PROCEEDINGS

NINTH

INTERNATIONAL CONFERENCE ON BIOMEDICAL ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

EDITED BY: JCH GOH & A NATHER

DEVELOPMENT OF INSTRUMENTATION FOR UPPER AND LOWER LIMB MOVEMENT RESTORATION

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Abstract: Neuromuscular Electrical Stimulation (NMES) systems have been used on restoration of upper and lower limb functions in spinal cord patients. An integrated approach is being used at UNICAMP. This approach includes multichannel stimulators, sensors and algorithms for closed-loop control, as well as artificial proprioception. This paper describes some of the devices developed, their applications, and some clinical trials, aiming at an effective man-machine system.

INTRODUCTION

Spinal cord lesions have important physical and psychological consequences for the individuals. through Neuromuscular Electrical Stimulation (NMES) can be used to restore motor and sensory functions, through adequate nerve stimulation [1], [2]. However, all NMES systems designed up to date allow spinal cord subjects to have their functions restored only inside a laboratory setup. Insufficient technological level and the lack of full knowledge of the underlying physiological phenomena are some of the limiting factors.

Overcoming these limitations is the goal of the Rehabilitation Engineering Group at Unicamp. This can be accomplished through three great areas of research: 1. Optimization of techniques for artificial movement restoration. 2. Generation of artificial sensations associated to the restored movements (artificial proprioception). 3. Investigation of motor control strategies in normal subjects and adaptation of these algorithms to NMES systems.

METHODS

The Rehabilitation Group is integrating the three areas of research cited above within one complete structure for man-machine systems.

Microcontrolled multichannel stimulator

Two 8-channel stimulators were already built and tested: one with manually-adjusted amplitude, and microcomputer-controlled (paralell port) activation sequence, frequence, and pulse width; and one with all parameters being controlled by a microcomputer. A new 16-channel microcontrolled neuromuscular stimulator was designed and built, and is currently undergoing tests. The new system allows closed-loop control (8 analog input channels for sensors) of all parameters, being fully programmable. A Motorola MC60HC11 microcontroller controls the system, allowing the user, through the keyboard or push-buttons, to select one of the functions (sit, stand up, keep standing, walk). The option is interpreted and the adequate muscle stimulations are then generated. Virtually any stimulation sequence and control algorithm can be implemented in the program memory of the system, allowing fine tuning of the system for each user.

Sensors for use with NMES systems

Sensors for NMES closed-loop control need to have the following characteristics: reliability, accuracy, easiness of placement and calibration, and minimal encumbrance. Some sensors have been developed: knee and elbow goniometers (using potentiometers), instrumented shoe insoles and gloves [3], and instrumented crutches (measuring vertical ground reaction forces and anterior/posterior moments)

Adaptive NMES control using neural networks

Adaptive control of gait swing generated by NMES in a spinal cord injured subject was achieved by an artificial neural network [4], with three layers and using knee and ankle goniometer signals as inputs. Output is proportional to changes in NMES pulse width (PW) at femoral and common peroneal nerves. Comparison with normal trajectories was made, and when both correlated well, an enhanced supervised backpropagation algorithm was applied with desired outputs corresponding to leaving PW values unchanged. The learning rate was set to 1.0. When correlation was poor, 10% magnitude changes were produced in 10% of the synaptic weights, chosen at random (Punishment). The chosen magnitude of the modifications and the number of altered connections are thought to modify the network's response without significantly affecting learning stability. Trial and error tests supported this idea. After tests with human intervention, the same procedures were used, but with automatic decisions instead of human intervention (on-line learning). For testing purposes, PW changes for on-line and off-line learning schemes were compared.

Substate diagrams

As each restored movement phase presents different mechanical boundaries, different control rules must be used during a whole cycle, which increases the system complexity. As an aid for designing such complex algorithms, a rule-based state machine structure with embedded substates was defined [5]. This structure can be used either as a stand-alone control structure (including self-learning algorithms), or combined with other techniques (like the neural networks cited above), in a mixed algorithm structure.

Artificial proprioception

Phi-tactile phenomenon can be used for transmission of information from paralyzed limbs to an unaffected body region (artificial proprioception). A special stimulator was built [6], [7] for the purpose of studying this phenomenon. The stimulator can generate triangular and sinusoidal waveforms, in three independent channels, to stimulate the skin, between sensation and pain thresholds. Through the use of three pairs of electrodes and these waveforms, elliptical figures can be "drawn" on the skin, above the lesion level of a spinal patient (figure 1). A code can then be defined to associate the generated patterns to upper limb grasping state and/or phases of paraplegic gait cycle.

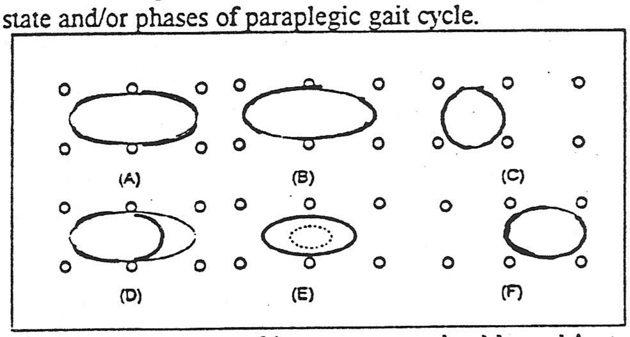

Figure 1 - Examples of images recognized by subjects, using the 3-channel Phi-tactile system

RESULTS AND DISCUSSION

Microcontrolled multichannel stimulator

The system is being tested, and it has proven able to generate pre-programmed stimulation sequences, switching between different operation modes (sit, stand, etc.) according to user input. Implementation of closed-loop algorithms is expected soon.

For a tetraplegic user, stimulation must be provided for trunk extension (paravertebral muscles), extension and abduction of the hip (gluteus maximus and medius), extension of the knee (quadriceps group), flexion of the knee and extension of the hip (hamstrings), ankle plantarflexion for push-off (gastrocnemius), and withdrawal reflex (peroneal nerve). Thus, there are 6 muscle groups for each side, and 12 channels are necessary for full gait restoration on a tetraplegic user (worst case). The stimulator's 16 channels are enough for restoring gait to higher level spinal cord patients.

Sensors for use with NMES systems

The FSRs used in the glove and the insoles have proven being adequate for closed-loop NMES applications. They present reasonable repetibility and linearity, providing adequate force feedback for the control algorithms. The instrumented crutches, as expected for a transducer using strain gauges, present excelent linearity and repetibility. They can be used to provide upper limb force feedback. Two main applications for this transducer are as an event detector (intention on giving a new step), and as an evaluation system for NMES control algorithms, allowing parameter optimization through reduction of upper limb loads. The goniometers also present reasonable characteristics, being adequate for NMES applications. All sensors are cheap, easy to place on the patient's body, and reliable enough for the application.

Adaptive NMES control using neural networks

Performance coefficients (proportional to correlation values; 1.0 indicates a perfectly normal step) with off-line network only were about 0.75. This value jumped to 0.91 and 0.92 following Reward and Punishment, respectively. When both schemes were applied in sequence, the coefficient was 0.83. Thus, according to clinical tests, the use of either Reward or Punishment strategies improved system performance. When both procedures were applied, performance has decreased. Also, for most situations, the automatic on-line learning scheme presented better results than the off-line system.

Substate diagrams

Rule-based control algorithms designed through substate diagrams have proven the easiness for design and the efficiency of the results. Figure 2 a sequence for overcoming small obstacles designed with the help of a substate diagram [8].

Artificial proprioception

Some important features regarding Phi-tactile phenomenon were foound in both normal and tetraplegic subjects: (A) It is possible to evoke a moving image on the skin. (B) Results were not good for triangular waveform. (C) Sinusoidal waveforms produce sensation of ellipses on the skin. (D) The tactile image is dynamic, and its position and direction depend on channel current intensities, the ratios between these intensities, and the ratio between modulation factors of the channels. (5) The generated ellipse is not always continuous, but can be interpreted adequately.

Figure 2 - Paraplegic patient overcoming a small obstacle through the use of a substate-based NMES algorithm

Clinical cases

Two typical cases are presented here:

Case A. Male, 32 years, 90kg, 1.90m. Complete paraplegic T6 level, 2-year lesion. This subject is paticuarly able to keep standing posture for more than 1 hour without quadriceps fatigue, being also able to keep balance with one free hand. Reciprocal gait was achieved in laboratory, trough 4 NMES channels minimum. This subject was the first complete paraplegic walking with NMES in Brazil.

During stance phase, quadriceps and gluteus maximus are stimulated. Swing phase is achieved trough triple withdrawal reflex, elicited by stimulation of the common peroneal nerve. The subject, using only NMES and a walker, could walk for about 300m before exaustion and fatigue became critical. Due to the intensive use of upper limbs for balance, pain in the hands, shoulders and neck were reported by the subject.

Case B. Male, 25 years, 70kg, 1.80m. Complete paraplegic T7 level, 4-year lesion. This subject had undergone conventional physical therapy, using a conventional HKAFO orthosis. Bilateral quadriceps NMES was added to the orthosis to help the subject in the tasks of standing up and sitting down. Knee joints are locked when the subject is in stance.

A multichannel stimulatior is used, with 2 channels applied to hip extensors of stance limb (gluteus maximus and adductor magnus), to reduce the shift of the center of gravity. Other 2 channels are used on the swing limb (erector spinae for trunk extension and common peroneal nerve eliciting the triple withdrawal reflex).

CONCLUSION

The 16-channel stimulator is ready for implementation of complex algorithms. Both neural network and ruled-based substates algorithms present good results in NMES control applications, and can be both implemented into one hybrid control system.

Sensors are reliable enough for providing input for the closed-loop system, and the use of artificial proprioception helps the user to share his or her body control with the artificial system, improving patient confidence towards the system.

The components of an integrated man-machine system are ready for use towards restoring both movement and associated sensations related to paraplegics and tetraplegics.

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ACKNOWLEDGEMENTS

The authors would like to thank FAPESP, CNPq, and CAPES (Brazil).