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STANDING OF PARAPLEGICS USING CLOSED-LOOP CONTROLLED STIMULATION

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Abstract

A study using ankle and knee closed-loop controls concurrently has been carried out with three complete paraplegic patients. They were implanted bilaterally with percutaneous electrodes of 76-micron, stainless steel, Teflon-insulated wire in the quadriceps, hamstring, tensor, sartorius, gracilis, abductor, gluteus maximus, foot dorsiflexor and soleus muscles. A set of four modified digital proportional-integral-derivative (PID) controllers were used in parallel for each knee and ankle to govern stimulation of the quadriceps and soleus muscles, providing knee extension and ankle plantar flexion. After open-loop controlled stimulation of the quadriceps to produce standing up, the knee extension was maintained with closed-loop contollers, providing stimulation to ankle plantar flexors only when knee flexion error was less than 5 degrees; and stimulation to both ankle plantar flexors and quadriceps when knee-flexion error exceeded 5 degrees. Knee stability was tested by application of external forces behing the knee to create a buckling moment. For small external moments, a counteracting moment was generated by the controller using soleus alone. A rapidly applied larger moment caused greater flexion of the knee and therefore the controller used quadriceps stimulation as well. Patients were able to stand using this system until muscle fatique caused degraded controller behavior, requiring pulse-widths above the allowed maximum of 150 microseconds. Stance control of this type should allow much less quadriceps stimulation, reducing both total energy demands and muscle fatique, and increasing patient confidence. Further development of this work is focused on application of slosed-loop control to walking.

Introduction

The use of open-loop functional electrical stimulation (FES) for standing of paraplegics has several inherent difficulties (1,2) which can be resolved through the use of feedback control. These include excessive muscle stimulation, resulting in fatigue, and potential safety problems due to the risk of falls from knee collapse. The minimum level of stimulation needed to prevent knee collapse must include a margin necessary to cover any muscle weakening due to fatigue during the stance. Because the patient has no way of voluntarily increasing the quadriceps force he is fearful that there might be collapse of his knees as a result of

some pertubation of stance introduced from the external environment. This fear, together with poor stability of the hips, requires the use of support during standing, either from parallel bars or from a standard walker (3). Many of the problems inherent in stance will also be present in walking, where additional difficulties will arise owing to the dynamics of the limbs.
Early experiments with closed-loop control of the knee were reported by Stanic in 1979 (4). His method was not applied clinically due to problems with repeatibility, sensors which lacked both cosmesis and reliability, and rapid muscular fatique. Additional closed-loop experience, also limited to external stimulation, was reported by Petrofsky (5) in 1984. The current study was undertaken to assess the possibility of utilizing ankle and knee closed-loop controls concurrently to improve stability during standing and improve patient confidence.

MATERIALS AND METHODS

Three complete paraplegic patients who have been involved in our laboratory's ongoing work on open-loop FES participated in the closed-loop study. Table 1 summarizes the data about their injury levels, ages and time in the study.

TABLE 1

PATIENT	AGE	INJURY LEVEL	TIME POST INJURY	TIME IN STUDY
B.K.	25	T 8/9	23 months	18 months
D.J.	27	T 11	47 months	7 months
S.W.	22	T 4	61 months	8 months

All patients have no sensory or motor function below the level of injury. They were implanted bilaterally with percutaneous electrodes of 76 micron, stainless steel, Teflon-insulated wire in the quadriceps, hamstring, tensor, sartorius, gracilis, abductor, gluteus maximus, foot dorsiflexor, and soleus muscles (6). The skin condition at each electrode site was cheked three times per week. Impedance was checked weekly for electrode breakage. The relation between pulse-width and torque for muscle stimulation at constant frequency and amplitude was determined using

the Cybex dynamometer, and subsequently incorporated in the design of controllers.
A set of four modified digital proportional-integral-derivative (PID) controllers were used in parallel for each knee and each ankle to govern stimulation of the quadriceps and soleus muscles, providing knee extension and ankle plantar flexion, respectively (7). The controller outputs provided pulse-width modulated signals at constant interpulse interval of 40 milliseconds; the stimuli were constant current (20mA), biphasic, charge-balanced pulses. Feedback of ankle angle was provided using cast brace shoe inserts with poteniometers attached to the mechanical ankle joints. Feedback of knee angle was obtained with goniometers which were incorporated into an elastic knee brace.
To provide knee extension for standing up from a chair, open-loop controlled stimulation of the quadriceps was applied. Once the patient was standing knee extension was maintained with closed-loop controllers operating in one of two modes. If the knee flexion error was less than 5 degrees, knee position was maintained by stimulating ankle plantar flexors only. If the knee flexion error exceeded 5 degrees quadriceps stimulation was initiated as well. The patient was allowed to stand with this system using the hands for balance. To test knee stability external force was applied behind the knees to create a buckling moment and the response of the system was observed.

RESULTS

Following the switch from open-loop to closed-loop control, quadriceps stimulation was reduced to zero by the controller as knee-angle error was driven to zero. Any needed small correction of knee angles was accomplished with soleus stimulation. When an external moment was applied to flex the knee, several responses occurred. If the moment was sufficiently small, a counteracting moment was generated by the controller using the soleus alone.
A rapidly applied larger moment caused greater flexion of the knee and therefore the controller used quadriceps stimulation as well. As the knee angle was driven to zero, quadriceps stimulation was discountinued by the controller and only soleus stimulation was used to maintain standing. At all times the stimulation pulse-widths were kept between o and 150 microseconds.
The patients were able to stand using this system until fatigue of the muscles caused degraded controller behaviour. If, after muscle fatigue, the controller required pulse-widths above the maximum allowed to be sent to maintain standing, then knee-angle error increased along with controller saturation and the trial was ended.

DISCUSSION

The ability to stand using only stimulation of the soleus is predictable from the analysis of normal standing. The foot plantar flexion moment becomes an extension moment at the knees and thereby locks them. This principle has long been used in bracing flail knees, where the foot is placed in slight plantar flexion in an ankle-foot orthosis, thus obtaining knee stability without using a knee-ankle orthosis. Stance control of this type should allow us much less quadriceps stimulation and thereby reduce the total energy demands of walking with functional electrical stimulation. In addition, muscle fatigue should be reduced by alternating between two muscle groups, allowing one to rest while the other is stimulated. As a result, the patient's confidence in his stability should be increased. Future development of this work is focused on application of closed-loop control to walking.

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