (selected according to the current value of the WSCOP). Similarly to the WSCOP signal, the RVGRF signal is divided into three regions: *Left*, *Balance* and *Right*. If the load bearing is divided between both limbs within the *Balance* region of the RVGRF signal, the stimulation pulse frequency at both electrodes of an active pair is set to 20 Hz. When the RVGRF falls into the *Right* region, indicating that more weight is supported by the right leg, the pulse frequency of the right active electrode is set to 60 Hz, while the pulse frequency of the left active electrode is set to 5 Hz. When the RVGRF falls into the *Left* region, the pulse frequency at the right active electrode is set to 5 Hz and the frequency of the right active electrode is set to 60 Hz. If the RVGRF exceeds the *Left* and *Right* boundaries defined by the three regions then (similar to the WSCOP code), neither electrode is active. A reason for selecting the lowest frequency to be 5 Hz is that the sensation of flutter on the skin is more comfortable than individual pulses delivered at lower frequencies. Also the latency for changing from one frequency to another is excessive if the low frequencies are utilized. The frequency coding was selected according to the prior studies of Riso *et al.* [14]. They assessed just noticeable differences (JND) in frequencies ranging from 2–100 Hz, which brackets the useful range for CF [10]. They found that the mean JND for changes in frequency, was around 30% at 5 Hz and around 20% at 20 Hz. In the RVGRF encoding scheme we used three discrete frequencies, namely 5, 20 and 60 Hz where the perceived change from 5 to 20 Hz and from 20 to 60 Hz is at least 3 JNDs apart. We, therefore, expected that subjects would be able to comfortably discern between the three different frequencies. The RVGRF encoding scheme is closely related to the limb loading/unloading mechanism by simultaneously raising the frequency at the active electrode on the side of the body, that is above the loaded limb and decreasing it at the unloaded side of the body. Such a representation seems intuitive to further simplify the mental processing load on a standing subject.

We arrived at the encoding scheme presented by extensive experimentation on five intact subjects who stood while wearing the measuring shoe insoles and simulating the Tracking experiment that is described

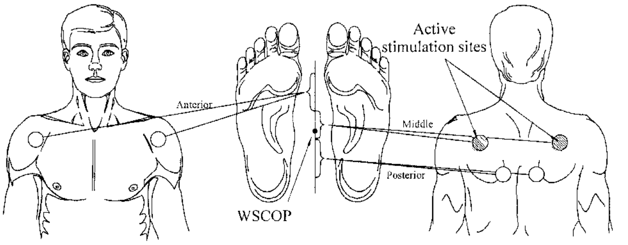


Figure 2. Spatial encoding of the WSCOP signal. The WSCOP signal range was divided into three regions: Anterior, Middle *and* Posterior. *Three pairs of stimulation sites were placed symmetrically on each side of the body. The location of the WSCOP in the* Anterior, Middle *and* Posterior *region corresponds to stimulation of the electrode pairs at the shoulders, lateral back site and medial back site, respectively. Only one pair of electrodes was active at any given time. If the WSCOP was not located within one of the regions, neither electrode pair was activated.*

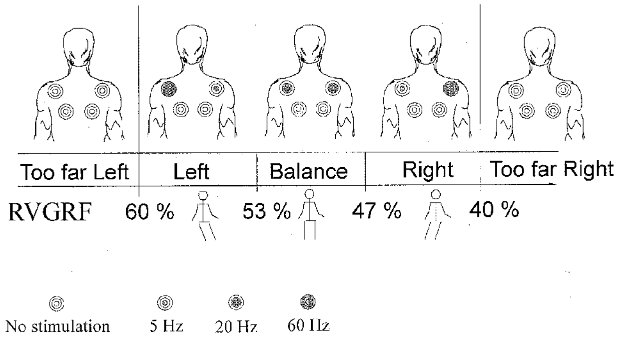


Figure 3. Frequency modulation scheme used to encode the RVGRF signal. The RVGRF signal range was divided into three sub-regions: Right, Balance, Left. *If the RVGRF was within the* Balance *region, both active electrodes delivered stimuli with a frequency of 20 Hz. If the RVGRF was located in the* Right *region the active electrode at the right side of the body delivered stimuli at 60 Hz, and at the other site the frequency was set to 5 Hz. When the RVGRF was in the* Left *region, the frequencies were reversed with respect to the previous case. If the RVGRF was not located in one of the sub-regions, neither electrode was activated.*

below. The sensory feedback encoding scheme was implemented in software running on a PC.

The electrotactile display consisted of six concentric surface electrodes placed on the torso as shown in figure 2. Each electrode has an active centre with a diameter of 5 mm, surrounded by a 5 mm insulating annulus and then by a 4 mm × 40 mm concentric ground electrode. Before placing the electrodes onto the stimulation sites shown in figure 2, the skin was coated with protective skin dressing wipe (Tens clean-cote™) to moisten it and to assure a stable electrode–skin contact. Biphasic stimulation pulses were delivered to the electrodes on each side of the body by means of two PC controlled electrical stimulators (designed and produced at our laboratory) with constant current multiplexed outputs. Pulse width was maintained at 30 μs, while the pulse amplitude was adjusted to elicit a comfortable sensation (typically around 15 mA) well above the sensation threshold. Special care was given to the placement of each electrode pair. Corresponding electrodes at each side of the body were placed to allow equal intensity sensations.

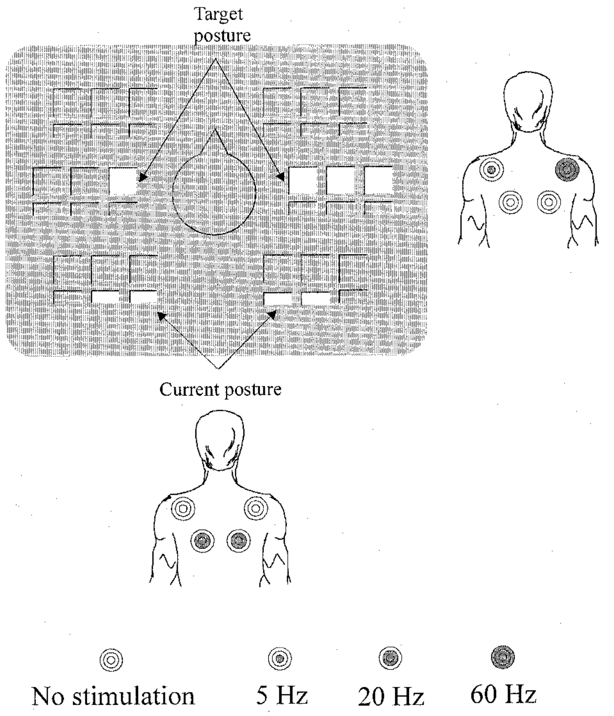


Figure 4. Visual display showing all six electrode sites. Three squares and three rectangles represent each stimulation site. The squares show the Target posture *which the standing subject has to achieve, while the rectangles signal the* Current posture *of the standing subject. The particular* Target posture *commanded by the display requests that the WSCOP should be placed in the* Middle *region while the RVGRF should be positioned in the* Right *region. The particular* Current posture *attained by a subject is such that WSCOP is located in the* Back *region while the RVGRF is located in the* Balance *region. The corresponding status of the ECF system is shown for both postures. Note that for both the target squares and feedback rectangles four elements are always illuminated. The state of a particular element depends on the target and feedback condition. The illuminated elements shift right, for example, when the imbalance in limb loading requested is to the right body side.*

Visual display

Figure 4 shows the visual display as it appears on the PC monitor. The visual display provides a top view of a subject and bilateral three element electrode arrays. The head of the subject facing upwards is drawn to the middle of the screen. The three stimulation sites are drawn symmetrically to the left and right sides of the head, denoting the three electrode sites located on the body of the standing subject. Each stimulation site on the screen is characterized by a set of squares and a smaller set of rectangles. Each such set is composed of three elements positioned medial to lateral. The sets of squares displayed a *Target posture* that a standing subject had to reach in the tracking experiments as will be described, while the rectangles provided visual feedback of the *Current posture* of the subject. Depending on the *Target* and *Current* location of the RVGRF signal, a different number of elements were active within the active set determined by the *Target* and *Current* WSCOP. An example of the presentation of a *Target posture* is illustrated in figure 4. Here, a standing subject had to achieve a posture where the WSCOP was in the *Middle* region, while the RVGRF was placed in the *Right* region. This corresponds to the status of the CF elecrotactile display where the pair of electrodes at the lateral back sites is active in such a way that the right electrodes deliver a 60 Hz stimulus train while the left electrode delivers a 5 Hz stimulus train. The *Current posture* of a standing subject is also displayed. Because the frequency of the stimulation at both back electrodes is 20 Hz, the two innermost rectangles are illuminated in the visual display.

Experimental evaluation of the cognitive feedback system

Subjects

Three male subjects with complete SCI (table 1) and in good physical condition participated in our study. Note that the level of SCI is very different among the three subjects. We intentionally selected subjects having different lesions. This was done to investigate the applicability of the two-dimensional CF in subjects with

Table 1. Description of the three paralysed subjects who participated in the tracking tests.

	Age (yr)	Height (cm)	Weight (kg)	Lesion	Cause	Time post injury
Subject 1	22	174	59	C7	Traffic accident	7 months
Subject 2	20	179	70	T2	Cut wound	12 months
Subject 3	34	170	59	L1–L4	Fall	8 months

various degrees of impairment. All subjects signed informed consents and the study was approved by the local ethical committee.

Tracking equipment

A tracking experiment was undertaken to evaluate the abilities of the subjects to interpret the sensory information provided by the two-dimensional electrocutaneous cognitive feedback (ECF) system. Tracking tests have been shown to be a useful methodology for the evaluation of sensory feedback codes [10].

Experimental conditions

The knees of the standing subjects were maintained in an extended position by means of long braces. The subjects were also fitted bilaterally with compliant ankle foot orthoses (stiffness approx. 2 Nm (deg^{-1}) to stiffening the ankle joints. Instrumented shoe insoles were placed between the ankle foot orthosis and the footwear. The electrodes were attached to the subject's skin as shown in figure 2. Subjects stood in a standing frame maintaining a C posture as shown in figure 1, and with both feet in parallel. They held onto the handles of the standing frame. They were asked to consecutively incline in the anterior, posterior, left and right directions to the extent where they could still comfortably maintain standing. In this way we assessed the feasible ranges of the WSCOP and RVGRF signals. Next, the visual feedback (VF) was displayed where only the *Current posture* was shown. The standing subject was instructed to move between nine possible postures corresponding to the three positions of sagittal plane inclination and three positions of left/right relative foot loading. If the subject's excursions into these regions were wide enough, the subject could easily switch between them. Next, we reduced the width of the regions and asked the subject to switch between the postures again. Through iteration in this manner (termed a *Short visual session*) we adjusted the size of the regions of the WSCOP and RVGRF signals to be small enough that the subject needed the aid of the visual feedback to maintain a requested *Target posture* (i.e. his residual proprioceptive sense was not adequate). The sizes of the adjusted regions differed slightly for each subject and were around 7% of the WSCOP and 7% of the RVGRF signals' full ranges.

Experimental protocol

A few descriptors should be defined to facilitate the presentation of the experimental protocol as follows:

(1) *Session* is a period when the subject was presented with a series of *Target postures*, via the visual display, which he then had to match. Each session consisted of approximately 10 trials, and a trial was defined as a period within which the *Target posture* was stationary. The duration of each trial was randomly selected between 10 and 14 s, and was judged to be sufficiently long for all of the subjects to match the various *Target postures*. The duration of each session was, therefore, limited to approximately 2 min. We felt that if the session duration was longer, the subjects might not remain fully concentrated on the task. A *Target posture* was randomly selected for each trial. Sessions were performed under the following conditions: while the subject was receiving ECG; ECF combined with VF; or finally without supplemental feedback.

(2) *One-dimension session* is a session where the *Target posture* was confined to one dimension requiring tracking either in the sagittal or frontal plane. In either plane, only three different *Target postures* were possible. During one-dimension sessions in the frontal plane only the electrode pair corresponding to the *Middle* region of WSCOP was active. During the one-dimension sessions in the sagittal plane only the 20 Hz frequency corresponding to the *Balance* region of RVGRF was utilized.

(3) *Two-dimension session* is a session where a *Target posture* was selected from a matrix of nine possible postures determined by three WSCOP regions and three RVGRF regions.

(4) *Short visual session* has already been described in a previous subsection.

Two consecutive days before the tracking experiment, all three subjects stood while receiving the ECF and VF. They explored the postural space separately for the sagittal and frontal planes. At this time the regions of WSCOP and RVGRF signals were set rather wide (12% of full range). This introductory standing was performed for 20 min each day (the subjects could not stand comfortably for greater durations).

The tracking experiment was conducted over five consecutive days. The protocol for the experiment is summarized in table 2. In the first four days only one-dimension sessions were performed. We felt that the subjects should be given enough time to become familiar with the task and encoding of both signals first in the one-dimension tasks for each of the planes separately before attempting to cope with the two-dimension task which was the primary goal of the investigation. On the first and third days the ECF was provided to the standing subjects in three frontal sessions followed by three sagittal sessions. On the second and the fourth days three frontal plane sessions with ECF provided were followed by a frontal plane session without ECF. Similarly, the following three sagittal sessions were concluded by a sagittal session without ECF. These two extra sessions without ECF were introduced in order to assess the ability of the subjects to track *Target posture* without ECF, but immediately after being exposed to the ECF. We expected that the prior exposure to the ECF might enable the subjects to calibrate their own sensory systems, presumably arm proprioception. Such a calibration might allow adequate tracking even without ECF, provided that the feet stayed at the same location. On each experimental day, the

Table 2. Experimental protocol for the tracking experiment.

			Plane		Feedback	
Day	Session number	Session type	Frontal	Sagittal	ECF	VF
1 and 3		Short visual session				
	1	One-dimension	X		X	
	2	One-dimension	X		X	
	3	One-dimension	X		X	
	4	One-dimension		X	X	
	5	One-dimension		X	X	
	6	One-dimension		X	X	
2 and 4		Short visual session				
	1	One-dimension	X		X	
	2	One-dimension	X		X	
	3	One-dimension	X		X	
	4	One-dimension	X			
	5	One-dimension		X	X	
	6	One-dimension		X	X	
	7	One-dimension		X	X	
	8	One-dimension		X		
5		Short visual session				
	1	One-dimension	X			
	2	One-dimension		X		
		Break				
		Short visual session				
	3	Two-dimension	X	X	X	X
	4	Two-dimension	X	X	X	X
	5	Two-dimension	X	X	X	
	6	Two-dimension	X	X	X	
	7	Two-dimension	X	X	X	
	8	Two-dimension	X	X		
		Break				
		Short visual session				
	9	Two-dimension	X	X		

subjects stood from the first session until the completion of the last session.

The two-dimension sessions were introduced on the fifth experimental day. However, the subjects first completed a one-dimension tracking test in the frontal plane without ECF, followed by a one-dimension test in the sagittal plane without ECF. In contrast to similar sessions conducted on the second and fourth experimental days these two sessions were conducted without prior exposure to the sessions with ECF. They were performed to compare the performance with the extra two sessions performed in each plane on the second and the fourth days. A short break then followed where the subjects were seated. After a short visual session, two two-dimension sessions followed where the subjects received ECF and VF feedback. In the following three sessions, VF was withdrawn leaving only ECF. Then, one session was performed without either type of supplemental feedback. The subjects were seated again for 15 min. After another short visual session the last two-dimension session was performed without feedback. These last two sessions were included following the same rationale as in one-dimension sessions.

All the subjects underwent the described protocol except for Subject 3 who (because of medical complications not related to the experiment) transferred from the rehabilitation centre to the hospital and was, therefore not available after Day 4. The experimental Day 5 for Subject 3 was conducted three weeks later.

Outcome measures

Each trial within every one-dimension session was evaluated in order to determine whether the tracking in a particular trial was successful or not. The following objective criterion was applied. If the time duration when the *Current posture* signal matched the *Target posture* signal, as demonstrated in the figure 5 (*b*), exceeded 50% of the total trial duration, a trial was judged as successful. The threshold of 50% was selected to account for two sources of error. The first is the initial reaction time the subjects needed to recognize the command and to change the posture, which could take up to 30% of the total trial duration. The second source was jittering of the *Current posture* signal, as shown in figures 5 and 6, which occurred as a result of

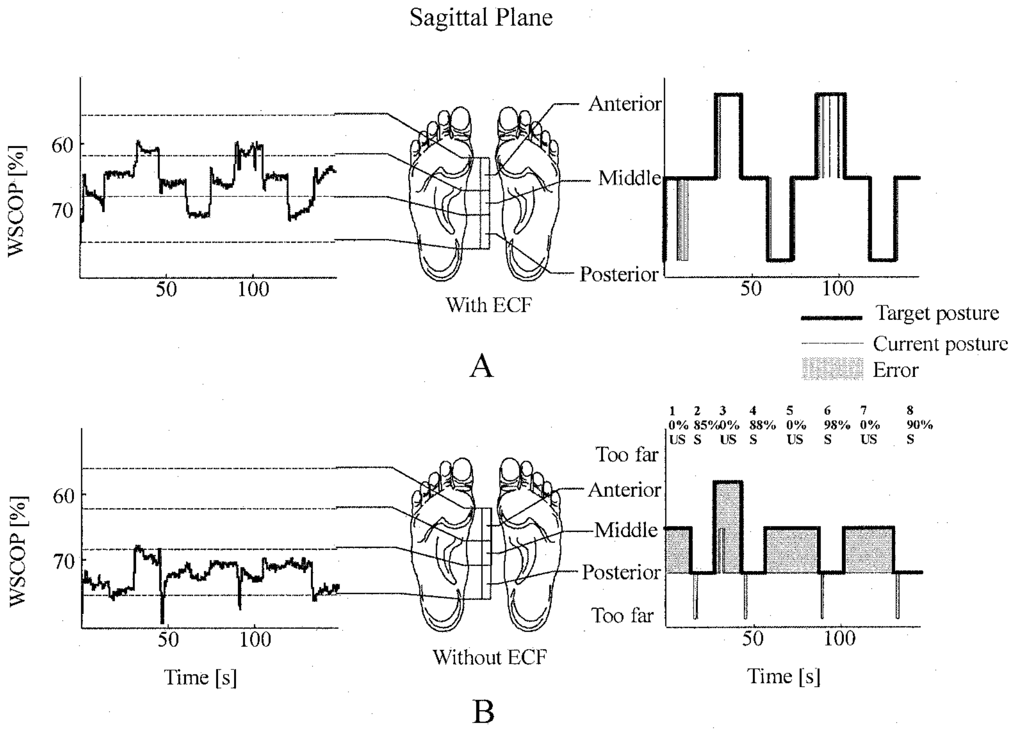


Figure 5. Representative sample of results for one-dimension sessions in the sagittal plane performed (a) with ECF and (b) without ECF. A time course of the WSCOP signal is displayed on the left-hand side of the figure. All three regions are also indicated. On the right-hand side of the figure the thick solid line represents the Target posture, *the thin line represents the* Current posture, *and the shaded regions show the discrepancy between these two signals. Each of the trials in the session performed without ECF is consecutively numbered. The percentage of time when the* Current posture *matched the* Target posture *in a given trial is displayed and each trial is judged to be either successful (S) or unsuccessful (US). If the relative time when the* Current posture *signal matched the* Target posture *signal exceeded 50% of the total trial duration, a trial was judged as a successful.*

the narrow widths of the regions the WSCOP and RVGRF signals were divided into.

In the two-dimension sessions, a trial was recognized as successful only if both tracking dimensions were successful. For every session, the successful trials were expressed as a percentage of the total of that session.

Results

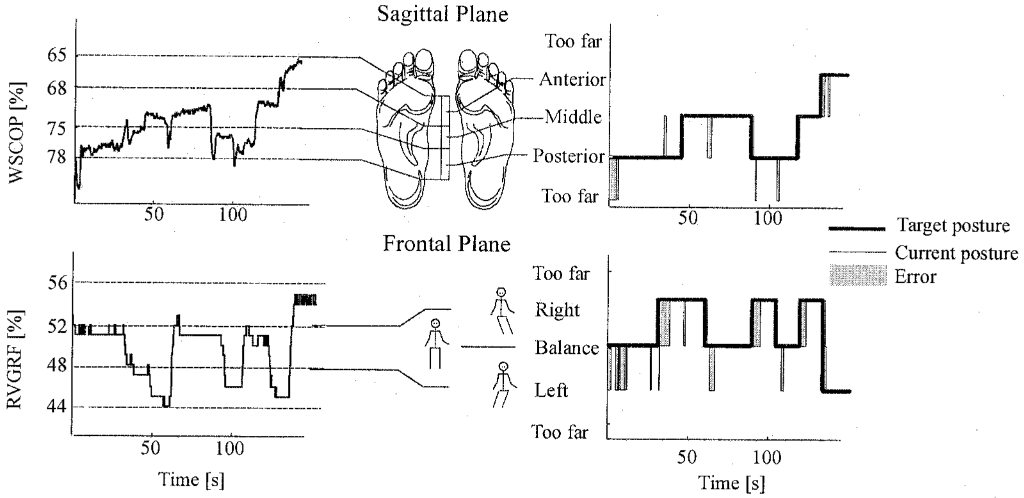
Figure 5 shows the performance of Subject 1 during two one-dimension sagittal plane tracking sessions. In figure 5 (a) the subject received ECF, while Figure 5 (*b*) shows the performance without ECF. The right-hand side of figure 5 shows the time course of the *Target posture* and the *Current posture* signals. The solid thick line represents the *Target posture* as it changed in random fashion throughout the session. The solid thin line represents the *Current posture* signal, which depends on the current value of WSCOP shown on the left-hand side of figure 5. The value of WSCOP is within the targeted region whenever the *Target posture* and *Current posture* signals are matched. Clearly, the tracking performance in figure 5 (*a*) differs significantly from the one shown in figure 5 (*b*).

Figure 6 shows representative two-dimension sessions performed by Subject 2 with and without ECF. When the ECF was delivered (figure 6 (*a*)) well-controlled posture shifts can clearly be seen, reflecting the presence of the 'reference' signal, which was correctly interpreted by the standing subject. In contrast, the success of the subject when tracking the *Target postures* without ECF was poor (figure 6 (*b*)).

Figures 7, 8 and 9 show the collected results for all the sessions performed by all three subjects.

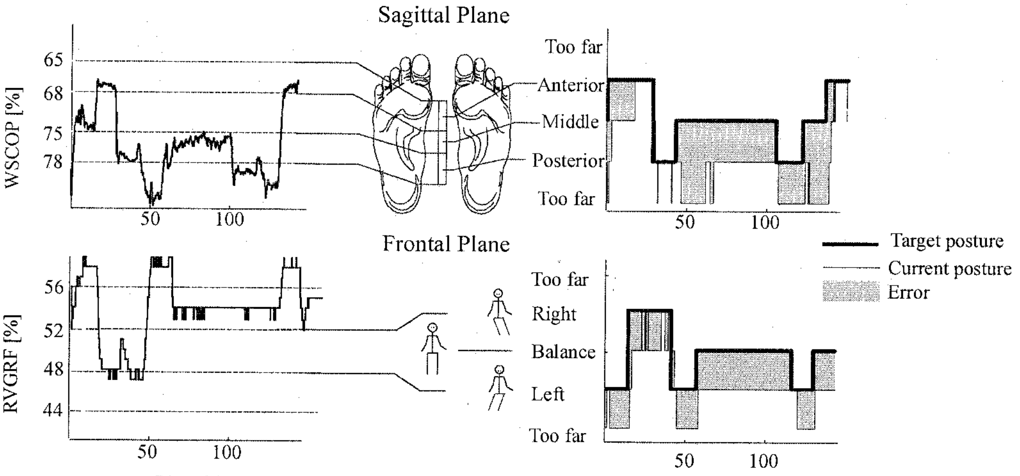
Subject 1

The performance of Subject 1 is shown in figure 7. We can observe a high percentage of successful trials in both planes already on Day 1 of the tracking experiment, indicating that the subject had little difficulty in interpreting the ECF signal. On Day 2, a similar performance in frontal plane tracking can be seen as on Day 1. The only exception was Session 2, where the subject appears to have become confused about which combination of stimulus frequencies corresponds to which posture. The sagittal plane tracking sessions were 100% successful. The same pattern was repeated on Days 3 and 4. These data show that although Subject 1



With ECF

A



Without ECF

B

Figure 6. Representative sample of results for two-dimension sessions in the sagittal plane performed, (a) with ECF and (b) without ECF. On the lower left display in parts (a) and (b), the time course of the RVGRF signal is displayed. On the right-hand side of the figure the thick solid line represents the Target posture, *the thin line represents the* Current posture *and the shaded regions show the discrepancy between the two signals.*

could accurately interpret the ECF code in both planes, the performance in the frontal plane was lower, suggesting that the frontal plane code might have been more difficult to interpret.

The results for one-dimension sessions performed on Days 2 and 4 without ECF, but immediately after the sessions performed with ECF, show that Subject 1 could track *Target postures* very well in the sagittal plane. In the frontal plane he was completely unsuccessful on Day 2 while on Day 4 he was successful in all trials. On Day 5 his performance for the one-dimension tracking without ECF was poorer compared to his performance on Day 4. The results of the two-dimension sessions performed with VF and ECF showed that the subject could reliably track the *Target postures* in both planes simultaneously. The results for the following three sessions performed only with ECF show that Subject 1 could reliably and accurately interpret the two-dimensional ECF code in the absence of VF. In the next session performed without ECF but immediately after the sessions with the ECF, Subject 1 could track less than 40% of the *Target postures*. Finally, for the last session performed also without ECF but after being seated for 15 min, Subject 1 showed very poor success.

Subject 2

Figure 8 shows the tracking results for Subject 2. His performance was very similar to the performance of Subject 1 in all of the sessions. In one-dimension sessions with ECF he could track absolutely accurately in the sagittal plane, while in the frontal plane, like Subject 1, he had

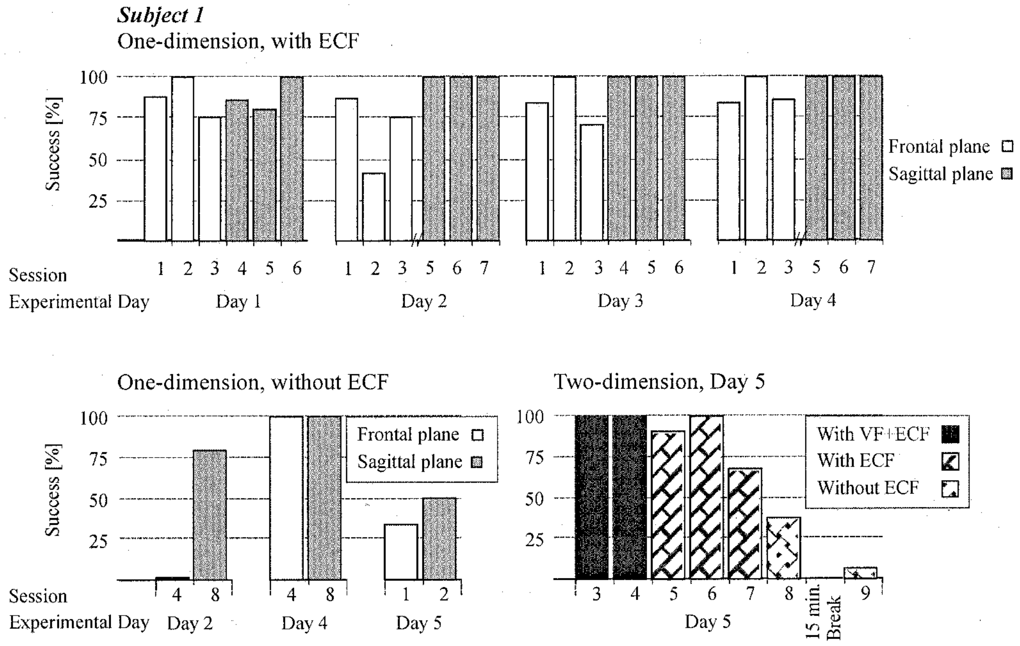


Figure 7. The results of the tracking tests for Subject 1. The upper graph shows the success of the subject while tracking one-dimension Target postures *while being presented with ECF. The lower graph at the left side shows the results for the one-dimension sessions performed without ECF. The lower graph at the right side presents the results for two-dimension tracking tests for various experimental conditions as indicated.*

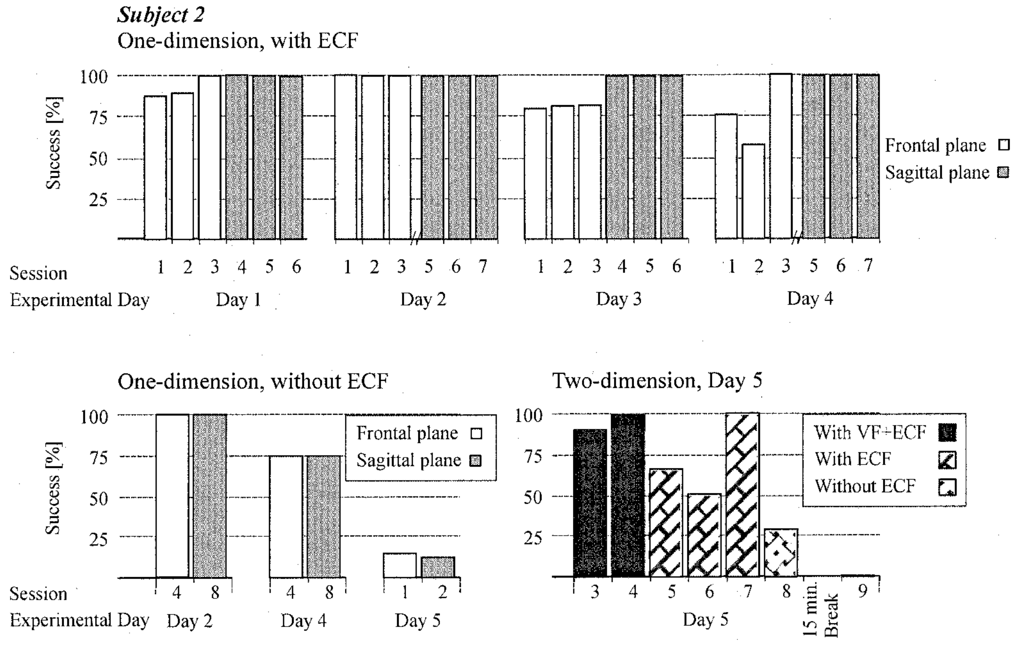


Figure 8. The results of the tracking tests for Subject 2. The upper graph shows the success of the subject while tracking one-dimension Target postures *while being presented with ECF. The lower graph at the left side shows the results for the one-dimension sessions performed without ECF. The lower graph at the right side presents the results for two-dimension tracking tests for various experimental conditions as indicated.*

modest difficulties. In the one-dimension sessions performed without ECF but immediately after the sessions with ECF (Days 2 and 4) Subject 2 could track the *Target postures* quite successfully, however that was not the case on Day 5 where there were no preceding sessions with ECF. This result is again very similar to the performance of Subject 1 under the same conditions. The results of tracking in two dimensions are also very similar to the results of Subject 1, showing that

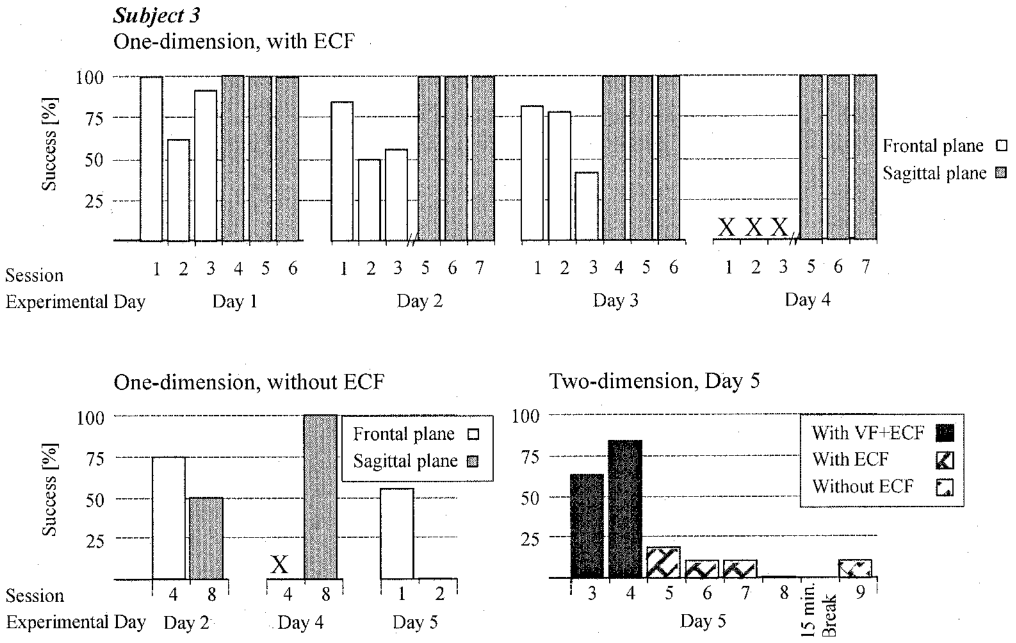


Figure 9. The results of the tracking tests for Subject 3. The upper graph shows the success of the subject while tracking one-dimension Target postures *while being presented with ECF. The lower graph at the left side shows the results for the one-dimension sessions performed without ECF. The lower graph at the right side presents the results for two-dimension tracking tests for various experimental conditions as indicated. X denotes the sessions that were not performed due to pain experienced by the subject.*

Subject 2 could reliably track the *Target postures* when presented with ECF information. Without ECF (Sessions 8 and 9) his performance was clearly much poorer.

Subject 3

Figure 9 displays the results for Subject 3. The results for the one-dimension tracking performed with ECF are similar to the results of Subjects 1 and 2. The first four sessions on Day 4 were omitted, because the subject could not track the *Target postures* due to pain he felt in the region of his trunk. The performance of Subject 3 was also similar in the one-dimension sessions performed without ECF but immediately after the three sessions performed with ECF. Only the results of the two-dimension sessions differ in comparison to the results obtained with Subjects 1 and 2. Subject 3 was able to track the *Target postures* when he was presented with VF and ECF; however, his performance was rather poor when presented only with the ECF information. While observing the performance for each trial of Sessions 5, 6 and 7 on Day 5 we could see the pattern of the WSCOP and RVGRF as shown in figure 6 (*a*), indicating that the subject was tracking the *Target posture.* The only difference was that wrong postures were tracked. It is possible that the subject may have confused the code between the postures and the ECF representation of them. This explanation is plausible since the tracking tests on Day 5 were conducted three weeks after the Day 4 sessions.

Discussion

The two main objectives of this work were: (i) to develop an ECF system that provides a paralysed standing subject with information on posture in the sagittal and frontal planes simultaneously and (ii) to explore whether the paralysed subjects could reliably interpret the two-dimensional ECF signal during the standing task.

Methodological considerations

The presented encoding schemes were developed through extensive experimentation with able-bodied subjects during standing in order to determine the simplest and most intuitive representation of the selected informational variables which would fit the cognitive abilities of a human. However, during standing of a paralysed individual the concentration of a subject must be shared between the task of maintaining standing and the task of interpreting the code presented. Therefore, we might expect that the cognitive abilities of paralysed individuals would be somewhat lower compared to an able-bodied one. In this light, each subject suffering from complete SCI represents a unique case. The residual sensory-motor and cognitive abilities determine whether a particular subject would be able to make use of the comprehensive two-dimensional cognitive feedback information. Furthermore, motivation, concentration and cooperation play an important role in the experiments described. These considerations are reflected in our experimental methods where we sought to minimize factors that could compromise a subject's ability to correctly interpret and make use of the two-dimensional CF. During each experimental day, great care was exercised while putting the electrodes on the subject's torso to assure equal sensation at each site. Also, the number of tracking sessions per day was limited to ensure a high level of concentration in each of the subjects. One of the key factors in the experiments we performed was the motivation of the subjects. For that reason the duration of the experimental evaluation was limited to five days. During the first four days the subjects were required to perform tracking experiments only in one plane at a time in order to gain confidence and a positive attitude toward the orthotic system. Additionally, the sessions where the ECF was withheld were performed only on the second, fourth and the fifth day to ensure that possible failures would not have a negative psychological impact on the subjects.

A visual display was found to be a very effective tool. It was not only essential for a standing paralysed subject during the process of learning the ECF coding scheme. It also served as a monitor for the experimenter who could (during short visual sessions) set up the regions of the WSCOP and RVGRF signals to the values that could be attained by a particular subject. The latter is very important for an objective evaluation of the ECF system since in this way we could be certain that the ability of a particular subject to track a given *Target posture* depended solely on the subject's cognitive abilities to accurately interpret the given codes.

Tracking experiments

The results of the tracking experiment have demonstrated the ability of each participating subject to accurately relate the current posture and the information provided by the ECF system for a single plane of movement. The results in all three subjects are very consistent. It was also demonstrated that two of the three subjects could do the same for two planes of movement simultaneously, after being first trained in interpreting the ECF code for each plane separately over four consecutive days. This indicates that the proposed encoding scheme is sufficiently simple to be learnt. The failure of the third subject to interpret the code in two planes may actually indicate that a period of training is necessary to achieve an adequate performance. Since three weeks passed from his one-dimension training sessions, it is most likely that the learned tasks were forgotten.

Inconsistency can be observed for each subject when looking at the success rates of the sessions performed without ECF under different conditions. For example, in the one-dimension sessions we expected that the tracking performance should be markedly different in the three cases: (1) with ECF, (2) without ECF but immediately after sessions performed with ECF (Days 2 and 4) and (3) without ECF and without a prior session performed with ECF (Day 5). Our expectations turned out not to be the case. However, the success rates for sessions performed without ECF are meaningless when observing a representative session without ECF shown in figure 5 (*b*). It can be clearly seen from the time course of the WSCOP signal that when the ECF was withheld the WSCOP remained for the majority of the session within the *Posterior* range of the signal. All four successful trials were successful only because the *Target posture* changed to *Posterior* on four of the trials, resulting in a 50% success rate for this particular session purely by happenstance. The possibility for this to occur imposes uncertainty regarding the outcome of the sessions performed without ECF in the one-dimension tracking. This is not an issue for the results of the two-dimension tracking where clear differences between all three conditions can be observed not only by looking at the representative examples shown in figure 6, but also from the success rates in the first two subjects, as follows. As expected, the tracking in the sessions performed without ECF after Subjects 1 and 2 were seated for 15 min was very poor. Also, better performance can be seen in the sessions performed without ECF but immediately after the sessions with ECF. These results suggest that the residual sensory apparatus of the standing subject (e.g. proprioception from the arms) might make use of the ECF as a calibration signal. However, when the posture of a subject changes after being seated and then stood up again, the calibration appears to be lost.

Because Subjects 1 and 2 exhibited good tracking ability using the ECF system despite the fact that they have high lesions (C-7 and T-2 respectively), a population of people suffering from paraplegia (to whom the developed ECF system is intended) should not have any difficulties arising from the current electrode configuration of the system.

A perspective on future development

The present form of the experimental ECF system is not suitable for everyday use in paraplegic standing. One problem is the form of the electrotactile display, since great care has to be exercised when placing the surface electrodes to assure that the sensation is the same at all of the stimulation sites. A practical system should make use of sub-dermal implanted electrodes, which have been shown to be very efficient in ECF systems [15]. Such a solution would present good reliability since all the wires would be hidden, and the electrode – tissue impedance would remain stable. A comparison between surface and sub-dermal electrodes regarding the number of JNDs for increases in frequencies has shown that a greater discernibility is obtained with sub-dermal electrodes. Moreover, sub-dermal stimulation also results in a more comfortable sensation [14].

Another problem with the developed experimental ECF set-up is the assessment of the GRF and COP under the feet. Even though we could reliably extract both signals from the shoe insole system, the latter is impractical for every day use, because it requires careful donning, doffing and calibration. An appealing alternative to the use of artificial sensors might be information obtained from natural sensors [16]. An investigation of the feasibility of obtaining natural sensory feedback from the cutaneous nerves innervating the foot sole is in progress. Preliminary results are very encouraging suggesting the possibility to derive GRF and COP signals from combinations of cuff electrode recordings obtained from branches of the tibial and sural nerves [17]. By making use of subdermal electrodes and natural sensing techniques the prospective ECF system would be fully implantable, which should increase its reliability and user acceptability.

Conclusion

A two-dimensional electrocutaneous cognitive feedback system for use in paraplegic standing was developed. We designed an encoding scheme where an underlying relationship between the location and frequency of the stimuli applied to the skin and the information signal, being WSCOP and RVGRL, was incorporated into an artificial communication system. The ability to interpret the code was investigated in tracking experiments during standing of three subjects paralysed due to SCI. The results indicate that the developed encoding scheme could be interpreted reliably if an appropriate preceding period of training is undertaken. Additionally, it was shown that the residual sensory system of the intact upper body was not sufficient to track different postures consistently when the supplemental cognitive feedback was withheld.

Acknowledgements

The authors would like to express their appreciation to the volunteer subjects and medical personnel who participated in the tracking tests, which were carried out at the Institute of Rehabilitation of the Republic of Slovenia, Ljubljana, Slovenia. Further, we extend our appreciation to Professor Dejan Popović for careful reading of the manuscript and many useful suggestions. The investigation was supported by the Danish National Research Foundation.

References

1. KRALJ, A., and BAJD, T., 1989, *Functional Electrical Stimulation: Standing and Walking after Spinal Cord Injury* (Boca Raton, FL: CRC Press).
2. KRALJ, A., BAJD, T., TURK, R., and BENKO, H., 1986, Posture switching for prolonging functional electrical stimulation standing in paraplegic patients. *Paraplegia*, **24,** 221–230.
3. MATJAČIĆ, Z., and BAJD, T., 1998, Arm free paraplegic standing: Part I—Control model synthesis and simulation. *IEEE Transactions on Rehabilitation Engineering*, **6,** 125–138.
4. VELTINK, P. H., and DONALDSON, N., 1998, A perspective on the control of FES-supported standing. *IEEE Transactions on Rehabilitation Engineering*, **6,** 109–112.
5. PHILLIPS, C. A., and PETROFSKY, J. S., 1986, A total neural prosthesis for spinal cord injury rehabilitation: the cognitive feedback system with a functional electrical stimulation (FES) orthosis. *The Journal of Neurological & Orthopaedic Medicine & Surgery*, **7,** 231–238.
6. TURK, R., BAJD, T., BENKO, H., and SEGA, J., 1982, Balance training by means of biofeedback. *Zdravniski Vestnik*, **51,** 108–109 (in Slovenian).
7. MATJAČIĆ, Z., and BAJD, T., 1998, Arm free paraplegic standing: Part II—Experimental results. *IEEE Transactions on Rehabilitation Engineering*, **6**, 139–150.
8. ANDREWS, B. J., BAXENDALE, R. H., BARNETT, R., PHILLIPS, G. F., YAMAZAKI, T., PAUL, J. P., and FREEMAN, P. A., 1988, Hybrid FES orthosis incorporating closed loop and sensory feedback. *Journal of Biomedical Engineering*, **10,** 189–195.
9. WINTER, D. A., PRINCE, F., FRANK, J. S., POWELL, C., and ZABJEK, K. F., 1996, Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology*, **75,** 2334–2343.
10. SZETO, A. Y. J., and SAUNDERS, F. A., 1982, Electrocutaneous stimulation for sensory communication in rehabilitation engineering. *IEEE Transactions on Biomedical Engineering*, **29,** 300–308.
11. KACZMAREK, K. A., WEBSTER, J. G., BACH-Y-RITA, P., and TOMPKINS, W. J., 1991, Electrotactile and vibrotactile displays for sensory substitutions systems. *IEEE Transactions on Biomedical Engineering*, **38,** 1–16.
12. RISO, R. R., IGNANI, A. R., and KEITH, M. W., 1991, Cognitive feedback for use with FNS upper extremity neuroprostheses. *IEEE Transactions on Biomedical Engineering*, **38,** 29–38.
13. SZETO, A. Y. J., and RISO, R. R., 1990, Sensory feedback using electrical stimulation of the tactile sense. *Rehabilitation Engineering*, edited R. Smith and J. Leslie (Boca Raton, FL: CRC Press), Chap. 3.
14. RISO, R. R., SZETO, A. Y. J., and KEITH, M. W., 1982, Comparison of subdermal versus surface electrocutaneous stimulation. *IEEE Frontiers of Engineering in Health Care*, edited by A. R. Potvin and J. H. Potvin (New York: The Society), 343–347.
15. RISO, R. R., IGNANI, A. R., and KEITH, M. W., 1989, Electrocutaneous sensations elicited using subdermally located electrodes. *Automedica*, **11,** 25.
16. SINKJAER, T., HAUGLAND, M., STRUIJK, J. J., and RISO, R. R., 1999, Long-term cuff electrode recordings from peripheral nerves in animals and humans. *Modern Techniques in Neuroscience*, edited by U. Windhorst and H. Johansson (Berlin: Springer-Verlag), Chap. 29.
17. ANDREASEN, L. N., JENSEN, W., VELTINK, P. H., and STRUIJK, J. J., 1996, Natural sensory feedback for control of standing. *Proceedings of 18th Annual Meeting IEEE Engineering in Medicine and Biology Society*, Amsterdam, pp. 57–58.