MULTICHANNEL STIMULATION OF THE LOWER EXTREMITIES WITH SURFACE ELECTRODES

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Abstract

FES of the lower extremities is executed with an 8 channel stimulator and surface electrodes to achieve standing and walking. By correct placement of the electrodes it is possible to control the extension, flexion and abduction of the hip joint and the extension, flexion and lateral fixation of the knee joint. The foot-joint is passively fixed by a special shoe. The stimulator is equipped to programm the movement pattern in six subdivisions: Standing up, standing, walking, stairs up and down, and sitting down. This allows the paraplegic to stand and walk with a good posture and well balance with relative little load on the upper extremties. The details of the procedure, the muscular training and the introduction of the handicapped to the method are discussed.

Introduction

The Functional Electrical Stimulation, FES, of the lower extremities has been executed so far in two ways:

- By using a limited number of surface electrodes, as proposed by Krajl, Vodovnik et al. (5,6,7);
- By applying multiple transcutaneous electrodes, used by Marsolais et al. (13).

The use of multiple transcutaneous electrodes permits a refined stimulation of antagonistic muscles and in principle a more sophisticated control of the movements of the limb. Because of the large number of electrodes this procedure seems to be more difficult to handle. It is therefore basically still bound to the laboratory.

Employing surface electrodes the m. quadriceps is stimulated by one channel to extend the knee. With the support of the hands this permits standing up and standing. In combination with walking aids and stimulation of the flexion reflex, walking is possible in a very basic way. This method needs only two stimulation channels for each leg. It is easy to mount and handle by the handicapped himself and might be used in the daily routine at home. During the last years a number of research groups started to use this method and recently not professionally educated people started to copy the method and sell it without adequate training of the handicapped.

This procedure fixes only the extension of the knee joint. The necessity to keep a stable posture has as a consequence the danger of incorrect positioning of the lumbar region and the pelvis, and probably a hyperlordosis and hyperextension of the knee joint. In addition the upper extremity tends to be overloaded by the task to keep the body stable.

The object of our study was therefore to improve on one side the upright position and the execution of the leg movements of a paraplegic handicapped by controlling the hip and knee joints actively through FES. On the other side the method should be kept easy enough that it might be used by the handicapped himself at home.

Stimulation sites:

Applying FES to the lower extremity it is in comparison with the other extremity to a larger extend sufficient to stimulate whole synergistic muscle groups. Therefore we choose surface electrodes for the FES.

In order to obtain a better stabilization of the hip and knee joints during standing and walking torques in the following directions have to be provoked:

- hip extension and abduction
- knee extension and flexion.

(The ankle joint might be passively stabilized by special shoes comercially available.)
To obtain sufficient hip abduction and extension the rear part of the m. glut. medius and the upper part of the m. glut. maximus might be stimulated by one channel. One large electrode is positioned below the christa iliaca, another small one in the region of the trochanter mayor. To obtain the knee extension the m. quadriceps is stimulated as by the second channel. In addition the m. rectus femoris executes a flexion torque on the hip joint, counter balancing the extension torque provoked provoked by the m. glut. maximus and the hamstrings. The stimulation of the hamstrings by the third channel supports the extension of the hip joint, as mentioned, and stabilizes the knee joint by an appropriately adjusted torque. In addition this muscle groups fix the knee lateral in both directions.

By means of 3 stimulation channels for each leg the paraplegic has a firm standing position. During walking the stimulation of the m. glut. med. conterlateral to the swinging leg, keeps the pelvis horizontal and thus supports the execution of the step. Equilateral of the moving leg the m. glut. med. might be stimulated also during the step phase. The abduction of the leg can be counterbalanced by a slight co-stimulation of the adduction by appropriate position of the upper hamstring electrode, guiding the leg straight forward during the end phase of the step.

A fourth channel is needed to elicit the flexion reflex. The electrodes have to be positioned to meet the following requirements:

- a sufficient elevation of the leg
- a straight-lined foot
- a slight dorsal flexion in the ankle joint

In Fig. 1 a scheme of the electrode positioning is shown.

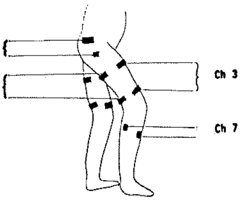

Fig 1: An example of electrodes positioning
using an 8 channal stimulator

In general the size and the position of the electrodes have to be chosen individually for each subject according to his stimulation situation. After the electrode positions stay constant the electrodes might be incorporated into a pair of elastic trousers. This easies the putting on of the electrodes in a repeatable position.

Technical methodology

According to the stimulation procedure explained above, the stimulator is equipped with the following properties (1,2):

- 8 independent and gavanically decoupled stimulation channels;
- stimulus pulse amplitude ≤ 100 mA, pulse duration 10 to 500 µsec, frequency 0,5 to 50 Hz;
- the stimulus pulses are current controlled and load balanced;
- 8 A/D-input channels for artificial sensors and digital inputs to control the operating program
- the controller is a Z80 microcomputer in CMOS technology;

- the communication is executed via a user guided menue, LCD-display and function keys,
- the operating system is devided into 7 sections:

  standing up
  standing
  walking
  stairs up
  stairs down
  sitting down
  training

  in each section the stimulus pattern for each channel might be programmed individually.
- in case of a failure, i.e. breaking of an electrode, an accustic warning signal is given and the program jumps into the step mode;
- the stimulator is battery operated and portable.

Muscle training procedure

The enforcement of the muscle training has to be kept between two boundary conditions: On one side the intention to build up muscle strength and fatigue resistance as fast as possible. On the other side th danger to overload the skeleton, joints, tendons and ligaments, which are at a reduced state in the paralyzed limbs. Whereas an early damaging of these tissues will be recognized soon, only little experience exists about disadvantageous effects becoming prominent during the course of time. Extrapolating from the experience gained in sports training and some incidents reported verbally after longer lasting use of FES we dicided together with the Paraplegic Ward of the Rehabilitation Center of Karlsbad-Langensteinbach - most of our practical application are executed with this Center - to conduct the training in a more conservative and moderate way. This is done especially with respect to the fact, that it is much more difficult to revert a chronic damage of a joint, ligament, or tendon of a paralyzed limb than of a normal one.

In contrast to the exercising strategy for healthy subjects less is known about an optimized stimulation procedure for restrengthening a paralyzed muscle Krajl et al. (1980) demonstrated that the isotonic exercising is more effective in increasing fatigue resistance compared to the isometric one. Medical investigations in sports on healthy muscles demonstrated that few moderate isometric exercises each day effectively increase muscle force and stimulate blood circulation and metabolism (MAREES, 1979).With the object of getting fast increase in muscle force and endurance with most preservation of patient's bones, joints, and ligaments we worked out an exercising strategy which can be summarized as follows:

- in order to avoid exhaustion of the stimulated muscles as well as overloading of the skeleton, joints, and ligamentum apparatus we begin exercising in a rather moderate way;
- stimulus amplitude, stimulation time and performed exercises are adapted to the individual capacity of the patient, a rigid time schedule doesn't exist;

- all the muscles/muscle groups needed for performing functional movement are trained simultaneously to get symmetrical muscle strengthening;
- a stimulation period is terminated and adequate recovery time is given when fatigue sets in, which is recognized by growing muscle tremor and fading of contraction;
- in the initial phase the muscles are exercised isometrically as it is more effective in increasing muscle strength compared to auxotonic exercise;
- the program is continued with auxotonic exercises to reduce muscle fatigue;
- as soon as the increase in muscle strength and endurance has reached the minimal required level for the functional task of standing a concomitant standing up training is started; this exercise turned out to be most effective in increasing both muscle force and fatigue resistance;
- the patients are encouraged to exercise regularly as dropping of stimulation sessions (a lazy spent weekend for example) results in a pronounced decrease in muscle capacity;
- a total stimulation time of 2 hours per day is exspected (one hour in the morning and one in the afternoon);
- the lowest possible stimulus frequency which still elicits a functional tetanic response is selected;

Emphasis is laid on the exercise of the m. quadriceps and mm. glutaei as they are later used for performing functional tasks requiring high and sustained muscle forces, for example, providing joint torques for standing-up and sitting-down, or for hip stabilization during gait. To further improve the posture of the patients while standing and walking the hamstrings are additionally trained.

Side-effects of Training

In addition to the intended increase in muscle strength and endurance most of our patients benefit from the well-known side-effects of electrical stimulation such as:

- stabilization and improved capacity of the circulation system when exercising in the standing position
- a better blood circulation in the stimulated extremities and adjacent parts of the body
- a more aesthetical appearance of the extremities due to stimulation induced growing of muscle bulk
- prevention of pressure sores

The decubitus prophylaxis is a specially desired stimulation effect as many of the paraplegics cannot sit for a prolonged time without some difficulty. In serious cases we stimulate the atrophied ischium muscles separately by means of a custom-made stimulation seat. In the lighter cases a sufficient prophylactic effect is obtained by stimulation of the glutaeus muscles during the daily exercising routine.
Unfavourable side-effects of FES haven't been observed till now. One of our patients suffered from an extensive ossification of the m. quadriceps femoris of one thigh. Surveying of the alkalic phosphatasis and X-ray findings gave no indications of an influence of the carefully applied electrical stimulation on the ossification process.

The disadvantage of this procedure is of course, that there does not exist a measurable parameter which allows to optimize the training strategy. On the other hand after the stimulation training the leg and pelvis region are generally in good condition. This is also of use for the daily life of the handicapped.

Standing and Walking

The standing human is an upright body with at least eight joints which has to be stabilized : head-thorax, thorax-pelvis, hip-, knee-, and ankle joints. Even such a powerful controller as the brain seems to be not capable to control this essentially unstable chain, if each joint is moving in an unpredictable independent manner. The brain solves the control task by fixating most of the joints during a movement or by stabilizing them dynamically in such a manner, that it is able to build a model of the dynamics of the movement pattern to be executed. Even if the model matches the actual dynamics of the body well, there are always enough perturbations the nervous controller has to compensate for in order to keep equilibrium - and often enough it fails to succeed.

A paraplegic patient has lost at least control of the lower three pairs of these joints. In the technical sense this implies the controllability, the voluntary control, of the hip and leg muscles, and the observability, the loss of the sensory feedback of the limbs themselves. Stiffening the paralyzed legs and pelvis passively by bracing or actively by FES is one prerequisite to stand up and walk again, but does not solve the problem to keep equilibrium. To the remaining part of the still voluntarily controllable body the artificially stiffened lower segment of the body appears as a foreign matter, which has to be stabilized additionally like stilts. The result is known, having not enough actuators left to compensate dynamically for the perturbation movements the paraplegic is falling down.

Because of this the dynamic control problem is converted into a static one: the handicapped uses crutches to gain a four to three point support.The equilibrium obtained this way is only semistatical because the human body is still moving in itself. The linkages between the limbs on one side and the body and the crutches on the other side are not fixed, especially when the handicapped wants to walk. One task of FES to obtain standing and walking is therefore to bring the not voluntarily controllable joints into such a fixed position, that the center of gravity of the human body remains between the points of support.

Securing the joints to keep equilibrium might be done by using a mixed active - passive fixation scheme, leading off with the knee joint by bringing it into a blocked position through the stimulation of certain muscles. The angles of the other joints are adjusted around the force vector generated in this way (8). This method needs only very few stimulation channels. Its disadvantages are: The body is not kept straight, the already restricted reserve of compensation is diminished, and the upper extremity has to produce more force.

Another way is to control the joints actively in a more extended manner. This procedure needs more stimulation channels. Its advantages are: Each joint might be actively controlled allowing a straight upright position, the equilibrium is easier kept freeing one hand more extendedly for daily use, and the energy consumption is less. In addition it provides the possibility to gain a better active overall stability of the whole body.

From the aspect of systems the lower extremities have to be controlled by FES in such a way, that they fit as smooth as possible into the reduced voluntary control of equilibrium executed by the upper part of the body. In order to meet this requirement the static and dynamic properties of the hip and legs have to operate in a predictive manner. They have to be stable in a wide range and support the stability of the entire system.

Besides this basic requirement to preserve stability in a range as large as possible other objectives have to be kept in mind:

- to create a good upright posture by providing a sufficient extension in the hip joint to move the pelvis in a normal position and avoid hyperlordosis;
- to releave the arms and shoulders as much as possible from the task to support the body and its center of gravity;
- to allow the swinging leg to move freely.

These conditions are all more or less linked and may be achieved only partielly.

By an appropriate placement of the electrodes the hip joint is actively fixed in the direction of:

- abduction by the m. glut. medius,
- extension by the m. glut. maximus and the hamstrings
- flexion by the m. rectus femoris.
- adduction might be added if necessary by the adductor group.

The knee joint is actively fixed in the direction of:
- extension by the m. quadriceps
- flexion by the hamstrings
- lateral side by the m. biceps femoris.

The active fixation of the joints may only be obtained by careful placement of the electrodes and selection of the stimulation strength for each muscle group. With this stimulation pattern a firm upright standing position is achieved in the sagittal, lateral, and rotational direction. Hands support is just needed to keep balance.

To stand up the paraplegic has to shift his center of gravity over his feet. The stimulation of the m. quadriceps and the mm. glut. is switched on in a ramp function and together with some support of the arms he may stand up. The slope of the ramp has to be chosen according to his time pattern of standing up. No foreward pull of the hands is allowed.

Switching to the gait phase the stimulation strength of the mm. quadricepes and the hamstrings is increased. During the swing phase on the swinging leg the reflex stimulation is switched on and the one of the mm. glut. is lowered.

In order to sit down the knee has to be brought out of its locked position. Therefore the stimulation strength of the mm. quadriceps is lowered a bit and the one of the hamstrings is shortly increased to unlock the knee. The final sitting down phase is supported by a slow decrease of the stimulation of the mm. quad. Fig. 2 shows a scheme of the stimulation-strength-time-pattern of the 4 channels.

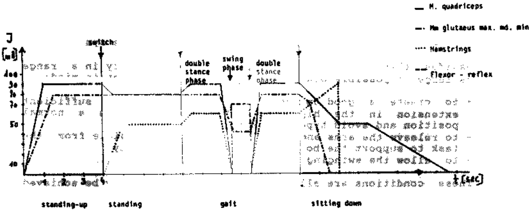

Fig 2: An example for a stimulation-strength-time-pattern during the different phases of locomotion (four stimulation-channels at each leg)

To achieve a good upright position during walking, one has especially to watch, that the pelvis does not stay back. The stimulation parameter we commonly use: Pulse duration 300 µsec; Frequency 20 Hz; Amplitude up to 100 mA.

As mentioned above we begin rather early with the training of standing. In doing so the appropriate electrode positions are early determined and vice versa the special training of the proper muscle parts is soon started.

In the course of our experience it was disadvantageous to stimulate:

- The anterior part of the m. glut. med. and the m. tensor faciae latae because of the hip flexion and rotational components;
- The lower parts of the m. glut. max. because of its rotational component and a co-stimulation of the isciatic nerve;
- The m. quadriceps too far proximal because this might provoke a stronger spasm of the m. rectus abdominis;
- The m. quadriceps too strong because this might stimulate all muscles of the thigh;
- The hamstrings too strong because the nn. tibialis and peroneus might be co-stimulated.

To avoid these effects it is advisable to search for a good position of the electrodes.

Conclusions

In general our experience proved so far, that the training of a paraplegic with FES needs a very careful supervision by a well experienced physiotherapist. We met a number of patients using inadequate positioned electrodes and wrong stimulation parameters, i. e. too strong stimulus strength or too high frequency. In some cases the posture of the body and the movement patterns had been trained in a wrong way leading to curvatures of the spine and the danger of damaging the joints.

These mistakes can be avoided by a thorough introduction which enables the handicapped to understand the procedure and the essential points he has to watch. In cooperation with the Rehabilitation Center at Karlsbad-Langensteinbach we practice a rather elaborate training programm for the in and out patients to assure that they handle the method appropriately.

The procedure reported here seems to give a good basis for this programm. It supports and stabilizes the hip and knee joints at a good posture during standing and walking. The muscle forces generated by stimulation and the loading of the upper extremities remain relatively low. On the other side 4 stimulation channels to be mounted at each leg might still be handled by a paraplegic in reasonable time.

In a more extended study we will examine concepts to control also the ankle joint and the abdominal-lumbar region. It is for instance possible to stabilize the ankle joint by stimulation without difficulties. During the step phase the swinging foot can better brought forward by a slight stimulation of the equilateral m. quadriceps and activation of the contralateral m. triceps surae during the final phase of the step. But a paraplegic has to be a truely good artifical walker to handle the resulting step width.

For this study a portable 16-channel stimulator is developed. Beyond the properties of the 8-channel stimulator it is equipped with two microcomputers. A control computer with the operating system generates continously the stimulation parameters and may execute feedback control. It has 16 A/D-inputs, 8 digital channels and 40 switches.

The second computer controls the time pattern of each channel, the output of the stimulation parameters, D/A-conversion, and the supervision of the electrode impedances.

With this stimulator the movement patterns might be programmed more complex. It may store the data of three patients. Both processors are connected by a dual ported RAM. The stimulator is battery operated at 12 V and uses ≤ 200 mA. The stimulator might be programmed by its own keyboard and an LCD-display with a users menue system. It can also be linked to a (portable) host-PC, which allows a more comfortable programming of the movement patterns and the graphic display of these patterns for all 16 channels. The stimulation data of the patients can be stored on a disc and transmitted forth and back to the stimulator.

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