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Paraplegics standing up using multichannel FES and arm support

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The suitability of multichannel functional electrical stimulation (FES) during the standing-up manoeuvre for therapeutic home use was investigated. Two spinal cord-injured subjects (SCI) participated in the study. Ankle plantar flexors, knee extensors and hip extensors were stimulated. The amplitude of the stimulation pulses depended on the current phase of raising. The sit-to-stand process was divided into three phases by detecting characteristic events in the vertical handle reaction force. It was found that the multichannel FES did not contribute to the decrease of the arm support force when compared with stimulation of knee extensors only. However, stimulation of the hip extensors could speed up the raising process. Increased repeatability and faster standing up were observed when the stimulation began before the start of raising.

Introduction

Daily standing and walking exercize with the help of functional electrical stimulation (FES) can improve the quality of paraplegics' lives, since these activities can help to prevent several physiological problems caused by paraplegia. The simplest walking pattern requires two pairs of electrodes per leg [1]. Stimulation of knee extensors locks the knee joint during the stance phase, while during the swing phase stimulation of the peroneal nerve triggers the withdrawal reflex. Since the application of such an FES system is relatively quick and easy in Slovenia, it is given to paraplegics for home use. Standing up from a wheel chair is achieved by stimulating both knee extensors [2]. The paraplegic starts the stimulation by pressing a button on the handle of the walking frame before beginning the standing-up manoeuvre. The fact that such standing up involves considerably more arm effort than walking can discourage patients from exercizing every day.

The possibility of increasing the efficiency of the sit-to-stand transfer by introducing additional stimulation channels was investigated. To avoid placing sensors on the patients' body and to minimize the number of subject-specific parameters that have to be determined, a simple FES control was implemented. The FES control used solely the signal of the vertical force exerted on the arm-supporting frame to trigger the stimulation patterns.

Several new FES control methods aimed to improve the standing-up process were proposed [3,4]. FES control strategies that support the movement driven by the voluntary upper body effort are particularly promising [5,6]. However, the complexity of a control strategy yields not only efficiency, but also the cumbersome application of a rehabilitative system, as several sensors need to be placed on the body and the patient's antropometric and musculoskeletal parameters have to be identified. Complex FES systems are difficult to use without the help of a physiotherapist and outside a laboratory environment.

Materials and methods

A subject with relatively little practice in FES usage (PS, male, complete T6 lesion, 70 kg, 185 cm, 7 months of FES usage) and an experienced FES user (MT, female, incomplete T4–T5 lesion, no active muscles, skin perception preserved, 71.5 kg, 171 cm, 8 years of FES usage) (figure 1) participated in the study. Both subjects completed a standard FES rehabilitation training at the Rehabilitation Institute of the Republic of Slovenia, where they learnt to walk with four-channel FES. They have continued to practise FES walking at home.

Monophasic rectangular current pulses with frequency 40 Hz and pulse width 300 μs were delivered through surface electrodes. The amplitude of the stimulation pulses varied according to the actual phase (figure 2). Three phases were defined: quiet sitting, rising and stabilization. To assess the influence of each particular stimulated muscle group on the manoeuvre, raisings with four different stimulation patterns were performed (figure 2). During the rising phase, the knee and hip extensors were maximally stimulated to reduce the required arm effort. When stabilization of the standing posture occurred, the stimulation of hip extensors was stopped and the stimulation of knee extensors was reduced. When standing, the function of the knee extensors is to lock the joints in the extended position, and excessive muscle fatiguing should be avoided. The ankle plantar flexor stimulation during the stabilization phase helped to maintain the knees locked while the subject was leaning forward slightly.

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Figure 1. Paraplegic subject MT during standing up with the help of FES.

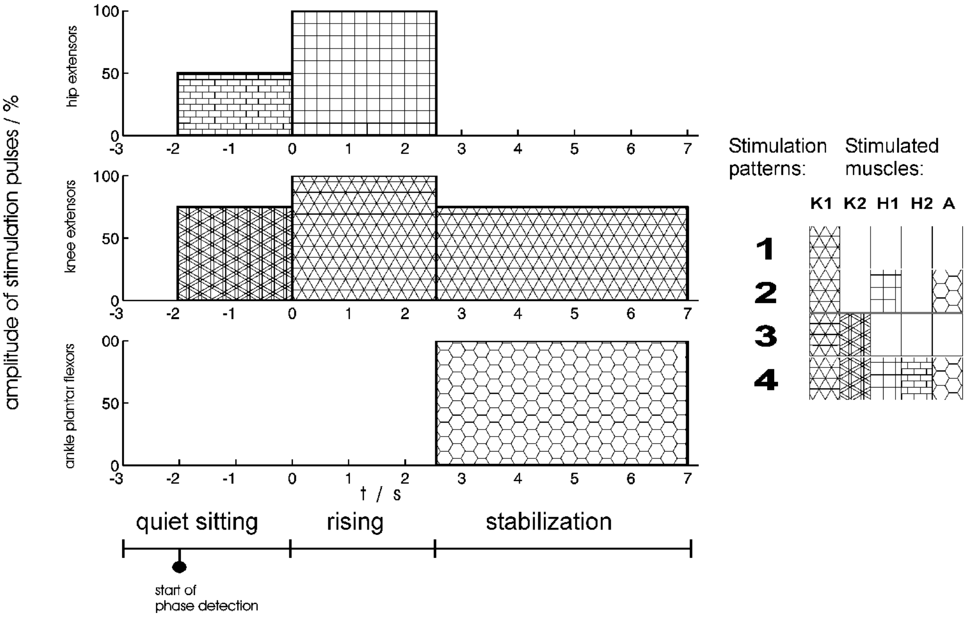

Figure 2. Stimulation patterns. The hatchings that appear in each row indicate which muscles were stimulated during a particular stimulation pattern: 1, knee extensors were stimulated during the rising and stabilization phase (K1); 2, in addition to the stimulation of knee extensors (K1), hip extensors during rising (H1) and ankle plantar flexors during the stabilization phase (A) were stimulated; 3, same as the stimulation pattern 1, except that the knee extensors were also stimulated during quiet sitting (K2); 4, same as the stimulation pattern 2, except that the knee (K2) and hip extensors (H2) were also stimulated during quiet sitting. The values 0 and 100% correspond to the threshold and saturation of the recruitment curve, respectively.

A skilled physiotherapist determined the threshold and saturation of the recruitment curve for each muscle group by appropriate muscle belly and tendon palpation. The stimulated muscles that mostly influence the reliability of standing up are knee extensors. Left threshold, left saturation, right threshold and right saturation of the knee extensors were 25.3, 44.6, 13.1 and 34.7 mA in MT, and 39.2, 71.4, 37.5 and 71.8 mA in PS. In the hip extensors of MT, the maximal stimulation intensity was adjusted according to the pain threshold.

The transitions between phases occurred when typical events in the time-course of the vertical handle reaction force were detected [7]. When the patient was ready to stand up, he started the phase-detection algorithm by pressing a button on the handle of the arm-supporting frame. The rising phase started when the derivative of the vertical handle reaction force began to increase noticeably:

$$\frac{dF_{\mathrm{hndl}}}{dt} > \mathrm{THRESHOLD}_1 \qquad (1)$$

The beginning of the stabilization phase coincided with the decrease of the handle force below its peak value:

$$F_{\mathrm{hndlMAX}} - F_{\mathrm{hndl}} > \mathrm{THRESHOLD}_2 \qquad (2)$$

At the beginning of the investigation, three trials were performed to adjust the parameters for phase detection. Only the knee extensors were stimulated in these first trials. The time-courses of the vertical handle reaction force and its derivative were analysed after each trial. The parameter $\mathrm{THRESHOLD}_1$ was set as low as possible to detect the intention to stand up quickly, but at the same time it was set sufficiently higher than the peaks of the force derivative during quiet sitting. The parameter $THRESHOLD_2$ was chosen in such a way that the stabilization phase occurred approximately at the instant of knee extension completion. $THRESHOLD_1$ and $THRESHOLD_2$ were set to 75 N s^{-1} and 200 N in MT, while in PS they were set to 75 N s^{-1} and 180 N, respectively.

Afterwards, the subjects stood up with four different stimulation patterns (figure 2). Each type of raising was performed three times. In the first type of raisings, only the knee extensors were stimulated (pattern 1). The stimulation of hip extensors and ankle plantar flexors was added during the second type of standing up (pattern 2). In patterns 3 and 4, stimulation was applied during sitting to assess the influence of the delay of muscle activation on the efficiency of the leg support.

The stimulation control algorithm was implemented on a 486 computer. The computer controlled two four-channel stimulators through optically insulated RS232 ports. The handle force was measured by a six-axis JR3 robot wrist sensor (JR3, Inc., Woodland, CA, USA) mounted under the right handle of the supporting frame. Symmetry of the standing-up manoeuvre with respect to the sagittal plane was assumed. The forces under the right foot and the seat support forces were assessed by AMTI force plates (AMTI, Inc., Newton, MA, USA). An OPTOTRAK contactless optical system (Northern Digital, Inc., Waterloo, Canada) measured the joint trajectories. The joint torques were calculated by a 15-segment inverse dynamic model of the body [8].

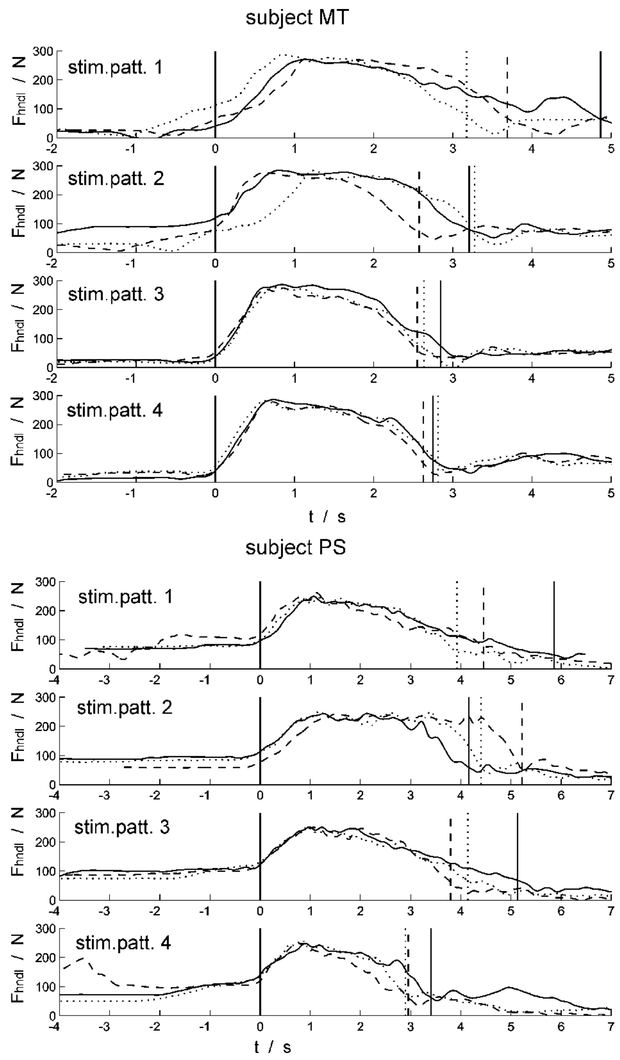

Figure 3. Vertical handle reaction forces. The first, second and third trial of each stimulation pattern are indicated by a solid, dashed and dotted line, respectively. The instant 0 coincides with the start of the rising phase and is denoted by a vertical line. The other three vertical lines indicate the beginning of the stabilization phase for each trial.

Results and discussion

It was our assumption that the stimulation of more muscle groups, rather than only knee extensors, would result primarily in reducing the arm effort. The vertical handle reaction force was chosen to evaluate the arm effort (figure 3).

The intensity of the arm force did not depend on the stimulation pattern. The standard deviation of the maximum arm force was 5.38 and 5.42 N in MT and PS, respectively. When MT was stimulated during quiet sitting (patterns 3 and 4), the duration of the rising phase was shorter and the time-courses were less variable. In PS, the shape of the arm force time-course was influenced by the stimulation of the hip muscles. At the end of the rising phase, the curves decreased faster when the hip muscles were stimulated (patterns 2 and 4), yielding noticeably shorter rising phase. The rising phase of PS was even further decreased when the stimulation began during sitting.

Figure 4 shows that the calculated maximal knee moments were low. Roughly, five to eight times higher moments were measured in intact persons by other authors [2,9]. Figure 4 also shows that the delay of muscle activation was sufficiently short. When the knee extensors were not stimulated during the sitting phase, the moment increased fast enough to reach its maximal intensity by the time of seat-off. It seems that the subjects stood up faster when the stimulation was delivered during sitting because they felt safer.

The transitions between phases were always detected by the stimulation control algorithm. The vertical arm force appears to contain sufficient information to distribute reliably the sequence of the phases along the raising manoeuvre, thus ensuring the desired delivery of stimulation.

Conclusion

The six-channel stimulation (patterns 2 and 4) did not diminish the intensity of the arm support force as

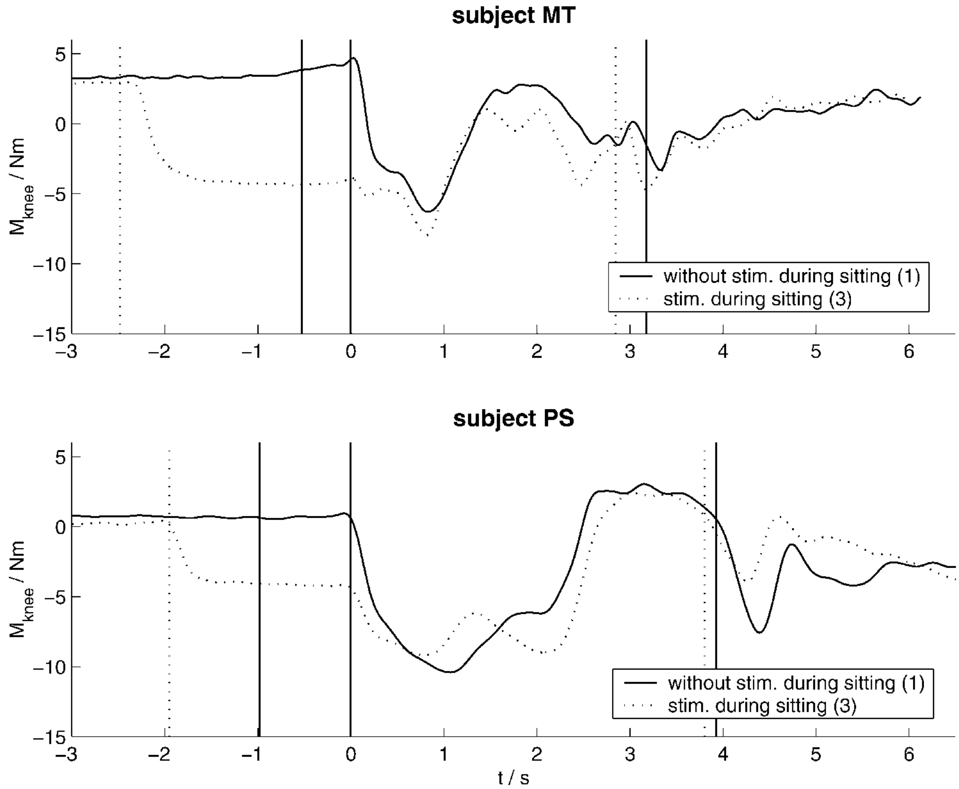

Figure 4. Knee joint moments in the sagittal plane. The solid line indicates a trial where stimulation of knee extensors began at the start of the rising phase (stimulation pattern 1). A trial with stimulation of the knee extensors during sitting is represented by the dotted line (stimulation pattern 3). The three vertical lines indicate the start of phase detection and the occurrence of the rising and stabilization phase. The instant 0 coincides with the start of the rising phase.

compared with the two-channel stimulation of knee extensors (patterns 1 and 3). The application of electrical stimulation during sitting helped the patients to stand up faster. Thus, the overall work effort was reduced because the peak arm forces were maintained over a shorter period. In PS, the addition of hip extensor stimulation speeded up the raising manoeuvre. The vertical handle reaction force proved a reliable signal for phase detection. In future studies, the rising phase could be split into more phases [7].

The subjects involved in the study completed a standard FES rehabilitation programme at the rehabilitation centre. The emphasis of the subjects' training at the rehabilitation centre was on reliable FES-assisted walking. Since raising requires higher muscle forces than walking, an additional muscle-strengthening programme might improve the results of the study. However, the main aim of exercizing with FES at home is to stand in an erect posture for as long as possible to prevent physiological problems caused by continuous sitting. After the end of a special strengthening programme, the additionally gained muscle mass would disappear, while standing up represents only a fraction of the total FES exercizing time.

It seems that the benefits of the multichannel FES system cannot justify the effort needed to place four additional pairs of electrodes. However, rather than for therapeutic use, multichannel FES standing up might be more suitable for frequent functional activities such as reaching highly placed objects. At present, only implanted electrodes can effectively avoid the need for cumbersome application of a multichannel FES system thus making it acceptable for frequent use.

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