Cyberthosis™: Rehabilitation Robotics With Controlled Electrical Muscle Stimulation

Patrick Métrailler, Roland Brodard, Yves Stauffer, Reymond Clavel & Rolf Frischknecht
Fondation Suisse pour les Cyberthèses, Monthey, Switzerland
Laboratoire de Systèmes Robotiques, EPFL, Lausanne, Switzerland
Unité de Neuroréhabilitation, CHUV, Lausanne, Switzerland

1. Introduction

Each year, following an accident or illness, over 200 new cases of paraplegia occur in Switzerland, and 1000 in France. This makes 7'000, respectively 40'000 para-tetraplegic patients in these countries. Since the Second World War, methods available for the treatment of medullar trauma at the moment of lesion, and for re-education, have evolved considerably. Nowadays, these methods allow in around 80% of medullar injuries, limitation of the damage to a partial lesion of the spinal cord. Unfortunately, only 10% of these patients ever recover autonomous walking [Zäch G.A., 2000].
Today paraplegics often benefit from walking re-education programmes on treadmills. Two, occasionally three physiotherapists are required to mobilise the patient's legs and pelvis. Unfortunately this work is extremely hard on the staff, and the movements are difficult to reproduce and obviously non-quantifiable. These manual treatments are slowly being replaced by robotic rehabilitation [Reinkensmeyer et al., 2004], much more capable of providing the repetitive and precise exercises demanded by modern methods. However, in cases where residual voluntary capacity is absent, or where there is muscular atrophy, the movements made are purely passive. The Cyberthosis Project presented below, allows active re-education, and preliminary testing has confirmed its great efficacy.

2. Cyberthosis Project

An orthosis is a device intended to correct or improve a deficient function or compensate for incapacity of a part of the body – trunk, member or segment of a member. A hybrid orthosis has the addition of one or several motors and sensors. The latter serves as a mechanical interface with the patient and allow the measurement of a limb's position, as well as the force generated by the subject. Its motors assist or resist the movement according to the therapy being applied. A new dimension has appeared with cyberthosis, this being a hybrid orthosis assisted by controlled neuromuscular electrostimulation.
Initiated by the Fondation Suisse pour les Cyberthèses (FSC), the Cyberthosis Project aims to combine closed-loop electrical muscle stimulation with motorised orthoses. This innovative concept not only allows automation of the treatment, but also an active participation of the patient's muscles. From this concept new devices have been developed in a general re-

Source: Rehabilitation Robotics, Book edited by Sashi S Kommu,
ISBN 978-3-902613-04-2, pp.648, August 2007, Itech Education and Publishing, Vienna, Austria

education process where recovery of walking did not feature as the only aim. It also integrated the benefits of electro-stimulated physical activity within an improvement to the quality of life for sufferers from medullar trauma and hemiplegics [Takahashi & Reinkensmeyer, 2003] through the reduction of complications due to immobilisation of the lower limbs.
The benefits of such treatment are obvious for the patient, but also for physiotherapists by releasing them from difficult and repetitive mobilisations.
The philosophy of Cyberthosis is founded on treatment in three stages. A dedicated re-education device corresponds to each phase; they are described in part 3, 4 and 5 of this chapter.

2.1 Medullar lesion

Medullar lesion is the result of an injury to the spinal cord. Its origin is usually traumatic, but it can also originate from an illness or an anomaly in the development such as discal hernia, tumour and spina bifida for example. The term paraplegic covers patients with paralysis of the lower limbs (dorsal, lumber or sacral lesions) as well as quadriplegics with paralysis of the four limbs (cervical lesions). Most patients with para- or quadriplegia have to get about in wheelchairs, but this is only the most visible consequence [Maury, 1981], [Grundy et al., 2002]. Several deficiencies, often hidden, result from the paralysis. At motor system level, these complications can be cardiovascular (adaptation to effort), muscular (atrophy), articular (limited movements), osseous (osteoporosis) and sensory. The resulting physical condition in these patients is insufficient for the recuperation of walking. The active muscular participation of the patient [Fitzwater, 2002] as well as their verticalisation [Postans et al., 2003], (basic principles of the Cyberthosis concept), permits the reduction of these secondary effects and in certain cases of incomplete lesions, to regain voluntary mobility.

2.2 CLEMS™[1]

CLEMS™ (Closed Loop Electrical Muscle Stimulation) is one of the basic principles of the Cyberthosis concept.
The benefits of the addition of functional electrical stimulation (FES) to mobilisation have been shown for the last 10 years [Frischknecht & Chantraine, 1989], [Belanger et al., 2000], [Rushton, 2003]. FES is used to stimulate the recuperation of a certain voluntary activity, especially in cases of incomplete paraplegia, as well as to reduce muscular atrophy and spasticity. To maximise the chances of recuperation, controlled electro-induced contractions are essential. They allow the respect of coherence between movement and the proprioceptive impulses generated by the muscular-tendinous system (Golgi apparatus and neuromuscular spindles). Information about amplitude and position supplied to the nervous system during a movement resembles as closely as possible to that produced by muscular contractions observed during a voluntary movement.
Classical FES, as it is open loop, is capable of following the activation sequences of muscles concerned in a movement. However, it is unable to adapt its intensity during the execution of the movement. A closed-loop control of the FES is therefore necessary to accomplish complex and repetitive movements such as the leg-press, pedalling, or walking in a similar manner to that produced naturally. Thus, CLEMS technology allows the closest possible reproduction of the kinematics and dynamics of natural movements. This can have considerable impact on the plasticity of the nervous system at both spinal and cerebral levels.

---

[1] Cyberthosis™, CLEMS™, StimMaker™, MotionMaker™, WalkTrainer™ and WalkMaker™ are commercial trade marks belonging to the Swiss Foundation for Cyberthosis

2.3 The Cyberthosis devices

The aim of research conducted for the Cyberthosis project is the re-education of paraplegic and hemiplegic patients; ideally as soon as possible after stabilisation of the acute phase so as to avoid muscular atrophy, but also during the chronic phase. For this, a process in three stages has been evolved.

MotionMaker™ is the first element in the process of rehabilitation [Schmitt et al., 2004a]; it is described in part 3 of this chapter. The patient's limbs can be mobilised passively or work actively in an electro-stimulated manner and/or voluntarily against resistance loads created by the motors. The aim of MotionMaker is to treat patients as quickly as possible, so as to limit the effects of an absence of movement. This means maintaining, or increasing muscular volume and capacity for patients in the chronic phase, to reinstate mobility of the joints, to train cardiac capacity and prevent neurological osteoporosis.

Once the subject has successfully completed training on MotionMaker, and attained sufficient physical condition, re-education of the motor patterns for over-ground walking can begin using the mobile device WalkTrainer™. This device is presented in part 4 of this chapter. Equipped with orthoses for the legs and pelvis, body weight support, and with CLEMS, this system allows near perfect mimicking of walking movements with the aim of stimulating nervous system plasticity.

WalkMaker™ is the third cyberthosis. This is a walking assistance device using CLEMS type electrostimulation. It offers people who have not regained sufficient walking autonomy with WalkTrainer, a functional orthotic gait [Goldfarb et al., 2003].

3. MotionMaker™

It consists of a couch and two orthoses enabling a controlled movement of the hip, knee, and ankle joints. The feet move in arcs parallel to the sagittal plane.

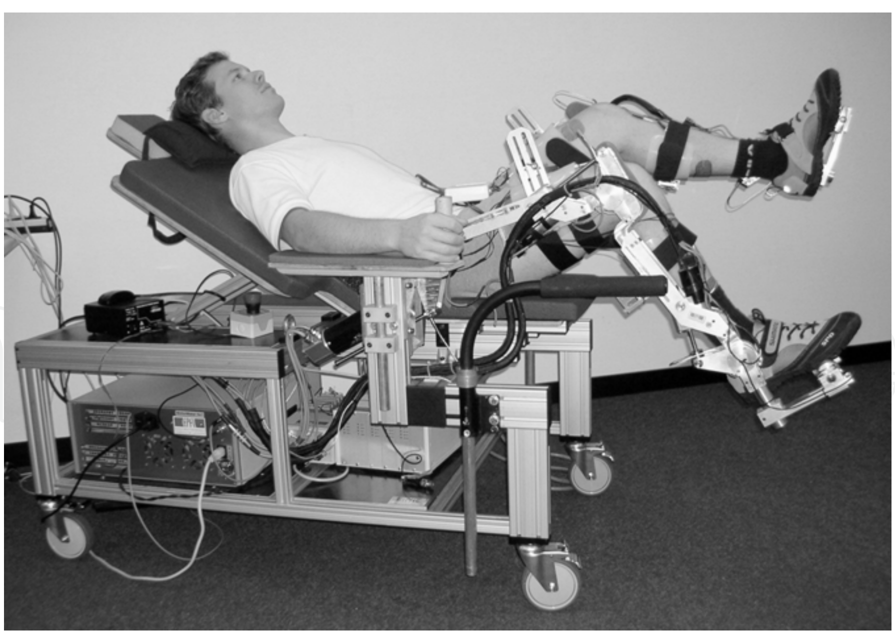


Fig. 1. Prototype of MotionMaker™ with an able-bodied subject.

MotionMaker is marketed by SWORTEC SA, a company dedicated to production and commercialization of the methods developed by the FSC.

3.1. An innovative concept

What is new about MotionMaker is essentially the coupling between the motorised orthoses, and the electrostimulation with closed-loop control. Each joint is motorised and equipped with sensors of position and articular moment. The sensors provide the control unit with the necessary information for the real-time adjustment of the electrical stimulation (CLEMS), during the execution of the movement. This adjustment takes into account the forces developed by the effect of electrostimulation, as well as the voluntary efforts made by the patients themselves. The aim of this control is to attain the level of force prescribed by the practitioner at the beginning of the exercise. According to the patient's muscular participation, the motors either assist or resist the movement. This allows active training throughout the articular range even in cases of great physical deficiency.

3.2. Technical description

The articulations of the orthosis are based on the principle of the variable length connecting rod and crank as shown in Fig. 2.

This type of orthotic joint allows the non-linear physiological curve of moment to be followed, according to the articular angle, and thus optimisation of the actuators' size. Calculation of the articular moments is made through the force sensors measuring axial amplitude in the actuator screw.

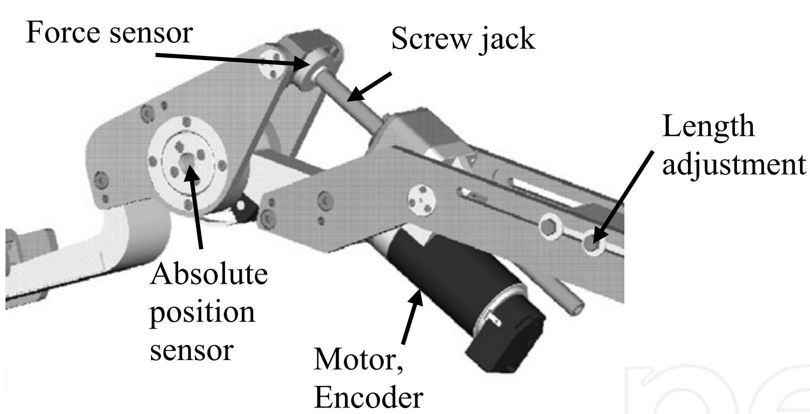


Fig. 2. Details of a MotionMaker joint.

Geometrical alignment between the robot and the patient's legs is ensured by adjustment to the length of the orthosis segments.

A dedicated electrostimulator has been developed to attain the performance required by the CLEMS control. The StimMaker™ has 20 channels of stimulation and allows modification of the electrostimulation parameters on 20 muscles with a reaction time of 0.5ms per channel.

Two systems are monitored on MotionMaker: the orthosis and the leg. Both being rigidly linked, their respective control loops must be uncoupled so that each system has its own physical

quantity to adjust. The choice is based on verification of the robot's position, and on the force of the legs. The CLEMS algorithm calculates the articular moments corresponding to the force prescribed at the level of the foot, or gets them from the initial instruction for a purely articular movement. The CLEMS algorithm uses these moments to define which muscles are to be stimulated, and then adjusts the amplitude of stimulation current supplied to these muscles throughout the movement. The stimulation technique is carried out by surface electrodes.
The comparison between the prescribed moments and those measured on the orthosis allows the adjustment of the electrostimulation but also the detection of disruptive elements such as spasms and clonus. In fact, electrostimulation and mobilisation can encourage involuntary reflex contractions that in certain patients can be considerable. To ensure the safety of the patient during an exercise, the system behaves in a carefully programmed manner following detection of a spasm. MotionMaker reacts to interrupt this spasm by reducing stimulation current, and lessening the osteo-tendinous constraints engendered by a compliant adjustment of the orthosis.

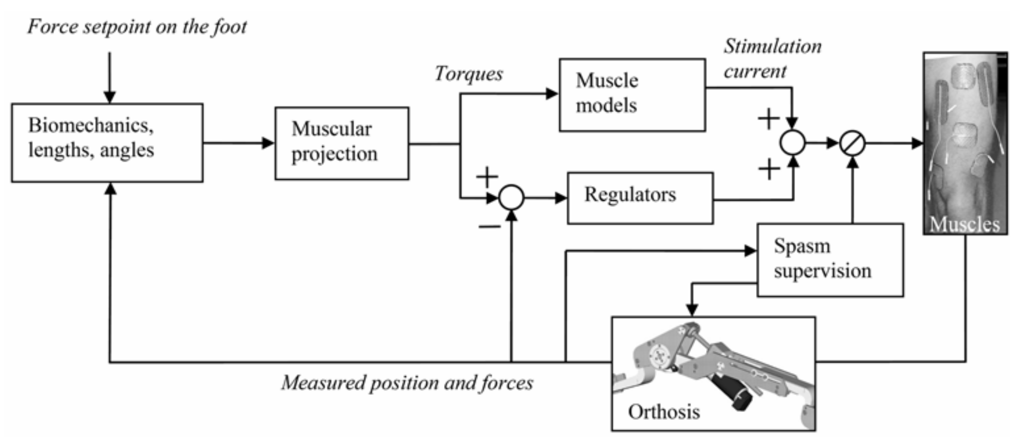


Fig. 3. Diagram of the CLEMS electrostimulation control unit.

3.3 Pilot clinical study

After having evaluated CLEMS with paraplegic patients using a simple knee orthosis [Schmitt et al., 2004b], the algorithm was tested using MotionMaker on able-bodied subjects [Metrailler et al., 2006a] with a leg-press type movement of extension-flexion. The results being satisfactory, a pilot clinical study was carried out [Metrailler et al., 2006b].
5 paraplegic patients (with lesions over 4 years old) – 4 with incomplete lesions and 1 with a complete lesion – conducted training sessions of 60 minutes on MotionMaker, 2 to 3 times a week over 2 months. The movements were leg-press type with alternate stimulation of the extensor muscles (Gluteus Maximus, Quadriceps and Gastrocnemius) and the flexors (Hamstrings and Tibialis Anterior). The principal aims of these tests were:

1. To confirm the inoffensiveness of the device.
2. To evaluate the possibility of carrying out controlled movements with paraplegic patients,
3. To confirm the possibility of increasing voluntary force and electro-induced force of subjects with incomplete medullar lesions,
4. To study the effect of movements with CLEMS on spasticity.

3.4 Results

All subjects were able to complete the whole training, there was no drop out. None of the participants felt unsafe at any time during the training sessions and they all appreciated the safety features of the MotionMaker™.

Fig. 4 shows the position of the patient during leg-press exercises. The patient is lying in dorsal decubitus position and pushes or pulls on his feet on a horizontal movement. Torque is measured on each joint and the resulting forces on the feet are obtained through biomechanical calculus.

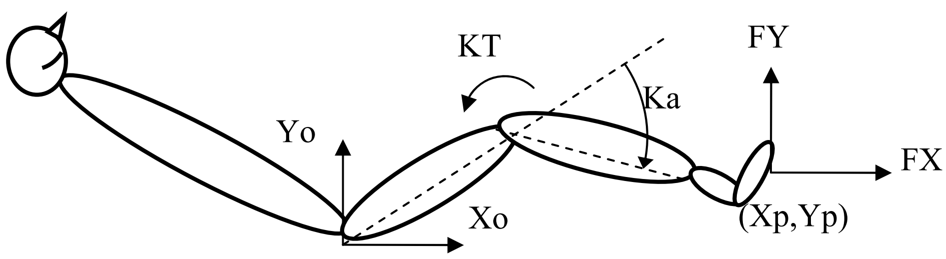


Fig. 4. Position of the foot (Xp, Yp), angle of the knee (Ka) and torque at the knee (KT).

The result of controlling the electro-induced force during extension and flexion of a leg-press exercise with a completely paraplegic patient is presented in the following diagrams. Fig. 5 (a) shows the X position of the foot (Xp), the horizontal force setpoint (FXs) and measured (FXm), the vertical force measures (FYm). The vertical setpoint force stays constant at 0N, the vertical (Yp) position remaining constant. Fig. 5 (b) shows the effects of theses forces on the foot at knee level. There one finds the torques setpoint (KTs) and measured (KTm), the angle (Ka) and the stimulation current of the quadriceps (KSc). It should be noted that the great differences between setpoint and measured values are due to saturation of the stimulation current at 70mA for safety reasons.

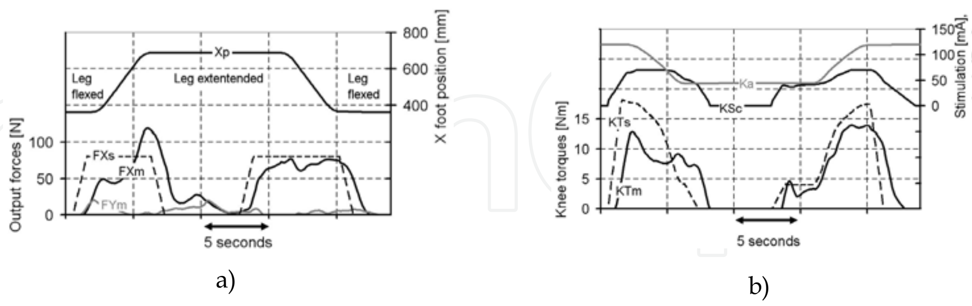


Fig. 5. a) Extension and flexion, with the position of the foot (Xp), the command force (FXs) the measured forces (FXm) horizontal and (FYm) vertical. b) Torques setpoint (KTs) and corresponding measurements at the knee (KTm), angle of the knee (Ka) and stimulation current of the quadriceps (KSc).

Through these measurements, it has been demonstrated that the force resulting from several muscular contractions can be controlled in amplitude and in direction and that the CLEMS algorithm is judicious.
During mobilisation exercises with CLEMS stimulation and voluntary force, the subjects with incomplete lesions experienced greater awareness in their limbs than when doing purely voluntary exercises. This increase in sensation seems to be due to better stimulation of the proprioceptive receptors with CLEMS stimulation. Thus, they could develop greater voluntary force with electric stimulation. The improvement in perception of their limbs enabled them also to increase their purely voluntary force in the course of the exercises.
After the two months of training, all the subjects with incomplete lesions (P1, P2, P4 and P5) had more than doubled their voluntary force, without electrostimulation, on at least one leg. Fig. 6 shows the evolution of their average voluntary force by series of exercise, in % between the first and last sessions. This increase in performance can be explained by an improvement of muscular function, by improved function of the spinal motor system linked to the neuronal plasticity, to a central motor control improved by the reactivation of dormant motor patterns or by a combination of these three elements.

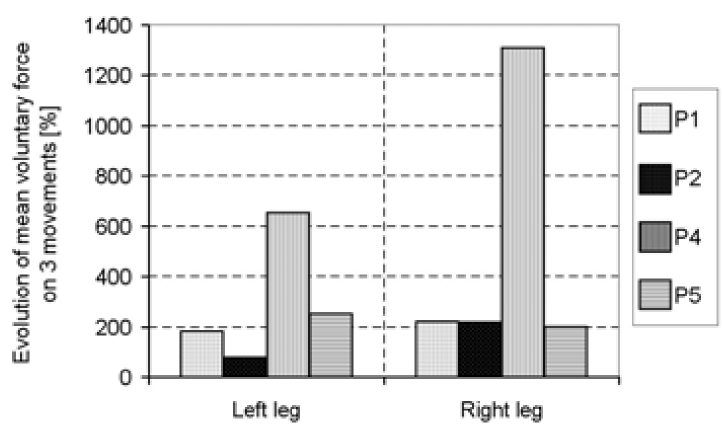


Fig. 6. Evolution, in % between the first and the last session, of the mean force developed voluntarily by the 4 incomplete paraplegic subjects, for the left and right legs, without electrical stimulation.

Fig. 7 shows the evolution of their average electro-induced force, in % between the first and last session. This increase in performance can be explained by an improvement of muscular function and by the increased stimulation current allowed by the patient's accommodation to electrical stimulation and the diminution of occurrence of spasms along the training program.
The activation of muscles in exercises of neurological re-education brings patients not only the recovery/conservation of good physical condition, but also the proprioceptive information essential for recovering the ability to activate of their own muscles. The example of patient P4 in our pilot study is particularly revealing. Fig. 8 shows the mean output power developed according to the type of exercise and the number of training sessions. The grey curve corresponds to the results of exercises with electrostimulation but without voluntary contribution, and the black curve shows the results of exercises with voluntary contribution but without electrostimulation.

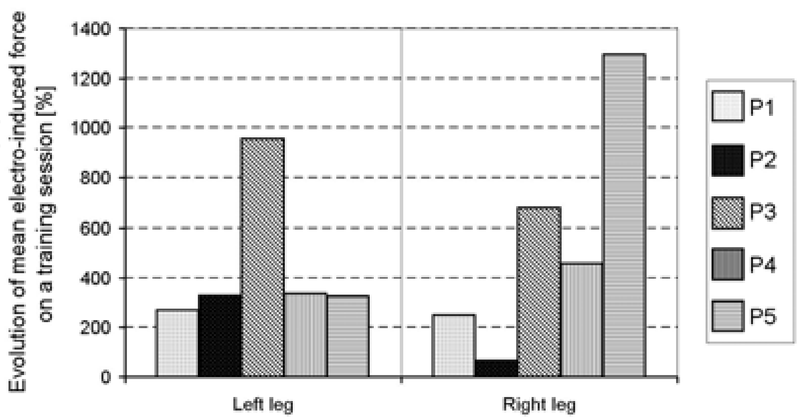


Fig. 7. Evolution, in % between the first and the last session, of the mean electro-induced force developed without voluntary participation, for the left and right legs.

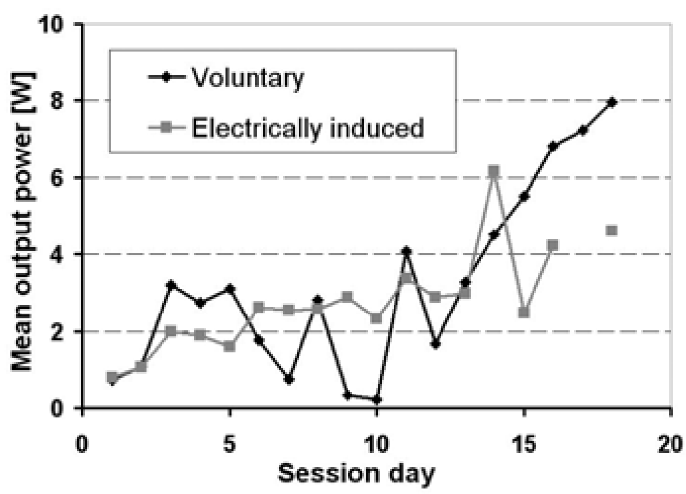


Fig. 8. Evolution of voluntary and electro-induced power for subject P4 in the clinical trial.

The evolution of voluntary force from session 10 shows a sudden and significant improvement in P4's voluntary power. This progress, being not related to the electrically induced evolution, tends to demonstrate the recovery of P4's motor pattern. This hypothesis was consolidated by the comments made by P4 concerning his capacity to use the muscles affected by his injury.

The mobilisation of the legs with electrostimulation has also had beneficial effects on the reduction of rigidity in the limbs due to hypertonia. Three of the five subjects were known to have considerable spasticity. Fig. 9 shows the evolution of mean spasticity measurements before and after each exercise session. The physiotherapists carried out manual mobilisations and graduated the resistance to movement according to the modified Ashworth Scale [Bohannon & Smith, 1987]. The reduction of spasticity lasted 2 to 3 hours after the session. This reduction was significant, hypertonia returning to levels close to those of able-bodied subjects, and it was felt to be most pleasant by the subjects concerned.

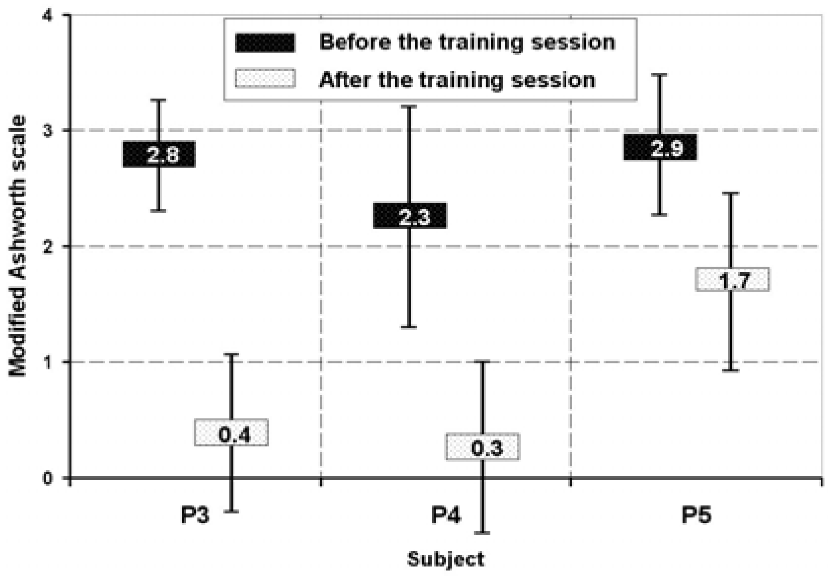


Fig. 9. Mean and standard deviation measures of spasticity before and after an exercise session.

4. WalkTrainer™

4.1. Concept

The technological developments and the promising results obtained from the clinical tests of MotionMaker, have led to the development of the second phase of the Cyberthosis project: WalkTrainer™.

The basic principle, namely closed-loop electrical muscle stimulation in conjunction with robotic assistance, is common to both these projects. The re-education of the walking motor patterns demands perfect emulation of the natural gait, which is why WalkTrainer offers training for over-ground walking. In fact, the kinematics and dynamics of the walking movement being different on a treadmill (modification of stride length [Dingwell et al., 2001] and of Electromyogram EMG [Arsenault et al., 2001]), the proprioceptive information differs. Motor patterns trained like this find themselves disrupted for over-ground walking. Locomotion with the subject moving in his environment, will not only stimulate the re-learning of over-ground walking functional motor patterns in the best possible way, but also its motivation, which constitutes an indispensable factor to the efficacy of re-education. Pelvic movement is essential to guarantee natural gait, which is why a pelvic orthosis was designed.

4.2. Components

WalkTrainer is composed of five mechatronic sub-assemblies that interact with the subject in two ways:

- Mechanically: the walking frame, the leg orthosis, the pelvic orthosis and the active suspension.
- Electrically: the CLEMS.

The main function of the walking frame is to follow the patient while moving. It serves as a mobile support for all the other components. Equipped with two differentially mounted wheels, it can operate in the plane and thus perfectly accomplish its task of following. Future versions will also have batteries on board to allow more freedom during training.

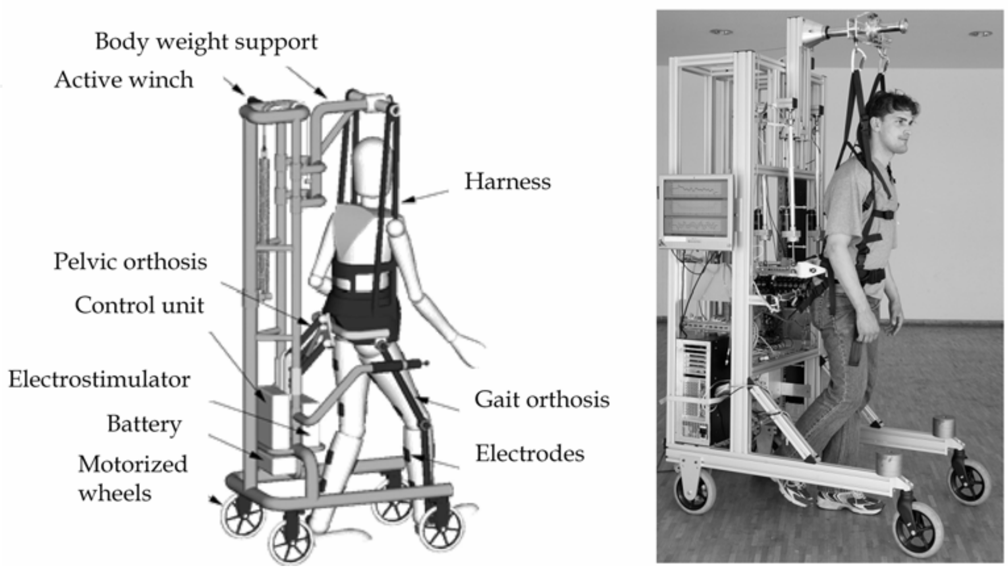


Fig. 10. a) Diagram of the principle of WalkTrainer™, b) partial execution with an able-bodied subject, without the leg orthosis.

The muscular condition of paraplegics, sometimes severe atrophy of the leg muscles, together with poor control of the postural muscles, must be taken into account. A harness allows controlled unloading of the legs, while supporting the patient's trunk. This suspension is termed 'active' as a motor combined with force and position sensors enable compensation of irregularities and force oscillations, due mainly to the preloaded spring and the different inertias at play.

The chosen kinematics for the pelvic orthosis is that of a parallel robot with six degrees of freedom. It is therefore possible for us to accompany the subject according to the three rotations and the three translations of space. The aim is to initiate the movements through the patient's pelvis and to guide it in a similar way to the work of a physiotherapist. The force sensors allow precise monitoring of the forces exerted on the subject. The work done by the pelvic orthosis is thus perfectly quantifiable, and can equally well be used in a diagnostic context.

The leg orthosis fulfils two functions of major importance. Firstly, positional measurement of the limbs of the subject is supplied in real time by the latter through the attached position sensors. The force the subject exerts on the orthosis is also measured by the force sensors. These two types of information are indispensable for the adjustment of the closed-loop muscular stimulation. Secondly, equipped with motors, the leg orthosis allows the patient's movements to be assisted.

The real-time muscular stimulator StimMaker, as described in 3.2 is also used with WalkTrainer. In this application the main muscles responsible for walking are targeted, i.e.:

Gluteus Maximus, Vastus Medialis, Vastus Lateralis, Rectus Femoris, Hamstrings, Tibialis Anterior and Gastrocnemius.

4.3. Global coordination

All the components described under section 4.2 must be coordinated to allow an interactive gait with the active participation of the subject, but without the latter being rushed by the machine.
Different strategies of co-ordination are envisaged. That currently employed consists of a master/slave relationship between the different components. The master component serves as a guiding element to the others. A logical choice for this function is the leg orthosis. In fact this latter is the keystone of CLEMS, thus of active re-education. Moreover, it includes all the necessary sensors for the measurement of the subject's activity (force and position). The master/slave relationship could therefore resemble that shown in Fig. 11.

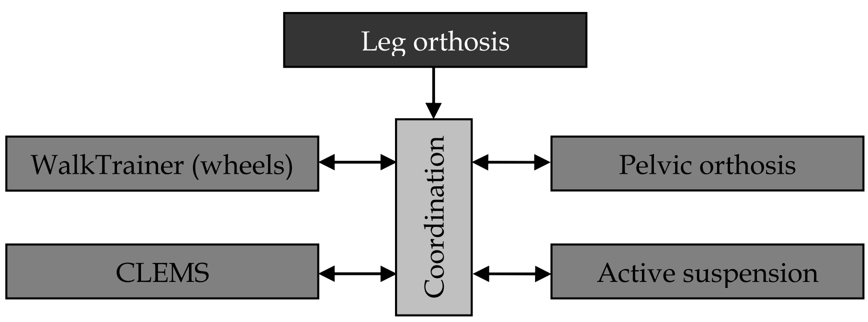


Fig. 11. Strategy of coordination between WalkTrainer's different components.

At the time of writing the leg orthosis was not available. However, an initial installation of the coordination strategy was set up. Instead of the leg orthosis, a footswitch placed under the subject's right leg served as the proprioceptive sensor to establish the position of the leg. Knowing the latter, it was possible to coordinate the movement of the pelvic orthosis with the subject's gait. The contact on the right heel was used to obtain two fundamental pieces of information: the frequency of steps and the phase difference between the legs and the pelvic orthosis. Knowledge of these two values then allows a trajectory of the pelvic orthosis guaranteeing synchronisation to be generated, under the condition that it does not rush the subject. This means that the synchronisation operates on a whole cycle and not instantaneously, which would induce acceleration that would be extremely unpleasant for the user.
The pelvic orthosis, Fig. 13, is able to guide the subject according to the six spatial degrees of freedom. These movements can be obtained with millimetric precision. However, to impose such movements in an inflexible way could generate great force on the subject, so to be considered negative, even counterproductive. It could thus be interesting to make the structure compliant in a controlled manner. One must however control these deviations exactly, and for this reason an algorithm allowing each degree of freedom in the orthosis to be made compliant independently and in a controlled manner, was installed.
This unit can be used to control interaction between the orthosis and the subjects so as not to rush them. Moreover, such an algorithm can be made progressive. It also allows the

subject's progress to be evaluated. In fact, it is possible to adapt the compliance to the subject's evolution. If subjects follow good trajectories with a compliant controller, this means that they are capable of generating these trajectories themselves.

The basic principle of this algorithm is the calculation of return forces in the operational space (OP), then their projection into the articular space (ART). In this paragraph, we assume this process takes place around a fixed point, but the same reasoning remains valid for any trajectory.

The OP error of the pelvic orthosis is calculated, then converted into OP force (in the case of a spring : Force = k•error). This force is projected into the ART space by means of the Jacobian matrix of kinematical structure [Sciavicco & Siciliano, 2001]. Finally the ART forces are applied to the pelvic orthosis, as illustrated in Fig. 12. It then remains to measure the ART so as to calculate a new OP error and so on.

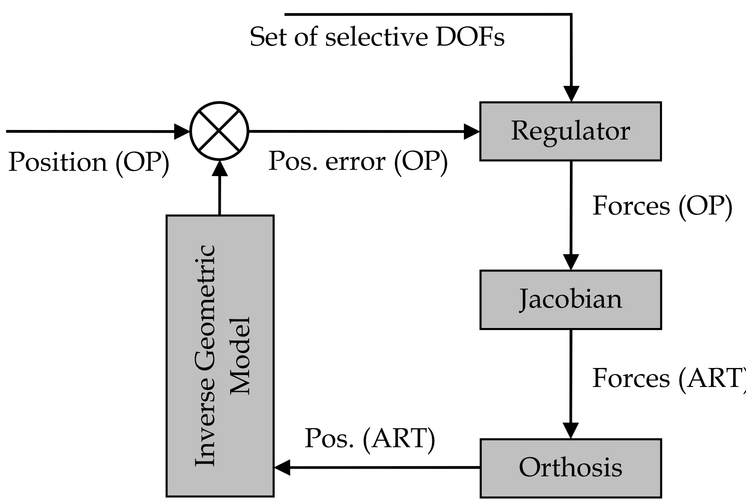


Fig. 12. Principle of selective compliance.

Initially static tests were carried out. A transverse force, Fig. 13, was applied to the orthosis and displacement in the operational space was measured.

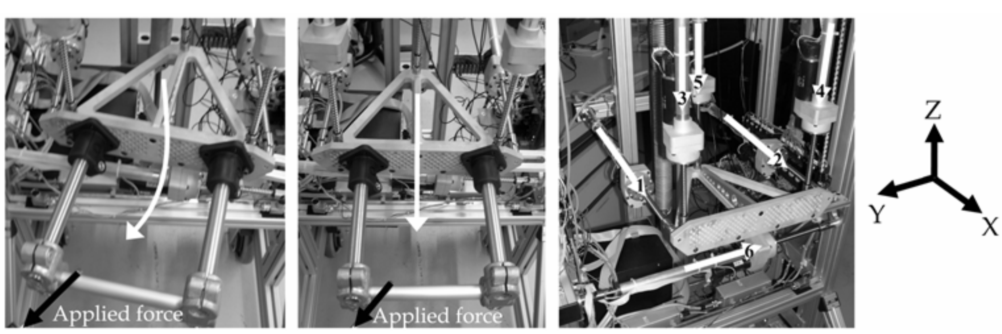


Fig. 13. Illustration of the functioning of selective compliance. Application of a transverse force with algorithm a) non-selective, b) selective, c) actuators responsible for advance (X) and rotation (Y).

In one case, Fig. 13(a), the advance axis (X) was made compliant in a non-selective manner by reducing the rigidity of the motors responsible for this translation. In the other case, Fig. 13(b), the advance axis (X) was made compliant in a selective manner. It can be clearly seen that with non-selective compliance, the translation (X) is added to by rotation around the vertical axis (Y). This originates from coupling of the translation (X) and the rotation (Y). The selective regulator however, guarantees a pure translation.

4.4. WalkTrainer and analysis of pelvic movement

WalkTrainer can also be used as a device for measuring pelvic movement for research or therapeutic purpose. To do this the addition of three sensors is necessary:

- An easyTrack200 6 axes sensor, which allows the real-time acquisition of the six degrees of freedom of the pelvis.
- A footswitch, which is placed under the subject's right heel. This signal is used to identify heel strike and lift and to compute the temporal measures in a repetitive gait cycle.
- Two potentiometric sensors, which link the subject to WalkTrainer, and actuate its servomechanism according to the subject's speed/position.

The easyTrack200 sensor is marketed by Atracsys SA. It enables, through an active tracer and linear cameras, the measurement of the 6 degrees of freedom of an object in space. A flexible pelvic belt, specially developed by an orthopaedist, is worn by the subject to carry the active tracer and also the mounting for the potentiometers, Fig. 14.

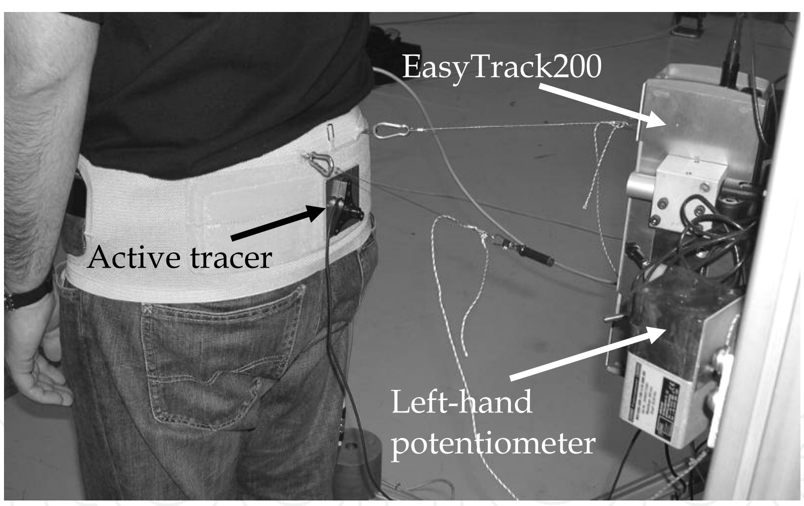


Fig. 14. Subject equipped for the measurement of pelvic movements.

Subjects then make two or three attempts at walking to familiarise themselves with the system. Then they repeat three series of measurements (1.4, 0.8 and 0.4m/s). A physiotherapist walking beside the patient governs the rate of travel, and WalkTrainer measures the effective speed. Several attempts may prove necessary before obtaining the desired walking speed. Each series takes place over a distance of around 20 metres and allows the acquisition of 15 walking cycles. The tracer's position relative to the pelvis is obtained through a calibration process.

The six degrees of freedom of the pelvis are thus measured, then processed with Matlab© using a graphic interface. Twenty people participated in the measuring campaign. These results will be used to generate trajectories for the pelvic orthosis based on a mathematical model including the walking speed and the patient's morphology, age, gender, etc. A typical vertical movement is shown in Fig. 15. The vertical line represents lifting of the right heel (~60% of the gait cycle). All the degrees of freedom are thus rapidly available in graphic form and in Excel© type files to facilitate analysis and exchange.

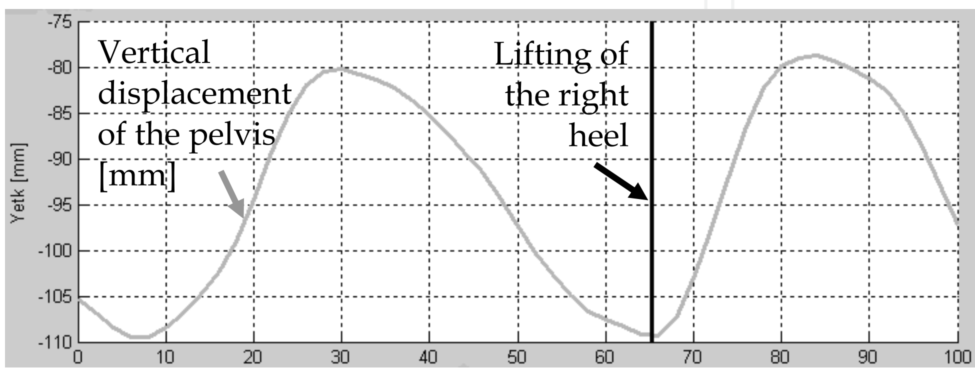


Fig. 15. Results of pelvic measurements, vertical displacement.

To enable the measurement of such movement it is essential to link WalkTrainer's position/speed to that of the subject by servo control. A special algorithm was developed for this task. It allows greater reactivity when necessary, while preventing the whole structure from following the slight oscillations of the pelvis according to the axis of advance.

5. WalkMaker™

5.1. Concept

WalkMaker™ will be a walk assisting cyberthosis using CLEMS type electrostimulation. The orthosis will serve as a mounting for the sensors required to control the electrostimulation, but will also have the function of helping and guiding the movements by active or passive actuators. It is intended for subjects who have not regained sufficient walking autonomy after exercising on WalkTrainer. These patients could benefit from WalkMaker to acquire a functional orthotic autonomous gait.

5.2 Challenges

The challenges in developing such a device are primarily mechanical. It has to provide sufficient rigidity to guide the limbs and pelvis, while also ensuring good compliance of certain degrees of freedom enabling smooth locomotion. The amount of guidance will be dependant on the neurological level of the lesion as well as the degree of paralysis.
The second challenge concerns the CLEMS electrostimulation which has to supply the basic energy of propulsion. The quality of control being directly linked to the quality of the muscular response obtained by training on MotionMaker and WalkTrainer, actuators mounted on the orthosis will probably have to filter the articular moments supplied by the muscles. Propulsion by the muscles and the use of a dynamic gait will permit reduced

energy consumption, be it electrical, pneumatic or other. Systems for recuperating energy during braking are also envisaged.
The final specification can only be established in terms of the results obtained with WalkTrainer. The main difficulty for this system is to propose an alternative at least as good as the wheelchair in functional terms, but also in terms of ease of use and implementation.

6. Conclusion

Cyberthosis brings a new approach to physical and neurological re-education. The patient regains his role as a protagonist in the movement, even if his voluntary mobility is reduced to nothing. This principle allows better emulation of the natural voluntary movements and so doing, places the patient in an ideal situation for relearning his motor patterns.
The first stage with MotionMaker has clearly shown the advantages of combining robotics and controlled electrostimulation to improve voluntary control. The activation of muscles in exercises of neurological re-education brings patients not only the recovery of muscle strength and joint mobility, but also the proprioceptive information essential for recovering the ability to activate by themselves their paralysed muscles. Training with WalkTrainer should allow one to go even further in the relearning of gait patterns by offering over-ground walking with controlled pelvic motion and muscle activity.

7. Acknowledgements

The Fondation Suisse pour les Cyberthèses would like to acknowledge the "Laboratoire de Système Robotique de l'Ecole Polytechnique Fédérale de Lausanne" as well as its associates for their scientific and technical support.
The FSC would also like to thank the "Loterie Romande" for its important financial help. The WalkTrainer™ project benefits from a grant made by the Swiss Innovation Promotion Agency, CTI Project N° 7485.2 LSPP-LS.

8. References

Arsenault, A.B., Winter, D.A. & Marteniuk, R.G. (1986). Treadmill Versus Walkway Locomotion in Humans: an EMG study. *Ergonomics*, Vol. 29, No. 5, 665-676

Belanger, M., Stein, R.B., Wheeler, G.D., Gordon, T. & Leduc, B. (2000). Electrical stimulation: Can it increase muscle strength and reverse osteopenia in spinal cord injured individuals? *Archives of Physical Medicine and Rehabilitation*, Vol. 81, No. 8, 1090-8.

Bohannon, R.W. & Smith, M.B. (1987). Interrater reliability of a modified Ashworth scale of muscle spasticity. *Physical Therapy,* Vol. 67, No. 2, 206-7

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R. & Sternad, D. (2001). Local Dynamic Stability Versus Kinematic Variability of Continuous Overground and Treadmill Walking. *Journal of Biomechanical Engineering*, Vol. 123, 27-32

Frischknecht, R. & Chantraine, A. (1989). Traitement de la spasticité par les agents physiques. *Annales de Réadaptation et de Médecine physique*, Vol. 32, 475-93

Fitzwater, R. (2002). A Personal View of FES Cycling. *Artificial Organs*, Vol. 26, No 3, 284-286

Goldfarb, M., Korkowsky, K., Harrold, B. & Durfee, W. (2003). Preliminary Evaluation of a Controlled-Brake Orthosis for FES-Aided Gait. *IEEE Transactions on Neural Systems and Rehabilitation Eengineering*, Vol. 11, No. 3, 241-8

Grundy, D., Tromans, A., Carvell, J. & Jamil, F. (2002). Medical management in the spinal injuries unit, In: *ABC of spinal cord injury*, Grundy, D. & Swain, A., 25-32, BMJ Books, London

Maury, M. (1981). *La paraplégie chez l'adulte et chez l'enfant*. Paris, Flammarion Médecine Sciences

Métrailler, P., Brodard, R., Frischknecht, R., Clavel, R. (2006a). Improvement of rehabilitation possibilities with the MotionMaker™. *Proceedings of Biobob2006, the first IEEE/RAS-EMBS international conference on biomedical robotics and biomechatronics*, Pisa, Italy

Métrailler, P., Brodard, R., Clavel, R., Frischknecht, R. (2006b). Closed loop electrical muscle stimulation in spinal cord injured rehabilitation. *Europa Medicophysica, Mediterranean Journal of Physical and Rehabilitation Medicine,* Vol. 42, 72-3

Postans, N.J., Malcolm, H.G., Hasler, J.P. & Douglas, J.M. (2003). FES augmented partial weight-gearing support treadmill training in acute incomplete SCI patients. *Proceedings of the 8th Conference of the International Functional Electrical Stimulation Society,* 135-37, Brisbane, Australia

Reikensmeyer, D.J., Emken, J.L., & Cramer, S.C. (2004). Robotics, Motor Learning, and Neurologic Recovery. *Annual Review of Biomedical Engineering*, Vol. 6, 497-525

Rushton, D.N. (2003). Functional Electrical Stimulation and rehabilitation – an hypothesis. *Medical Engineering & Physics*, Vol. 25, 75-78

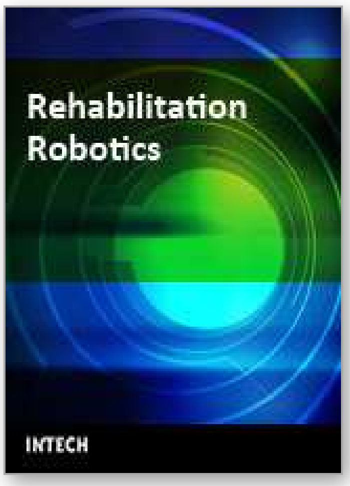
Schmitt, C., Métrailler, P., Al-Khodairy, A., Brodard, R., Fournier, J., Bouri, M., Clavel, R. (2004a) The MotionMaker: a rehabilitation system combining an orthosis with closed-loop electrical muscle stimulation. *Proceedings of the 8th Vienna International Workshop in Functional Electrical Stimulation,* 117-20, Vienna, Austria

Schmitt, C., Métrailler, P., Al-Khodairy, A., Brodard, R., Fournier, J., Bouri, M., Clavel, R. (2004b). A study of a knee extension controlled by a closed loop functional electrical stimulation, *Proceedings of the 9th Conference of the International Functional Electrical Stimulation Society*, 135-37, Bournemouth, United Kingdom.

Sciavicco, L. & Siciliano, B. (2001) *Modelling and control of robot manipulators*, Springer-Verlag, New-York

Takahashi, C.D. & Reinkensmeyer, D.J. (2003) Hemiparetic stroke impairs anticipatory control of arm movement. *Experimental Brain Research*, Vol. 149, No 2, 131-40

Zäch, G.A. (2000) Espoir ou illusion. *Paraplégie N0 87*, Bulletin officiel de la Fondation Suisse pour la Paraplégie, Nottwil, 2-3



ISBN 978-3-902613-04-2
Hard cover, 648 pages
Publisher I-Tech Education and Publishing
Published online 01, August, 2007
Published in print edition August, 2007