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Influence of Electrically Stimulated Ankle Plantar Flexors on the Swinging Leg

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Abstract: The influence of functional electrically stimulated ankle plantar flexors on the swinging lower extremity was studied in incomplete spinal cord injured persons. Stimulation sequences with different time and frequency parameters were delivered to ankle plantar flexors and knee extensors and to the peroneal nerve. The results of kinematic assessment showed that stimulated calf muscles provide noticeable forward and upward propulsion to the swinging leg. **Key Words:** Ankle plantar flexors—Kinematic assessment.

The ankle plantar flexors generate noticeable energy during the push-off phase of human walking. In the studies performed in normal persons (1,2), it was found that only some of this energy continues upward through the knee joint, and a small amount of energy continues across the hip joint to the trunk. Therefore, it appears that the work of ankle plantar flexors provides the kinetic energy for the initiation of the swing phase. In this investigation, it was our aim to study the influence of electrically stimulated calf muscles on the effectiveness of the swinging leg movement. In surface electrical stimulation, rather large electrodes are usually placed over both the m. soleus and m. gastrocnemius (3,4). The gastrocnemius muscle, which extends from the heel to the thigh, is a biarticular muscle. Immediately after the start of the push-off phase, when the knee is in a slightly flexed position, m. gastrocnemius not only maintains the ankle in plantar flexion, but also further flexes the knee. It was hypothesized that functional electrical stimulation (FES) of the ankle plantar flexors could raise the heel and prepare the leg for the swing phase, provide upward and forward propulsion to the swinging leg, and enable knee flexion while shortening the swinging leg.

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METHODS

The FES assisted push-off was realized by controlling three stimulation channels delivered to the ankle plantar flexors and knee extensors and to the peroneal nerve. FES of the knee extensors, being active during the entire midstance phase, was discontinued. Electrical stimulation was delivered to the ankle plantar flexors. Adequate swing phase was accomplished by triggering the flexion response. Proper timing of the 3 stimulation sequences was based on experiences from previous work. An important gait parameter is the delay between the start of the train of stimuli delivered to the peroneal nerve and the maximal knee and hip flexion obtained during the elicited withdrawal response. This latency was found to be in the range from 0.5 s and 0.75 s (5,6). Similarly, a delay of 0.3 s was observed between the start of the train of stimuli delivered to the ankle plantar flexors and maximal vertical reaction force (4). Based on this data, the duration of flexion reflex stimulation was selected to be 0.5 s while the duration of stimulation of the ankle plantar flexors was 0.3 s.

Six combinations of stimulation sequences, characterized with different time and frequency parameters, were investigated in the present study. They are displayed in Fig. 1. The first set belongs to our present simple FES gait pattern for which only the knee extensors and flexion reflex were stimulated (5). A hand pushbutton was used to discontinue the

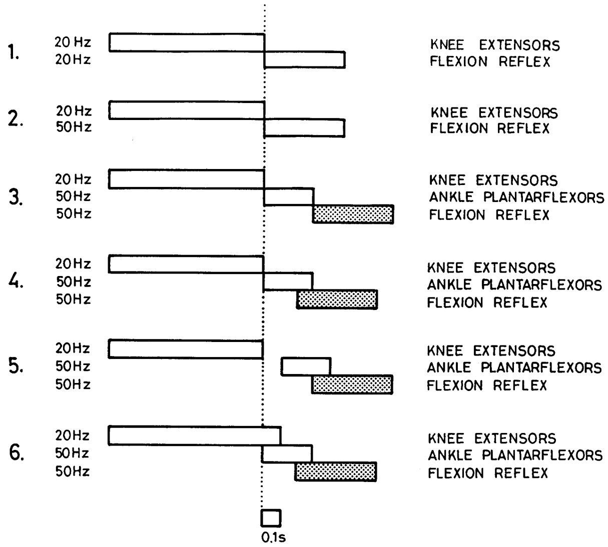

FIG. 1. The electrical stimulation sequences delivered to the knee extensors and ankle plantar flexors and to the peroneal nerve are shown. The vertical line belongs to the instant of hand pushbutton triggering.

stimulation of the knee extensors and to start the flexion reflex. The stimulation frequency in both channels was 20 Hz. In the second set of stimulation sequences, the afferent stimulation frequency was increased to 50 Hz to reduce the latency of the withdrawal response (6). In the next 4 combinations of stimulation sequences, the FES of ankle plantar flexors was added. To obtain strong and fast propulsion, 50 Hz stimulation frequency was used with the efferent stimulation of the calf muscles. The four stimulation sequences are characterized by different delays with regard to hand triggering and different types of stimulated muscle group coactivations. The positioning of the surface electrodes over the knee extensors and ankle plantar flexors and the peroneal nerve was the same as described in our previous work (3). The amplitudes for all 3 stimulation channels were selected before the test when the subject was in the seated position. In all 6 combinations of the stimulation sequences, the same amplitudes were used for each subject. The amplitude for flexion reflex triggering was adjusted to a 50 Hz stimulation frequency.

Repeated measurements were performed in spinal cord injured (SCI) patients. The incompletely paralyzed patients had the following spinal cord lesions: T11, T12 (subject I.M., 34 years old); C7 (subject T.P., 24 years old); C7 (subject B.S., 18 years old); and C6 (subject L.G., 18 years old). All incomplete SCI patients were selected from the group of SCI subjects having 1 leg almost completely paralyzed whereas the other leg was under voluntary control and sufficiently strong to provide safe standing. The 3 channel FES was therefore applied to them unilaterally only. During the measurement, the incomplete SCI subjects stood supported with the help of parallel bars. The subjects first entered the push-off phase and then the swing phase by voluntarily activating the hand pushbutton. The experiment was repeated 3 times in each incomplete SCI subject tested.

The described stimulation sequences were generated by an 8 channel MC68HC16 microcontroller based stimulator. The stimulation parameters such as pulse amplitude (0–150 V), pulse duration (50–800 μs), and frequency (5–100 Hz) were selected independently for each channel. The amplitude of the stimuli was adjusted manually by means of potentiometers. Stimulator functions were selected through a hierarchical menu-oriented control system, accessible through an LCD screen and 3 pushbuttons. The movements of the swinging leg were assessed by a contactless OPTOTRAK measuring system (OPTOTRAK/3010, Northern Digital Inc., Waterloo, Ontario, Canada), including 2 precalibrated position camera systems, which permitted measurement of 3-D marker coordinates at the 50 Hz sampling rate and accuracy of 0.35 mm. Four OPTOTRAK markers were placed at the estimated anatomical positions of the hip, knee, ankle, and metatarsal joints in the sagittal plane. The OPTOTRAK data were collected and checked with a PC computer and further processed on a Unix-based HP 9000/700 workstation with commercial MATLAB software and custom-written subroutines.

RESULTS

The aim of the present investigation was to evaluate experimentally the effectiveness of the FES delivered to the ankle plantar flexors to obtain an improved swing phase of walking. It was hypothesized that ankle plantar flexors provide necessary propulsion to the swinging lower extremity. Two parameters were found particularly interesting to estimate the swinging leg movement: maximal horizontal swing of the metatarsal joint and maximal vertical swing of the knee joint. The first parameter indicates the effectiveness of propulsion forward direct and it corresponds to the step length. The second parameter demonstrates the propulsion of the swinging limb upward and is therefore interesting when planning tasks such as stepping up onto sidewalks or climbing stairs.

The results of the assessment of the maximal horizontal swing of the metatarsal joint in the sagittal plane are displayed in Fig. 2. The first 2 columns

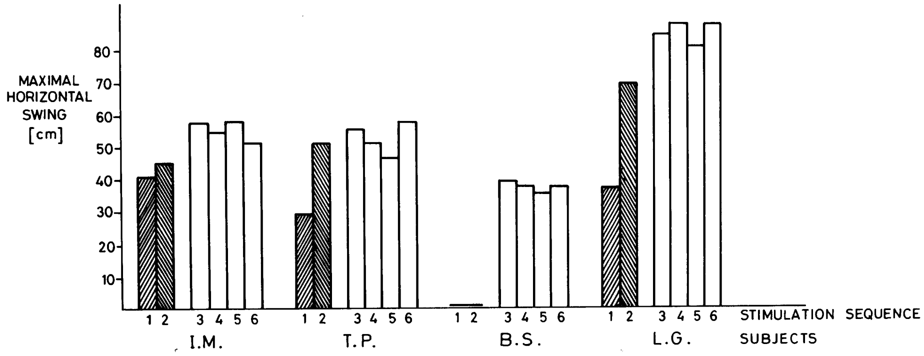

FIG. 2. The maximal horizontal swing of the metatarsal joint, resulting from the application of 6 stimulation sequences, is shown for each of the 4 incomplete SCI patients.

belong to the stimulation sequences 1 and 2 for which only the flexion reflex was elicited, first with 20 Hz stimulation and second with 50 Hz stimulation. The next 4 columns represent the stimulation sequences 3–6 for which the stimulation of the ankle plantar flexors was added. Stimulation of the ankle plantar flexors resulted in improved responses in all 4 incomplete SCI patients. The influence of stimulated calf muscles was especially evident in subject B.S., for whom the flexion reflex alone was unable to move the limb forward. Differences among the 4 stimulation sequences that included the ankle plantar flexors stimulation were small and could not be considered significant. For 2 patients (T.P. and L.G.), increasing the stimulation frequency of the flexion response (stimulation sequence 2) resulted in noticeable improvement of the forward swing. From the results obtained for patient L.G., it can be seen that step lengths over 80 cm can be obtained with 3 channel stimulation of the paralyzed limb which exceeds the step length of normal walking. Similar results were obtained when measuring the maximal vertical swing of the knee joint (Fig. 3). The highest amplitudes were assessed in patient L.G., indicating that the stimulated extremity can be lifted sufficiently to be placed on a sidewalk or a stair. The effect of the ankle plantar flexors on the swinging leg is somewhat more pronounced when observing vertical lift of the lower extremity.

DISCUSSION

When we compared the results of our previous work during which the energy of the stimulated ankle plantar flexors was delivered to the trunk (3,4) with the results of this investigation during which the same energy was transferred to the swinging leg, we concluded that the latter approach is more advantageous for FES walking for incomplete SCI patients. We demonstrated that small differences in the timing of the stimulation sequences of the knee extensors, flexion reflex, and ankle plantar flexors have an insignificant effect on the movement of the swinging extremity.

Electromyographic recordings have shown that the muscles of the swinging leg are predominantly inactive during the swing phase. The assumption was made, therefore, that no muscular moments are pro-

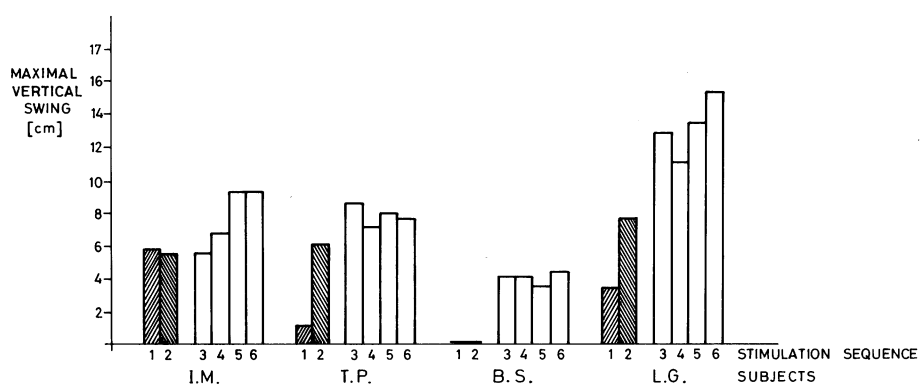

FIG. 3. The maximal vertical swing of the knee joint as accomplished by the 6 stimulation sequences is shown for each of the 4 incomplete SCI patients.

vided to any of the joints of the extremity after the initial positions and velocities of the joints have been established at the beginning of the swing phase (7). The swing phase of the human gait was described as a ballistic motion. According to our observations in incomplete SCI subjects, it appears that the stimulation of calf muscles alone can provoke the swing phase of walking.

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