

THE MOTION MAKER™: A REHABILITATION SYSTEM COMBINING AN ORTHOSIS WITH CLOSED-LOOP ELECTRICAL MUSCLE STIMULATION

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Abstract

The aim of this paper is to present an active functional device using Closed-Loop Electrical Muscle Stimulation liable to rehabilitate spinal cord injury and hemiplegic individuals. "MotionMaker™" is a stationary programmable test and training system for the lower limbs developed at the Ecole Polytechnique Fédérale de Lausanne. It is composed of two orthoses comprising motors and sensors, and a control unit managing the electrical stimulation with real-time regulation. This allows leg movements with the desired characteristics of position, speed and torque. Initial tests have been carried out. The results provide elements for an objective and quantitative evaluation of the performances of the MotionMaker™, which ensure a reliable contribution to the diagnosis, assessment and recovery of functions during the rehabilitation process.

Introduction

Paralysis resulting from spinal cord injury (SCI) may cause extensive medical secondary complications [1]. These may slow down the rehabilitation program and can be prevented by moving the paralysed limbs and maintaining muscular trophicity with functional electrical stimulation (FES). Moreover, to be efficient, especially in the incomplete lesion, FES must stimulate the muscles as faithfully as possible in accordance with the sequence of muscle contraction for a given movement. The kinematics and the dynamics of the movement must be respected at best. Therefore, a closed-loop control of the FES is essential to achieve complex and repetitive movements such as press-leg and cycling. For this, the FES must be combined with an orthosis including motors or brakes and sensors. Such an orthosis is called a hybrid orthosis [2].

Adding closed-loop electrical muscle stimulation (CLEMS), the hybrid orthosis becomes a "Cyberthosis" which is the contraction of the words cybernetic and orthosis, concept proposed by the Swiss Foundation for Cyberthèses (FSC: Fondation Suisse pour les Cyberthèses). The

advantage of using a cyberthosis is to be able to create an active and progressive muscle participation which passive mobilization exercises made by therapists do not allow.

Our group first developed a knee orthosis to verify the feasibility of CLEMS applied selectively and simultaneously to the rectus femoris, vastus lateralis and vastus medialis [3]. The results of simple knee joint extension with valid and incomplete SCI individuals has given the essential information needed in order to design a complete lower limb hybrid orthosis with three degrees of freedom (DOF): hip, knee and ankle.

The purpose of this paper is to present a stationary programmable test and training system for the lower limbs activated by electrical stimulation. This device is called "MotionMaker™" (Fig. 1). It is composed of two orthoses with 3 DOF comprising motors and sensors, a control unit managing the electrical stimulation and the motors with real-time regulation, a multi-channel electrostimulator and a worktable. This allows SCI individuals to sustain or make leg movements with the desired characteristics of position, speed and torque. The aim is efficient strengthening of the muscles, the development of endurance, as well as joint mobility and movement coordination.

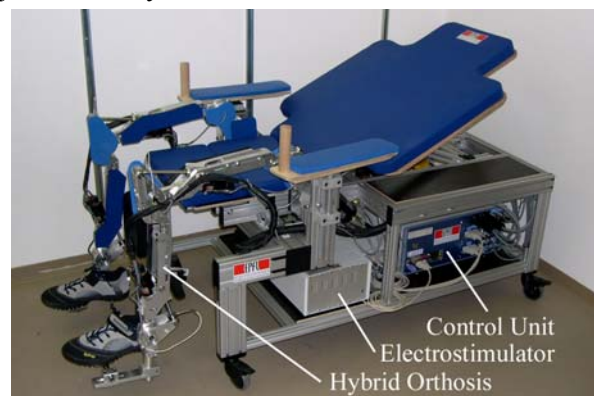


Fig. 1: MotionMaker™ prototype

Material and Methods

MotionMaker™ design description

The version of the MotionMaker™ described here is the first prototype (Fig. 1) used as a research tool for study on valid subjects (in our laboratory) and

SCI individuals in a specialized clinic which is collaborating in the project (CRR: Clinique Romande de Réadaptation - suvaCare). It was built for functionality evaluation and data acquisition. The product design issues will be addressed after the results of the first clinical trials in order to optimize the device and thus warrant a further development. The MotionMaker™ was designed to meet requirements of adjustment to fit people from 150 to 190 cm in height. Comfort was also taken into account with an adequate foam mattress. The control unit and the electrostimulator are placed inside the frame. The patient transfers from the wheelchair to the device at the front or slightly beside it. He must be assisted in this operation.

Orthosis

The orthosis (fig. 2) is an exoskeleton placed on the external side of the leg. It includes three joints: hip, knee and ankle. Crank systems activated by a screw jack controlled by a DC motor drive each joint motion. The joints being pin axis, the orthosis runs only in a sagittal plane. Although the knee joint is polycentric, inducing a sliding instantaneous center of rotation and a slight movement of the sagittal plane, the pin axis is a good approximation of the knee motion.

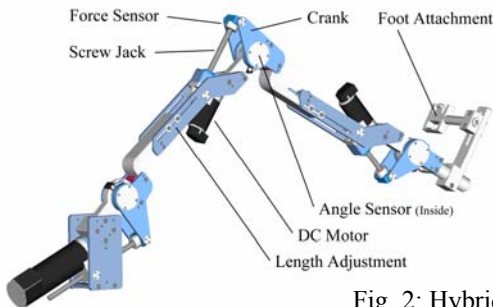


Fig. 2: Hybrid Orthosis

The lengths of the leg segments can be manually adjusted. The joint ranges of motion as well as the applicable human torque are resumed in Table 1.

Motion [deg], Velocity [deg/sec], Torque [Nm]		Hip	Knee	Ankle
Range of Motion: Ext. / Flex.		5 / 120	10 / 130	45 / 25
Velocity		110	110	110
Torque: motion way Muscle Work		<i>Isotonic max. strength at isokinetic velocity of 110</i>		
Extension	Concentric	Gluteus Maximus 50	Quadriceps 50	Gastrocnemius 50
Extension	Exentric	Rectus Femoris 80	Hamstrings 30	Tibialis anterior 30
Flexion	Exentric	Gluteus Maximus 50	Quadriceps 50	Gastrocnemius 50
Flexion	Concentric	Rectus Femoris 80	Hamstrings 30	Tibialis anterior 30
Maximum Torque		-	190 at 40°	190 at 0°

Table 1: Joint range of motion and torque (0°= straight leg)

In addition, for safety reasons, manual adjustable joint stops can limit the range of movement of every single joint whenever indicated.

Worktable

The main function of the worktable is to place the patient in a good and comfortable position for the exercise and to adjust both orthoses to the subject. Fig. 3 shows the different adjustments (DOF). Currently these are made manually; for the next version they will be automated.

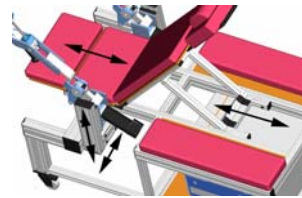


Fig. 3: Worktable DOF

Control unit

The controller consists of an intelligent central unit, namely an industrial PC with a real-time extension and an axis interface board and amplifiers. The control architecture adopted to control the MotionMaker™ is composed of a motion control and electrostimulation management. The controller synoptic is shown in Fig. 4. It is highly flexible and is built with different modules, some of them working as real-time processes composing the real time controller (RTC). The software modules composing the control unit are as follows:

- *The Graphical User Interface (GUI)* used to communicate with the real-time motion server (RTMS) by using the communication library (dll).
- *The Communication Library.* This interface, provided as a *dll*, allows communication with the RTC and renders it invisible to the user. Thus, all the high-level instructions necessary to set up the motion and the CLEMS control are made available.
- *Real-Time Motion Server.* The RTMS is the main door of the RTC. It receives orders and parameters from the GUI via the *dll* and dispatches them to the processes concerned (motion generator, motion controller or CLEMS controller).
- *Motion generator.* It generates the trajectories with specified geometry and given dynamics. This motion generator (MG) also communicates with the CLEMS control to carry out the movement or not.
- *Motion controller (MC).* It attends to the regulation of the set-points on each axis.
- *Library of Forward and Inverse Kinematics.*
- *CLEMS controller.* It carries out the regulation of force values using muscle stimulation.
- *Library of Input/Output Functions.*

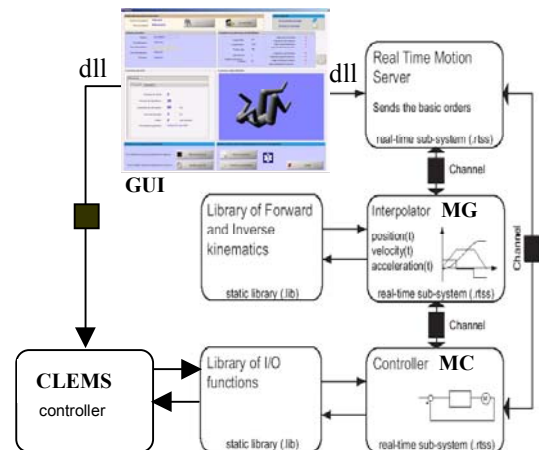


Fig. 4: Motion control principle and software

Electrostimulator StimWave™

In order to fulfil the MotionMaker™ FES requirements, a high-performance electrostimulator has been developed. It consists of 20 independent modular channels. The parameters of each are real-time controllable by the central unit via a common serial link. Each channel is able to generate rectangular biphasic symmetrical current pulses up to 100 mA. The compliance voltage is about 200V. The frequency and the pulse width are adjustable within a range of 10 to 85 Hz and 100 to 300 μ s respectively. To avoid parasitic current flow between the electrode pairs, each channel output is electrically floating. The main concern was patient security. Therefore different sorts of hardware and software security systems have been implemented, such as pulse timeouts, programmable current limitation, command relevancy tests and communication checksum.

FES control

Self-adhesive electrodes of different shapes are placed on the principal muscles of both limbs; Rectus Femoris (RF), Vastus Medialis (VM), Vastus Lateralis (VL), Gluteus Maximus (GM), Hamstrings (H), Tibialis Anterior (TA) and Gastrocnemius (G). This allows us to give active torques to all joints.

Pulse width is kept constant at 300 μ s to ensure optimal stimulation and frequency is set in regard to the subject's muscle reaction. Current amplitude is adjusted up to 100 mA by the CLEMS control so muscle strength follows the control command.

Protocol

After 10 minutes of warm-up stimulation at 10 Hz-frequency, we started with isometric stimulation of all muscles at 30 Hz or 50 Hz to observe the subject's tolerance and muscle response to electrical stimulation (Fig. 5). Press-leg exercises with controlled strength and velocity followed in the test.

Subjects

#	IN	Sex	Age	NL	IS	TSI	MP	SP	S
1	RF	M	48	T9	A	4	0-1	2	1
2	EA	M	60	T8 R, T5 L	D	8	2-4	0	2
3	JB	M	77	C5	D	2.5	1-4	1	1
4	PG	F	79	T2	C	3	1-4	1	1

Table 2: Subjects. IN: Initials, NL: Neurological Level, IS: Impairment Scale, TSI: Time Since Injury [month], MP: Muscle Power (min & max), Sp: Spasticity, S: # of sessions, R: right, L: left.

SCI patients were screened during a three-month period (February-May 2004). Four eligible spinal cord inpatients (3 males and one female), 48 to 79 years old (mean 66) gave their written consent. Subjects were classified according to the NISCI-92 nomenclature [4]. Spasticity was measured

according to the modified Ashworth scale [5]. All but one had incomplete spinal cord lesions. Table 2 resumes the characteristics of the patients.

Clinical observation

Three patients had one session and one had two sessions. There were no drop-outs during the study. The sessions lasted 100-120 minutes. The duration was closely related to electrode application on both legs and individual performance in transfer from the wheelchair to comfortable installation on the MotionMaker™. None of the four patients complained of pain during the test period nor developed pelvic or leg pressure sores, or fractures, or had increased spasticity. One patient had a lumbar brace and 2 cervical collars. None complained of pain or discomfort. All subjects agreed to participate in further sessions.

Results

Preliminary valid subject testing

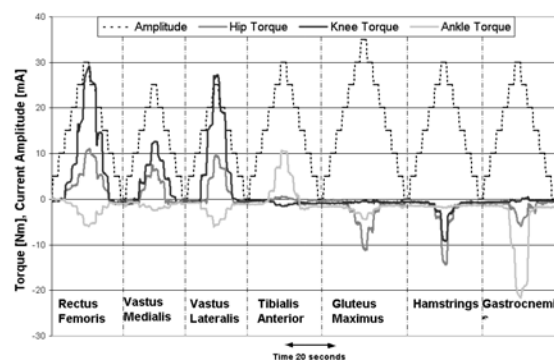


Fig. 5: Isometric stimulation valid subject (CS)

Fig. 5 shows a result of an isometric stimulation. Each muscle is activated with increasing-decreasing amplitude steps. Torques due to muscle contraction are plotted in function of time. A horizontal movement of the ankle defines the press-leg trajectory. The aim is that the resulting force applied by all muscles follows the value of 30 N (*Force Order*) in horizontal direction (*Force X*) and 0 N in vertical direction (*Force Y*). Fig. 6 shows a result of five FES press-leg extensions.

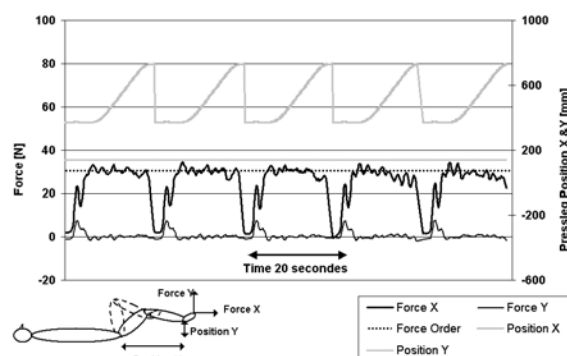


Fig. 6: Press-leg with CLEMS, valid subject (PM)

Preliminary SCI individuals testing

Due to muscle atrophy and no FES adaptation of our SCI individuals, stimulated strengths were low and difficult to control. A long training program with the MotionMaker™ will demonstrate its ability to overcome these phenomena. On the other hand, our device allowed us to measure the residual voluntary strength of our SCI subjects during press-leg movement. JPB performed two extensions with approx. 150 N.

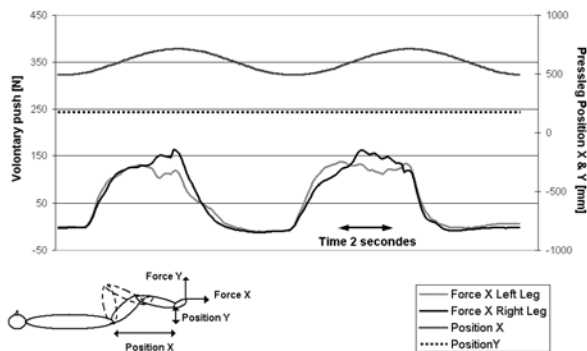


Fig. 7: Press-leg measurement of residual voluntary strength of incomplete SCI subject.

The next step will be to increase muscle strength by adding CLEMS stimulation with voluntary contribution.

Discussion

Using the MotionMaker™, complications due to immobilization should be prevented more effectively and rehabilitation to restore gait should speed up.

Cyberthosis with its CLEMS real-time control can resolve two basic concerns restricting the capacity of FES system for fitness movement or assisted gait. The first is the difficulty to control selectively and simultaneously the contractions of several muscles by means of FES. This is mainly because of the non-linear response of the muscle contraction by FES and the inconsistent behavior of the electrically-induced muscle contraction. The second is a rapid muscle fatigue, which could be a consequence of the first concern. The CLEMS provides pulse amplitude modulation by a feedforward controller including proportional, integral and derivative (PID) algorithm to achieve just-sufficient muscular contractions. This is a solution to get just enough joint torque to produce a correct, desired limb trajectory, with or without external loads created by the orthosis motors themselves. Force and position sensors give the necessary feedback to the CLEMS controller.

The MotionMaker™ is the first device of an innovative three-stage rehabilitation program initiated and managed by the Swiss Foundation for Cyberthoses. When the patient has recovered a

sufficient physical condition with the MotionMaker™, it will be possible to begin specific walk training on a device which must respect gait kinematics and dynamics (momentum conservation). The "WalkTrainer™" (Fig. 7), a mobile system providing training and assistance for gait in a vertical position, will do this. Paralyzed patients, properly prepared and trained, could, at this stage, be fitted with a walking cyberthosis: the "WalkMaker™" (Fig. 8). This device, enabling an autonomous gait, will be aimed at patients for whom SCI does not allow a full gait recovery and who still need FES assistance. The WalkTrainer™ is in the process of development and the WalkMaker™ will be designed later, after acquisition of clinical data from the first two devices.

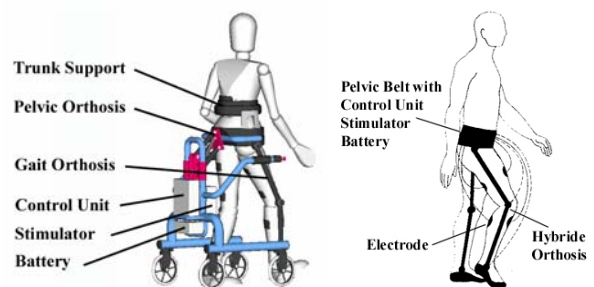


Fig. 7: WalkTrainer™

Fig. 8: WalkMaker™

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