

A Study of a Knee Extension Controlled by a Closed Loop Functional Electrical Stimulation

C. Schmitt¹, P. Métrailler¹, A. Al-Khodairy³, R. Brodard², J. Fournier¹, M. Bouri¹, R. Clavel¹

¹ Lab. de Systèmes Robotiques, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

² Fondation Suisse pour les Cyberthèses, 1844 Villeneuve, Switzerland

³ Clinique Romande de Réadaptation - suvaCare, 1951 Sion, Switzerland

Web-site : lsro.epfl.ch/mdb/cyberthese.php, www.suva.ch/fr/home/suvacare/clinique_romande.htm.

E-mail : carl.schmitt@epfl.ch, patrick.metrailler@epfl.ch, jacques.fournier@epfl.ch, mohamed.bouri@epfl.ch, reymond.clavel@epfl.ch, roland.brodard.fsc@bluewin.ch, abdul.al-khodairy@crr-suva.ch.

Abstract

The purpose of this study was to evaluate the feasibility to develop a new hybrid orthosis called "cyberthosis" using selectively closed loop electrical muscle stimulation. The knee joint was taken as the basis for the study and a knee orthosis including motor and sensors was specially designed to perform the closed loop functional electrical stimulation control. A four-channel electrical stimulator was used as well as a feedforward controller including a proportional, integral, derivative algorithm, both developed at the Ecole Polytechnique Fédérale de Lausanne. Eight subjects with incomplete spinal cord lesion were recruited for this study. The data collected have shown that it is possible to follow an isotonic torque command during an isokinetic knee extension by closed loop electrical stimulation of the rectus femoris, vastus lateralis and vastus medialis separately. Following these encouraging results, a first stationary cyberthosis, the "MotionMaker™", was developed and tested on healthy individuals.

1 Introduction

Spinal Cord Injury (SCI) is aggravated by complications : muscular atrophy, articular ankylosis, bedsores, spasticity, poor circulation in the affected limbs, loss of cardiovascular fitness, urinary and intestinal problems or osteoporosis [1][2][3]. To prevent these complications, regular mobilization of the paralyzed limbs from the outset of the lesion has been advocated to ensure the proper working of the different metabolisms and body functions. The aim of this project is to develop a hybrid orthosis for muscular and lower limb movement training activated by electrical muscle stimulation [4]. This equipment must ensure the kinematics and the dynamic similitude to natural movements such as cycling, standing up or walking. It should allow more efficient prevention of complications and improve the possibility of recovering voluntary walking.

In order to get the best kinetic and dynamic similarity of movement for re-education including functional electrical stimulation (FES), a combination of an orthosis made up of motors and sensors, and a closed loop electrical muscle stimulation (CLEMS) real-time control was suggested by the Swiss Foundation for Cybertheses (FSC : Fondation Suisse pour les Cyberthèses). The concept of "Cyberthosis", contraction of the words cybernetic and orthosis, was introduced to name this complex hybrid orthosis.

This paper describes a feasibility study made on a single joint. A knee orthosis (KO) with one motor and several sensors, combined with a CLEMS system to stimulate and control selectively and simultaneously several muscles, was specially designed for this study. The results of simple leg extensions with SCI individuals should give the first features needed to develop complete lower limb cyberthosis with three degrees of freedom.

2 Methods

2.1 Subjects. After approval of the protocol by the ethics committee, the closed loop electrical muscles stimulation knee orthosis (CLEMS-KO) prototype was tested on six healthy subjects. SCI patients were screened during a two-month period (February and March 2003).

Seven patients with one or more of the following were excluded: fixed contractures or contraindication in mobilization of the knee, spasticity ≥ 2 according to the modified Ashworth scale upon flexion or extension of the knee [5], autonomic dysreflexia [6], known intolerance to electrical stimulation, pressure sore under treatment or seating time < 2 hours, normal voluntary muscle power of the quadriceps according to ASIA [7].

Eight eligible spinal cord injured patients (6 males and 2 females, 7 inpatients and one outpatient), 34 to 56 years old (mean 45.25), gave their written consent. Subjects were classified

according to the NISCI-92 nomenclature [7]. All had incomplete spinal cord lesions. Patellar tendon reflex was scored following Meythaler et al. [8]. The characteristics of the patients are resumed in Table 1.

#	IN	Sex	Age	NL	IS	TSI	Spasticity	QP	PR	DO
1	BD	F	53	C7	C	42	Quadriceps 1 Hip adductors 1	4	3	no
2	VM	F	56	L3 R, T10	L	C	3	0	0	yes
3	GN	M	41	L4	D	2	0	3	2	yes
4	QA	M	40	T6 R, T3	L	D	20	0	3	no
5	MA	M	36	D11	C	4	0	4	0	no
6	AF	M	34	S1 R, L2	L	D	1.5	0	3	no
7	BJ	M	51	T11 R, L1	L	D	1	0	3	yes
8	DM	M	51	C5	B	4	Biceps 1 Hip adductors 1	0	0	no

Table 1 : Subjects. IN : Initials, NL : Neurological Level, IS : Impairment Scale, TSI : Time Since Injury [month], QP : Quadriceps Power, PR : Patellar Reflex, DO : Drop-out, R : right, L : left.

2.2 Electrical Stimulator. We used a programmable four-channel electrical stimulator (Fig. 1) specially developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL), with which the current waveform as well as real-time amplitude modulation, pulse width and frequency can be selected. After trials on healthy individuals, rectangular, biphasic pulses with an amplitude within 0 to 100mA, pulse width of 300µs and frequency of 50Hz were chosen. Three pairs of self-adhesive electrodes were used to stimulate separately rectus femoris, vastus lateralis and vastus medialis [9].



Fig. 1 :
Electrical stimulator
StimWave™ 1

2.3 Knee Orthosis. The KO consists of an electrical DC motor, an angular position sensor and a force sensor (Fig. 2). This device allows isokinetic and isotonic extension with CLEMS. The motor provides the force resistance, i.e. a joint torque up to 50Nm, and a speed regulation up to 110°/s during exercise.

2.4 Control. The force sensor measures the strength given by the muscles. If the strength corresponds to the torque command value for the exercise, the motor allows the movement with isokinetic speed. If not, the pulse amplitude is modulated by the PC controller to achieve a just-sufficient muscular contraction.

The torque due to body weight is identified before exercise. At the same time, the three muscles are identified in terms of strength-stimulation and strength-angle characteristics. These parameters are used by the feedforward

controller including a proportional, integral, derivative (PID) algorithm.

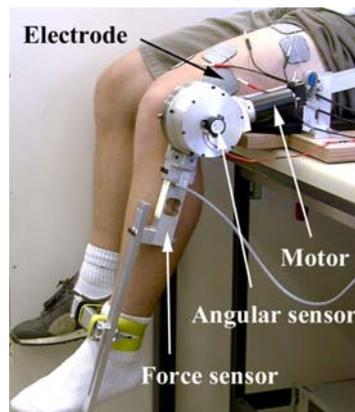


Fig. 2 :
Knee Orthosis
Setup

3 Results

3.1 FES Closed Loop Control. The graph in Fig. 3 shows the typical results we obtained. The measured torque follows the torque command inducing the isokinetic movement. All trial values were 10 °/s, within 1-10 Nm, extension from 100° to 40°, with 0° corresponding to the straight leg.

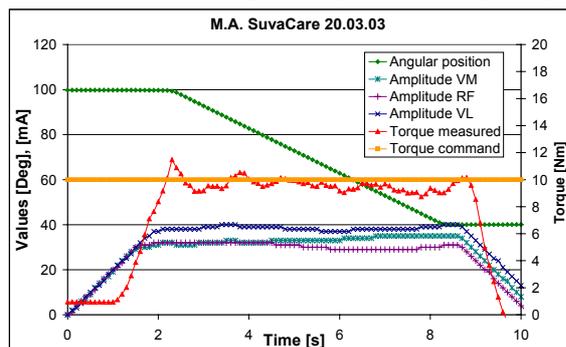


Fig. 3 : FES control of the knee extension for an isotonic & isokinetic movement

In some cases, spasms interfered with our control. When this occurred the spasm's torque peak was detected. The controller was then able to stop the process and/or to release the stress in time.

3.2 Clinical observation. All patients had at least one session. There were three drop-outs during the study: VM had an associated plexus lesion and did not respond to FES, BJ recovered full muscle power before the second session and GN was discharged after the second session. Four patients had 3 sessions at one week intervals. Overall, 16 sessions were accomplished.

The sessions lasted 20-90 minutes. The duration was closely related to individual performance in transfer from the wheelchair to comfortable installation on the module. None of the seven patients complained of pain during the test period nor developed pelvic or leg pressure sores, fractures, or had increased spasticity. As often with FES, slight hyperemia beneath some of the electrodes occurred with several patients and

disappeared within 15 minutes of the end of the stimulation. All subjects agreed to participate in the second "MotionMaker™" phase if they were asked to (see 4.1 below).



Fig. 4 : Knee orthosis with SCI subject

4 Discussion and Conclusions

The results with the CLEMS-KO were encouraging from the point of view of safety and tolerance. This study has shown the ability to perform knee extensions by CLEMS applied to three muscles of the quadriceps selectively.

Following these good results, a first "MotionMaker™" prototype was developed and tested on healthy individuals. By mid-March 2004, it was ready for bilateral leg passive movement and closed loop muscle stimulation as described earlier. A 48 year-old male patient presenting complete T11 paraplegia with impairment scale A was invited to participate in the clinical trial.

4.1 Current and future work. The MotionMaker™ is a stationary programmable test and training system (Fig. 5 and Fig. 6). It is composed of two orthosis with three degrees of freedom including motors and sensors, a multi-channel electrostimulator and a control unit managing the electrical stimulation with real-time regulation. This allows SCI patients to have full leg movements with the desired characteristics of position, speed and torque.



Fig. 5 : MotionMaker™

To stimulate two legs in a complete movement, we need 14 FES channels (rectus femoris, vastus medialis and lateralis, tibialis anterior, gluteus maximus, biceps femoris, gastrocnemii). We developed a 20-channel electrical stimulator. All parameters (current, pulse width and frequency) are adjustable in real-time by the PC controller.

The MotionMaker™ allows the exercise of movements like press-leg, cycling (with adjustable crank length and position), sit to stand, walking, and others with a whole kinematic chain. Each muscle can be identified in terms of strength-stimulation and strength-angle in order to use it optimally and reduce fatigue.

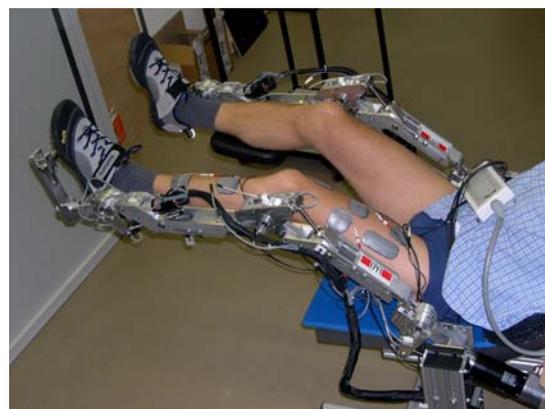


Fig. 6: MotionMaker™ Prototype with healthy individual

Acknowledgements

We would like to express our sincere thanks to the SCI patients who volunteered to take part in the study. We are grateful to the FSC, the EPFL and to the Swiss Lottery (Loterie Romande) for their financial support.

References

- [1] Le CT, Price M. Survival from spinal cord injury *J Chronic Dis.* 35(6):487-92, 1982.
- [2] Garland DE, Stewart CA et al. Osteoporosis after spinal cord injury. *J Orthop Res.* 10: 371-378. 1992.
- [3] Phillips WT, Kiratli BJ, Sarkarati M et al. Effect of spinal cord injury on the heart and cardiovascular fitness. *Curr Probl Cardiol.* 23:641-716. 1998.
- [4] Popovic D, Sinkjear T. Control of movement for the physically disabled. *Springer.* 277-281, 2000.
- [5] Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Physical Therapy.* 67 (2), 206-207, 1987.
- [6] Gutmann L (ed). Spinal cord injuries. Comprehensive management and research. *Blackwell, Oxford,* 1973.
- [7] ASIA neurological standards committee 2000 (eds). *International standards for neurological classification of spinal cord injury.*
- [8] Meythaler JM et al. *Am J Phys Med Rehabil.* 71: 321-327, 1992.
- [9] Vanderthommen M. Contribution à l'étude fondamentale et clinique de l'électrostimulation neuromusculaire. *Université de Liège, mémoire de doctorat.* 1993-94.