Multichannel FES Standing-up

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Abstract - *Spinal cord injuried (SCI) subjects can raise from a chair by the help of arm support and open-loop electrical stimulation of the knee extensors. The knee joint torques produced by electrically stimulated knee extensors are normally low. Thus extensive effort of upper extremities is required. The aim of the investigation was to study the influence of the stimulation of ankle plantar flexors and hip extensors on the efficiency of standing-up process.*

SCI subject performed raising from sitting to standing position with surface electrical stimulation of different combinations of muscle groups. The stimulation sequences depended on the phase of the sit-to-stand process. The current phase was detected by measuring the vertical handle reaction force. A robot wrist sensor was used to asses the handle reaction force. The stimulation amplitude for each particular muscle group was scaled to fit between the treshold and saturation value of the recruitment curve. The body kinematics was assessed with contactless optical system. The ground and seat reaction forces were measured with force plates. A 3-dimensional model was used to compute the joint torques.

No major differences were noticed between the different types of raising. Additional electrodes on hip extensors and ankle plantar flexors seem not to be justified for daily use of functional electrical stimulation. Standing up is a realtively quick process. It appears that the patient cannot react properly in order to use his stimulated lower extremities to support the standing-up to a larger extent.

Keywords: functional electrical stimulation, standing-up, paraplegia

1. Introduction

Daily standing and walking exercise by the help of functional electrical stimulation (FES) can improve the quality of paraplegic persons' life. These two activities can help to prevent several physiological problems caused by paraplegia. The ability to raise from a chair is necessary in order to enable a paraplegic person to practice standing and walking at home without the help of a physiotherapist. Paraplegic patients usually stand up using arm support and open-loop stimulation of the knee extensors [1]. As such standing-up requires considerably more effort than standing or walking, it can discourage the patients from exercising every day [2] .

The efficiency of the sit-to-stand transfer can be improved by stimulating more muscle groups than the knee extensors only. The stimulation intensity of each muscle group has to be controlled in order to achieve an effective use of electrically stimulated lower extremities. Control strategies taking into account the patient's voluntary activity are particularly promising [3, 4]. There are two drawbacks of these strategies: either quite complex model of the subject or many sensors are required.

The aim of the present investigation was to study the influence of the stimulation of hip extensors and ankle plantar flexors on efficiency of standing-up process. The stimulation control approach was simple in order to minimize the number of sensors. Thus, the system could be easily adapted to everyday comfortable use.

2. Instrumentation

The spinal cord injuried subject was seated on a chair with dimensions identical to a comercially available wheelchair. During standing-up the subject made use of arm support. The stimulation control algorithm was implemented on a 486 computer. The algorithm used the vertical handle reaction force to determine the phase of the standing-up process. The handle reaction force was assessed by a six axis JR3 robot wrist sensor mounted under the right handle of the supporting frame. The JR3 output was sampled at 200 Hz and filtered by the second order Butterworth filter with 10 Hz cut-off frequency. The PC computer controlled two four channel stimulators through optically insulated RS232 ports. Three channels of each stimulator were used for a single leg. The stimulators were mounted to the front side of the supporting frame. The stimulators provided rectangular monophasic current pulses.

The body movement was assessed with contactless OPTOTRAK system (Northern Digital Inc., Waterloo, Canada). The system measured 3D positions of infrared markers which were placed in the approximate centers of the patient's right side joints of the upper and lower extremities. It was assumed that the body moves symetrically with respect to the sagittal plane. The calculation of the net joint moments required also the measurement of seat and ground reaction forces. These forces were measured using two AMTI force plates (AMTI, Inc., Newton, MA, U.S.A.). One force plate was placed under the patient's right foot, while the other under the seat. All data for off-line computation were sampled at 50 Hz.

3. Methods

The multichannel FES assisted standing-up was studied in a single paralyzed SCI person. The subject has been using FES for 8 years. She was injuried at T4-T5 spinal cord level. Her weight was 71.5 kg and height 171 cm.

The vertical handle reaction force was used to indicate the current phase of the sit-to-stand process. This variable can be measured easily as the sensor is fixed in a walking frame or crutch and not on the patient's body. Because only one sensor is needed, the system is relatively inexpensive. Three phases were detected: quiet sitting, raising and stabilization. When the patient was ready to stand up, he started the phase detection algorithm by pushing a button on the handle. The raising phase started when the derivative of the handle reaction force begun to increase significantly:

$$\frac{dF_{handle}}{dt} > THRESHOLD_1 \tag{1}$$

The stabilization phase occured when the knee joint was fully extended. The beginning of the stabilization phase coincided with the decrease of the handle force below its peak value:

$$F_{handleMAX} - F_{handle} > THRESHOLD_2 \tag{2}$$

Three muscle groups were stimulated: hip extensors, knee extensors and ankle plantar flexors. The stimulation frequency was 40 Hz, the pulse width 300 µs, while the pulse amplitude varied according to the stimulation sequence (Figure 1). A skilled physiotherapist determined the threshold and the maximal stimulation value of the recruitment curve for each muscle group by palpation. As the sensation was preserved in the selected SCI subject, the amplitude of electrical stimulation was adjusted according to the pain threshold. The stimulation sequences were scaled in such a manner that 0 % and 100 % represented the maximal value and the saturation, respectively. During the raising the knee and hip extensors were maximally stimulated in order to reduce the required arm effort. When stabilization of the standing posture occurred, the stimulation of hip extensors stopped and the stimulation of knee extensors was reduced. When standing the function of knee extensors is to lock the joints in the extended position, therefore, excessive muscle fatiguing should be avoided. The ankle plantar flexors stimulation during the stabilization phase helped to maintain the erect posture.

The subject performed raising in the manner, she was trained during the rehabilitation program (Figure 2). In the beginning three trials were performed to adjust the parameters for phase detection. Only the knee extensors were stimulated in these first trials. Afterwards four types of raising were performed with different combinations of stimulated muscle groups:

1. stimulation of knee extensors during rising
2. stimulation of all muscle groups during rising
3. stimulation of knee extensors during sitting and rising
4. stimulation of all muscle groups during sitting and rising

In stimulation patterns 1 and 2 the muscles were not stimulated during the sitting phase. In types 3 and 4 the stimulation started as soon as the subject pushed the button on the handle. The computer emitted a voice signal 1 s after the start of the stimulation. This was a command for the patient to start the standing-up. However, the beginning of the raising phase was detected by the computer. Three trials of each type of raising were measured.

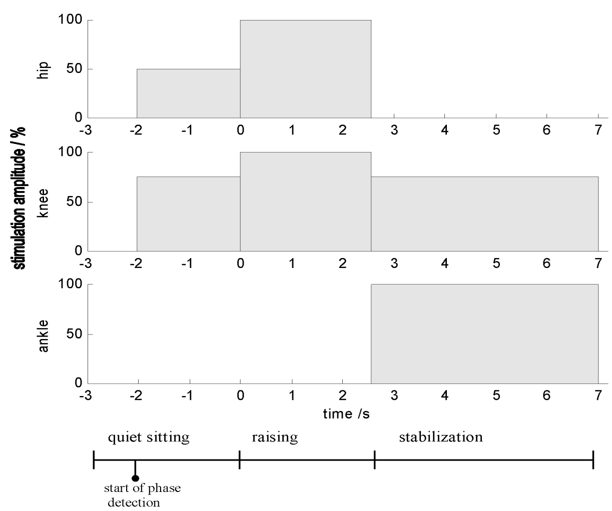

Fig. 1: Stimulation sequence during raising of type 4

4. Results

The vertical handle reaction force, its derivative, and the knee angle during typical raising of the paraplegic subject are shown in Figure 3. The time 0s coincides with the start of the raising phase. The dotted, dashed, and solid vertical lines indicate the start of phase detection, the beginning of the raising phase and the start of the stabilization phase, respectively. The transitions between phases were always detected correctly. The vertical arm force appears to contain sufficient information about the current state of the standing-up process.

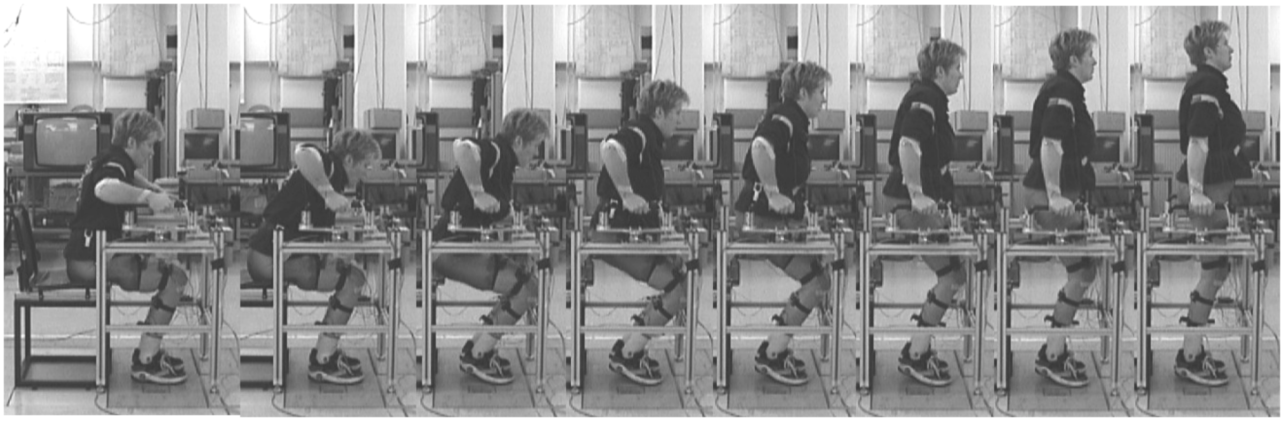

Figure 2: Paraplegic subject during standing-up

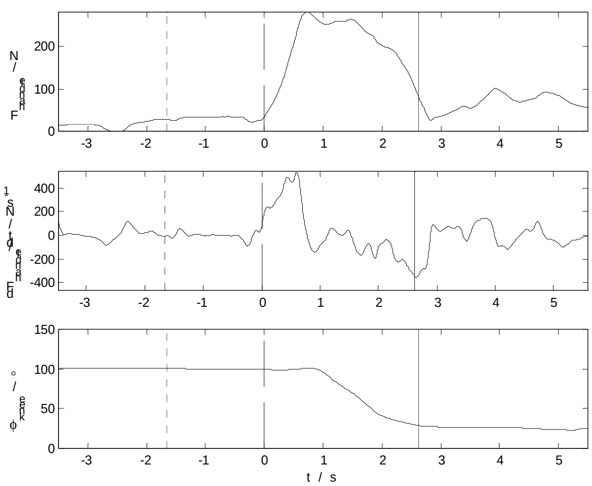

Fig. 3: Standing-up phases detection

The stimulation of more muscle groups, rather than only knee extensors, is primarily intended for reducing the arm effort. The vertical handle reaction forces during different types of raising are compared in Figure 4. The average time courses of three trials are presented in Fig. 4. No major difference can be observed. When the subject was stimulated while sitting, the handle force rised towards the peak value and decreased faster. The patient tried to stand up as close to the sound signal as possible. This explains fast raising. The peak values of the handle reaction force were similar during all four types of raising.

In Figure 5 the knee moments of two trials are presented. The effect of the stimulation of knee extensors during sitting can be easily observed. The average time interval between the start of stimulation and the instant when the knee torque increased over 95% of its peak value was 0,79 s. When the knee extensors were not stimulated during sitting, the knee torque peak was found to occur approximately at the moment of seat-off. Thus, the delay of muscle activation did not affect the contribution of the knee extensors to body lifting significantly. On the other hand the stimulation before the standing-up initiation apperas not to deteriorate the standing-up manoeuvre.

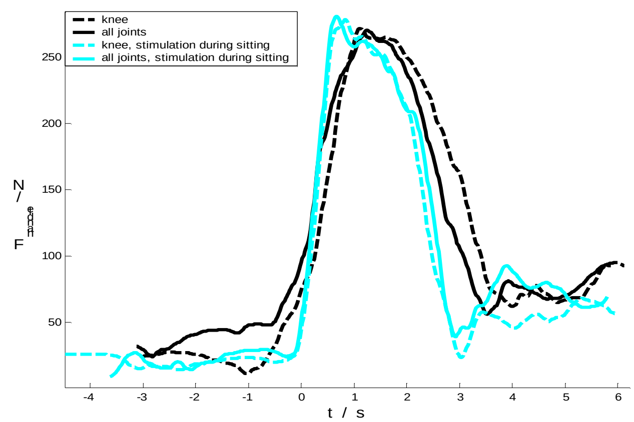

Fig. 4: Comparison of vertical arm forces during different types of standing-up

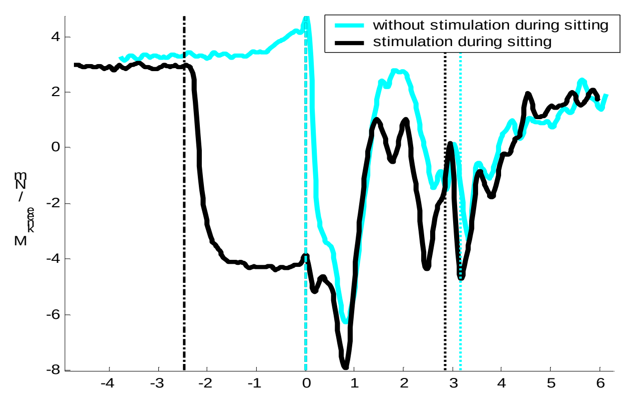

Fig. 5: Knee moment during standing-up with only knee extensors stimulated. The vertical lines represent the start of stimulation, the start of raising and the beginning of stabilization phase.

No major effects of ankle plantar flexors stimulation were observed (Figure 6). When the patient was in the standing position, the ankle joint seemed to reach the limit of its range of dorsal motion. The passive joint moment acted in the same direction as the moment due to stimulation. The moment caused by the stimulation did not have a noticeable role, as the passive moment was considerably higher. The subject was standing on the toes because of the contractures limiting the ankle joint's range of motion.

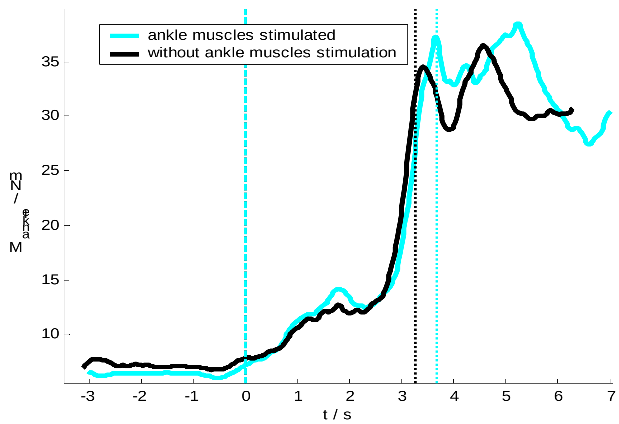

Fig. 6: Ankle moment during raising with stimulation of knee extensors (type 1) and with stimulation of all muscle groups (type 2).

The hip torque pushed the joint into the flexion at the moment of seat-off (Figure 7). This probably occured because the electrodes placed over the knee extensors activated also the rectus femoris muscle group. The torque produced by the rectus femoris neutralized the effect of gluteus maximus stimulation.

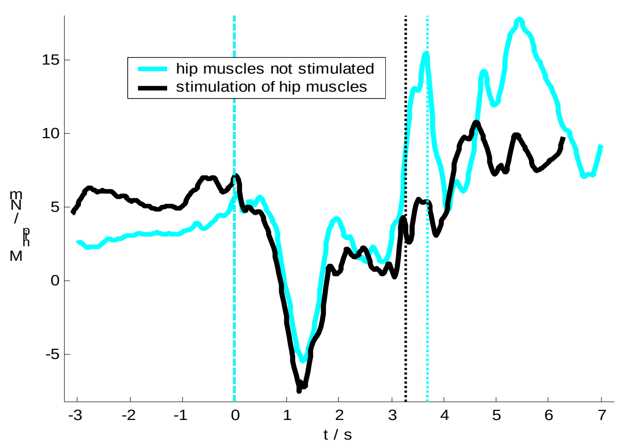

Fig 7.: A raising trial with stimulation of knee extensors (type 1) and a raising with all muscle group stimulated (type 2).

5. Conclusion

The patient included in this study was an experienced FES user who excelled in mastering standing-up with on/off activation of knee extensors. However, the subject did not adapt her rising to take advantage of several stimulated muscle groups. Even when the patient was provided with additional information about the state of the lower extremities, she was not able to react. The process of raising on average lasted only about 3s. This problem can be partially solved by designing a controller that adapts the stimulation to the voluntary effort. The efficiency of the controller would be limited by the rising times of the stimulated muscles which reached 0.9s in our study.

Sufficient information was provided by the vertical handle reaction force to correctly distinguish between the phases during standing-up. By the help of reaction forces the standing-up could be divided into more phases [5]. However, because the stimulated muscles produced insufficient joint moments, the raising phase was not split into more phases.

Although the patient’s stimulated muscles were strong enough to provide reliable standing, they were not able to produce sufficient torque to disburden the arms during the standing-up maneouvre. The average knee joint moment at seat-off was only 14 Nm, while the moment at the knee joint due to arm action was 128 Nm. The sum of these two moments is comparable to the maximal knee joint moment of a healthy person standing-up without arm support (about 160 Nm according to [6]). The maximal horizontal distance from the knee joint to the center of mass of the upper body during raising was 0.21 m. During quiet standing this distance reached only about 0.03 m. It is evident that the knee moment during raising should be at least seven times larger than during standing in order to enable standing-up without arm support.

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