PARAPLEGIC STANDING SUPPORTED BY FES-CONTROLLED ANKLE STIFFNESS

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Abstract

The objective of this study was to investigate whether a paraplegic subject is able to maintain balance during standing by means of voluntary and reflex activity of the upper body while being supported by closed loop controlled ankle stiffness using FES. The knees and hips of the subject were held in extended positions by a mechanical apparatus, which restrained movement to the sagittal plane. The subject underwent several training sessions where the appropriate level of stiffness around the ankles was maintained by the mechanical apparatus. This enabled the subject to learn how to use the upper body for balancing. After the subject gained adequate skills closed-loop FES was employed to regulate ankle stiffness and in subsequent standing sessions the subject had no difficulties in maintaining balance. When the FES support was withheld the balancing was not possible.

Introduction/Background

Restoring standing by means of functional electrical stimulation (FES) after spinal cord injury has been a subject of research for many years [3]. The early approaches used open-loop stimulation to hold the knees extended. The hips were hyperextended while subjects used the arms to maintain balance. Hunt *et al.* [1] have shown that paraplegic standing without arm support can be achieved for short periods. In [1], the subject was assumed in the simplest configuration as a single-link inverted pendulum.

All previous control schemes cannot be called "functional" because either the subject has to use his arms to stabilise himself [3] or the subject is restricted in his freedom of movement by rigid and rather conservative simplifications [1].

Matjačić and Bajd [4] have demonstrated that a paraplegic subject, after appropriate training, is able to stabilise himself using his trunk muscles if a certain level of stiffness around each ankle joint is present (approx. 10 Nm/deg). In [4], the ankle stiffness was applied by hydraulic actuators, which acted as artificial ankle joints. Recently, Hunt *et al.* [2] have shown that ankle stiffness can be controlled by FES.

The aim of this study was to substitute the action of hydraulic actuators [4] with closed loop FES [2] and investigate the feasibility of "functional" paraplegic standing [5].

Methods

The experimental device called the "multi-purpose rehabilitation frame" (MRF) was used to brace the knees and hips of the paraplegic subject and restrain the movement to the sagittal plane as shown in Figure 1. The device is described in detail in [6]. The subject in our study was not able to keep his upper body upright without holding himself onto the frame due to his rather high level of lesion (T5) and his rather weak trunk muscles. But since the frame is moving with the subject's lower body, this does not prevent the subject from falling over and requires active balancing to maintain standing.

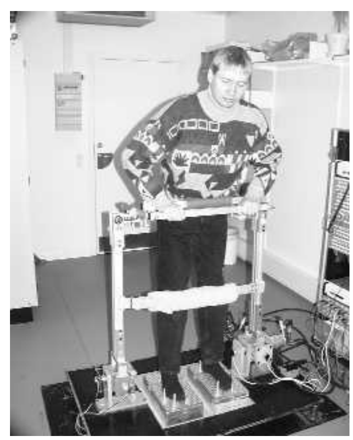

Figure 1: Subject balancing while standing in the MRF.

First, the subject underwent several training sessions where the appropriate level of stiffness around the ankles was maintained by the MRF. This enabled the subject to learn how to use the upper body for balancing at a stiffness level of 8 Nm/deg. The subject gained adequate balancing skills after three sessions of balancing that lasted up to half an hour.

After the initial three sessions the closed-loop FES control of ankle stiffness was introduced. The paraplegic subject stood on two AMTI forceplates with the knees mechanically locked by a leather belt as shown in Figure 1. The frame supported the subject around the pelvis and permitted motion in the sagittal plane in a range of ±18° around the vertical position. The angle of inclination of the frame in the sagittal plane θ_S was measured by potentiometer and multiplied by the desired stiffness value (typically 10 Nm/deg) which provided the total reference moment $m_{ref,total}$. According to the relative load distribution the total reference moment was distributed between the left and right ankles (c.f. Figure 2). The blocks labeled "left ankle" and "right ankle" in Figure 2 are each closed-loop moment controllers of the form shown in Figure 3, where u means the control signal, pw^{plan} and pw^{dorsi} mean the stimulation signal for the plantarflexor and dorsiflexor muscles, respectively.

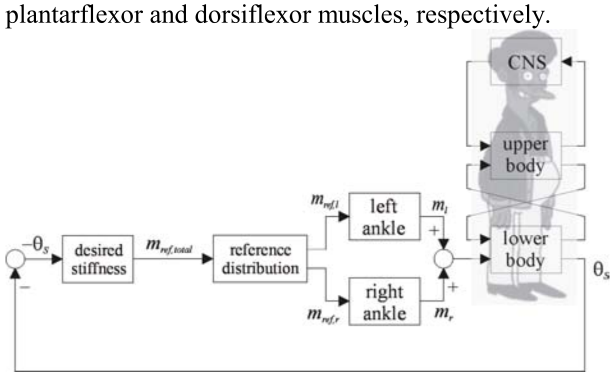

Figure 2: Block diagram of the experimental situation.

There exist four separate controllers, one for each muscle group with common states for plantarflexor and dorsiflexor muscles of each leg and a suitable scheduling strategy. The controllers were designed by pole assignment based on an empirically-determined linear dynamic model of the muscles' response to open-loop stimulation of PRBS form [1].

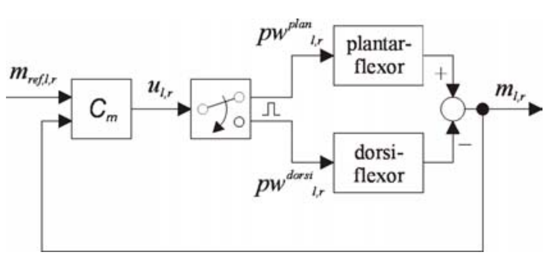

Figure 3: Closed-loop structure for left and right ankle moment control.

The plantarflexor and dorsiflexor muscles of each leg were stimulated using surface electrodes. The stimulator produced rectangular monophasic pulses and was driven by a PC (which also ran the control algorithm) via the serial port. The stimulation frequency was constant at 20 Hz. The amplitude of the pulses was constant and set to 60 mA during the experiment while the pulsewidth was varied from 0 to 500 µs. The experiment was performed with one paraplegic subject, T5, male, 38 years old, 8 years post injury.

Results

Figure 4 shows a typical standing trial. After the stimulation was switched on the subject was released and was balancing on his own under the influence of the FES controlled ankle stiffness, which was specified as 10 Nm/deg. The frame provided a stiffness of 10 Nm/deg in the frontal plane (restraining movement only to the sagittal plane) and 2 Nm/deg in the sagittal plane, which only compensated the load imposed by the weight of the frame.

The plots at the bottom (fourth row) show the angle of inclination of the frame, i.e. the lower body (c.f. Figure 2). The plots above show the reference moment m_{ref} (dashed line) and actual measured moment m for the left and right leg (third row). The upper plots show the stimulation signal of the plantarflexors pw^{plan} (first row) and the dorsiflexors pw^{dorsi} (second row).

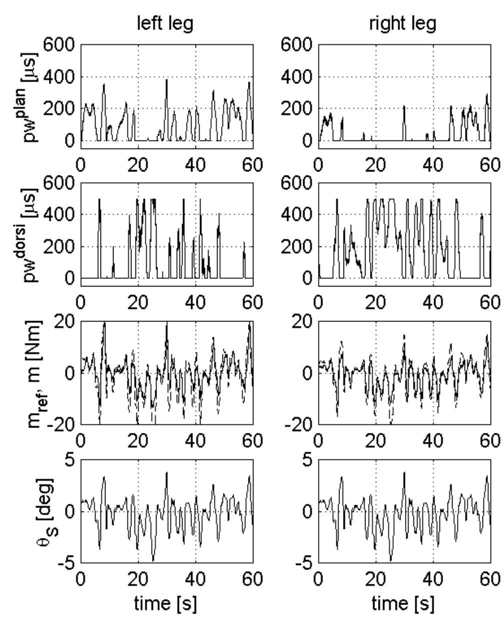

Figure 4: Typical standing trial.

The important result is that the angle of inclination remained bounded to ±5° over the entire duration of the test, indicating the ability of the subject to successfully balance for the duration of one minute.

An impression of the accuracy of the stiffness control is given in Figure 5 where moment versus angle is plotted. The measured moments of left and right leg were added up. The straight line shows the specified stiffness of 10 Nm/deg while the dots mark the actual measured values.

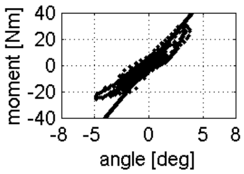

Figure 5: Specified (straight line) and achieved (dots) stiffness (same data as in Figure 4).

In order to emphasise the stabilising contribution of the FES-controlled stiffness, we show another trial where we switched off the stimulation after 30 s (see Figure 6). This happened at a time when the subject was almost in the vertical position. After the stimulation was switched off the subject immediately started to fall over. Then, he was set back into the neutral position by the experimenter and fell again. This was repeated three times but the subject was not able to stand without stimulation.

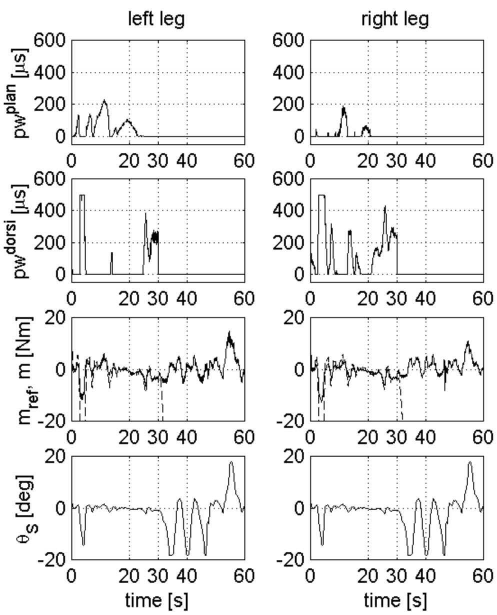

Figure 6: Standing trial. The stimulation was switched off after 30 s.

Discussion/Conclusions

The results have shown that paraplegic standing can be achieved by implementing the control strategy proposed in [4, 5] when closed-loop FES is used to control ankle stiffness. The subject in our study had to support his trunk by holding onto the frame due to his rather high level of lesion and his weak trunk muscles. A subject with a lower lesion and adequate trunk muscle strength should be able to perform the balancing task by using his trunk muscles alone and thus leaving the arms to perform a functional task. The results demonstrate the feasibility of stable paraplegic standing, when supported by FES-controlled ankle stiffness. FES-controlled ankle stiffness makes an essential con-tribution to the overall control scheme and enables the patient to stand. This implies that when the patient's residual abilities are adequately trained, quite simple FES control strategies can be sufficient for stable standing.

Future work will incorporate closed-loop control of the hip stiffness by using FES of abductor muscles in order to enable posture switching from one leg to the other. This can reduce fatigue and extend the periods of standing [5].

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