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ARTIFICIAL QUADRIPLEGIC GRASPING: NEUROMUSCULAR ELECTRICAL STIMULATION SEQUENCES AND INSTRUMENTATION DEVELOPMENT FOR EVALUATING PREHENSION

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Abstract: This work presents the use of neuromuscular electrical stimulation (NMES) towards restoring hand function. Muscle activation sequences were defined to perform activities of daily living. Grasp control needs quantitative evaluation of the artificially generated movement. Studies on isometric grasp can be obtained through an ergonomic, handle-based dynamometer. Furthermore, since muscle properties change with time, on-line checking on grasp properties is also necessary. For this purpose, force and position transducers are presented. System evaluation was based on normal activity studies and show adequate behavior for the purpose of their design.

INTRODUCTION

An important function of the upper limbs is grasping and manipulating objects. In spinal cord injured patients, communication between supraspinal centers and muscles below the injury level is often completely absent, resulting in severe paralysis of affected limbs. NMES systems have been used as an important rehabilitation tool, since electrical stimulation has the potential for exciting every muscle with intact peripheral enervation [1]. Movement control needs muscle regulation under wide different conditions of loading, fatigue, and muscle length. For this purpose, quantitative evaluation of the artificially generated movement is necessary. This work discusses NMES in upper limb rehabilitation and introduces some electronic devices for evaluating grasp performance.

MATERIALS AND METHODS

NMES Rehabilitation Program

Eight quadriplegic subjects (C4-C6 levels) were part of the program. These subjects retain some voluntary shoulder and elbow control, but no voluntary hand function is achieved.

An 8-channel microcomputer controlled stimulator was used, thus allowing the implementation of several strategies for grasping. A voltage output signal with monophasic, square, 300 microseconds pulse width and frequency of 25 Hz was used. In spite of fixed pulse width and frequency, the amplitude was variable to achieve muscle excitability threshold.

Muscle selection was based on kinesiological and electromyographical studies of normal subjects and electrical stimulation feasibility, resulting in six muscles: Extensor Carpi Radialis (ECR), Extensor Digitorum Communis (EDC), Flexor Digitorum Profundus (FDP), Lumbricalis (L), Abductor Pollicis Brevis (AbPB) and Opponens Pollicis (OpP). Small adhesive surface electrodes were placed over the motor sites of the selected muscles.

Definition of temporal and spatial sequences is required to co-ordinate the movements. Several sequences of muscle activation were defined to perform cylindrical grasp, palmar and lateral prehension and parallel extension grip.

Devices for grasping evaluation

The strength of an electrically induced muscle contraction can be controlled by pulse amplitude or pulse width modulation. To improve stimulation performance, a map of stimulation parameters has been used to modulate force output [2]. Aiming at characterizing the force output in artificially activated muscle, an ergonomic dynamometer was designed and built. The knowledge of the relationship between force and stimulation parameters for each muscle activation sequence, and for each subject, allows the definition of specific stimulation maps.

A specific hydraulic interface based on mechanical characteristics of a metal diaphragm [3], linked to a pressure sensor over a hydraulic system, was used. For the calibration procedure, each hydraulic mechanism, adequately sealed, was positioned in a material testing machine (Instron). The output voltage was linearly proportional to the applied loads (0-200 N). Each hydraulic mechanism was attached to an ergonomic handle that provide hand positioning with thumb action avoided during isometric tests (Fig. 1).

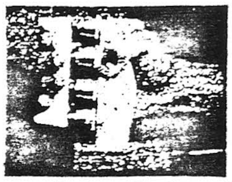

Figure 1 - Ergonomic handle based dynamometer.

Normal subjects were positioned with the elbow at 90° and the forearm parallel to the floor. Handgrip strength was measured three times, with 90 seconds rest period between trials and the highest measure was recorded.

Since artificially activated muscle properties change with time, on-line grasp properties monitoring is also needed. For this purpose, closed-loop control systems have been developed for feedback regulation of hand function [4]. Grasp performance is characterized by means of the opening size of the grasp space and the forces exerted on the object. Feedback position is necessary before contact since no force is exerted. After contact, force feedback is more important. If the object is rigid, finger joint angles remain the same. On the other hand, if the object is not rigid, feedback position is needed to prevent object deformation and also object breaking.

Force sensing resistors (FSR) provided by Interlink Electronics were used as force sensors. Cylindrical grasp was chosen for sensor performance evaluation. In this grasp pattern force contributions are larger for the distal phalanx of long and index fingers. Based on this information, the FSR's were attached to the fingertips of the thumb, index, and long fingers of a Lycra™ commercial glove [5]. In order to calibrate the system normal forces ranged from 0-15 N were used.

The instrumented glove was tested on normal subjects to investigate its feasibility as force feedback supplier. The subjects had to reach, grasp and manipulate rigid cylindrical objects as on a drinking task. The objects had the same diameter, but weights varied from 2-10 N. The range of object weights and the grasping model were selected to represent the functional range of grasp forces attained in common daily life activities.

The finger joint position sensor (Fig. 2) consists of a 1 mm thick steel sheet attached to an acrylic support. This element was attached proximally to the joint, on the dorsal surface of the finger segment. The proximal end of the sheet was instrumented by a strain gauge. A second acrylic element, attached distally to the joint, has a slot in which the steel sheet slides during motion. The sensor show a good sensitivity and a linear response to flexion angle. The calibration process can be made by means of angle or opening size of the hand (object diameter). Tests were performed with the sensor on the proximal interphalanx joint.

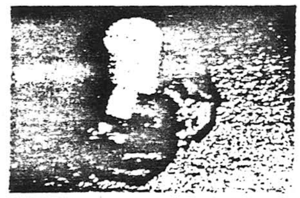

Figure 2 - Finger joint position sensor.

RESULTS

NMES Rehabilitation Programme

Seven subjects achieved good grasp performance in all grasp patterns studied. In spite of fixed stimulation parameters and the use of surface electrodes, it was possible to obtain the desired movements.

The sequences used allowed subjects to demonstrate their ability to hold and release objects that are encountered in daily living, permitting activities such as eating, drinking and writing (fig. 3). Sub-phases defined in the studied sequences as opening, positioning and closing allowed a smooth grasping movement.

(a) (b) (c)

Figure 3 - Grasping patterns - (a) cylindrical / palmar grasp, (b) and (c) lateral grasp.

The best sequence for cylindrical and palmar grasp was obtained by using EDC, AbPB, ECR for opening and positioning and ECR and FDP for closing. These grasping patterns use the same muscle activation sequence. Pulse amplitude and object size allow the differentiation between these patterns. For cylindrical grasp the objects were bigger resulting in larger finger joint angles when compared with palmar grasp.

Parallel extension grip could be achieved by stimulation of EDC, AbPB for opening and positioning, and L for closing. This pattern was used to grasp plain objects such as a sheet of paper and a book. The activation of Lumbricalis results in metacarpal joint flexion with interphalanx extension of all fingers and thumb, allowing a functional positioning to grasp plain objects.

Activities such as eating and writing can be performed by lateral grasp as shown in figure 4 (b) and (c). The object was positioned between lateral surface of the index finger and palmar surface of thumb. The best sequence for this purpose was obtained by using EDC, ECR and FDP for opening and positioning and ECR, FDP and OpP for closing.

The manipulation of the grasped objects could be achieved by voluntary control of shoulder and elbow, since all subjects retained these movements.

Devices for grasping evaluation

All transducers were tested on normal subjects to investigate their feasibility, and also to acquire knowledge about normal grasping function. That can be used as a reference standard when NMES is used to generate artificial grasping function.

In isometric grasp tests, it was observed that men are stronger than women, and that maximum values for both ranged respectively between 500-700 N and 300-400 N. Since artificial activated muscles develop very small grasping forces (i.e. functional forces) [6], some methodological procedures have been defined. The force versus time curve analysis allows the identification of some physiological parameters such as fatigue indexes, impulse, maximum strength, and time to reach the maximum strength.

The tests with the instrumented glove show that the system was effective for 73.3% of the events. It was verified that in cylindrical grasp, most of the subjects exerted force by the thumb and index finger with long finger being an auxiliary one. Regarding the shape of the force curves, it was common to find force peaks associated with the instants of grasping and releasing, which are probably necessary to overcome the inertia of the object. Statistical analysis of the results have also shown that the amplitude of exerted force is an individual characteristic and there is a linear relationship between force and object weight.

Regarding the finger joint sensor, tests show the independence of its response with respect of the distance between both acrylic supports. Sensor position regarding the joint changes the response. It was also verified that finger joint angle regarding object diameter is an individual characteristic, due to anatomical parameters, such as, hand and finger sizes. Thus, for functional use sensor must be customized for each subject.

CONCLUSION

The stimulating sequences allowed subjects to hold and release objects, permitting daily living activities. Sub-phases defined in the studied sequences allowed a smooth grasping movement despite the fact that the force was not controlled during the movement, due to fixed stimulation parameters. Better performance could be obtained with force modulation during grasping. This requires the study on force variation regarding stimulation parameters and also the identification of physiological parameters such as fatigue and the time to reach the maximum strength. This kind of study could be performed by the ergonomic handle based dynamometer, thus contributing with the definition of the best stimulation map for each subject.

Referring to movement performance evaluation a control system employing a combination of force and finger position feedback can provide grasp regulation under different conditions. The instrumented glove and finger joint transducer presented good performance, being able to accurately characterize grasp performance during object manipulation. The success rates verified are relatively high considering that a system aimed at a functional application must be customized for individual users. This is due to the fact that there is a great variation within the population of persons with quadriplegia, in grasping patterns achieved by NMES.

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