SERIOUS GAMES FOR ROBOTIC REHABILITATION OF ANKLE MOVEMENTS

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Abstract. *This paper presents a set of computational games specially designed for robotic rehabilitation. The proposed games were developed to interact with an active ankle-foot orthosis which deals with rehabilitation of ankle movements of pos-stroke patients. The active ankle-foot orthosis can be configured to perform exercises to improve patient skeletal muscle strength, regarding two ankle movements: dorsiflexion and plantarflexion. The games are designed and programmed considering specific characteristics of both movements, including range of movement and maximum forces. Also, protocols for each game are specified, they set the level of challenge the game have to impose to the patient, the number of challenge occurrences during the game, and the time of rehabilitation sessions. The interaction between the patient and the robotic system considers an impedance control, implemented by a Series Elastic Actuator (SEA) attached to the ankle joint. This control strategy allows the therapist to specify the desired behavior of the joint during the rehabilitation session. The complete system uses the game-based framework for robotic rehabilitation developed in our laboratory. It consists basically in the integration between rehabilitation robots and computer games developed in XNAC# platform.*

Keywords: *robotic rehabilitation, serious games for health, active ankle-foot orthosis*

1. INTRODUCTION

A high number of people worldwide suffer some motor disability as result of traumatic lesions or pathology, like encephalic vascular accident (EVA), cerebral palsy, and muscular dystrophy. The EVA or stroke, as it is commonly named, is one of the most fatal diseases in Brazil and in the world, and occur mainly in below 65 years hold individuals. In 2008, it was responsible for approximately 6 million of deaths. Besides the high number of deaths, a stroke can results in severe disabilities, which occur in 50% of the survivors (Nichols-Larsen *et al.*, 2005).

The integration of robotic systems with computer games has presented expressive results regarding rehabilitation of after stroke patients (Hogan *et al.*, 2006). The use of virtual environment based in games gives to the therapists the opportunity to treat specific movements, with the patient feeling the therapeutic process less tedious (Riva, 2000). According to Sveistrup (2004), the virtual reality is an effective rehabilitation method, since can perform the rehabilitation with a functional focus in a motivational context. Also, from the data generated by the robotic devices (position, velocity, force, etc) and the games (score, parameters), it is possible to evaluate the patient using analytical scales and historical results. The robotic systems have two main tasks: to map the user's movement to the virtual environment and to apply the haptic feedback to the patient, so he/she can feel the results of his/her interaction with the environment.

The use of games in rehabilitation of ankle movements was addressed by researches of the *Rutgers University* (Girone *et al.*, 2000). They developed a game where an airplane, controlled by the patient through a pneumatic platform, has to fly through some arches on the screen. The scheme collects the forces and torques performed by the patient. The level of difficulty of the game is controlled by the therapist, which increases or decreases the speed of the airplane as well as the number of the arches displayed during the rehabilitation session (Deutsch and Boian, 2001).

Mirelman *et al.* (2007) present a study where 15 men and 3 women with lesions after stroke in the malleolar region were divided into two groups and performed three months of treatment using the Rutgers platform and virtual reality or not. The dorsiflexion movements of the patients were affected by the lesions, they were not able to walk for more than 50 feet. Patients who did not use virtual reality performed the protocols through instructions of a therapist. Experiments were conducted three times a week, during one hour. According to the authors, the patients who use the virtual reality had an evolution in its ability to ride in comparison with the other patients.

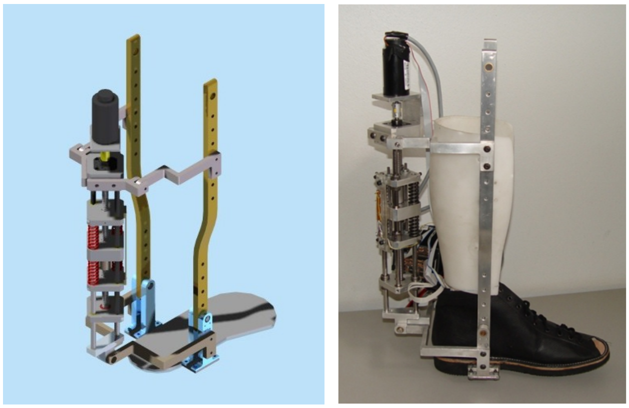
This paper deals with the development of computer games for the robotic rehabilitation of ankle movements. The proposed games are designed considering a set of issues pointed out by therapists with relation to which movement is being evaluated (dorsiflexion or plantarflexion), the range of movement, the level of applied forces and, mainly, which pathology is being treated. Three games were developed and tested in an active ankle-foot orthosis, using the game-based framework developed in our laboratory to integrate the games with our rehabilitation robots. Our active ankle-foot orthosis

(AAFO) is driven by a series elastic actuator (SEA), a specific actuator which can perform force and impedance control by measuring the applied forces through the elastic series deformation.

The paper is divided as follows: Section 2 presents the AAFO and SEA features; Section 3 presents a short description of serious games concept; Section 4 presents the game-based framework which integrates the robot device with the game inputs; Sections 5 presents a set of 2D and 3D games developed for rehabilitation of the ankle, considering both dorsiflexion and plantaflexion movements, and some preliminary results; finally, Section 6 presents the conclusions.

2. ACTIVE ANKLE-FOOT ORTHOSIS

In this section the interactive robot AAFO, Fig. 1, is briefly described (more details can be found in Jardim and Siqueira (2009)). It was designed considering anthropometric measures - such as limb dimensions and masses - normally observed in a healthy human (Winter, 1990). A series elastic actuator is mounted on the back of the device and moves the ankle-foot orthosis through a four-bar mechanism.



(a) (b)

Figure 1. Active Ankle-Foot Orthosis (AAFO). (a) design, (b) initial prototype.

The ankle joint ranges of a normal gait pattern are used as input to the actuation mechanism design. Tab. 1 shows the typical values for the human ankle during walking and the maximum values for the human ankle obtained from Winter (1990) and the proposed AAFO range of motion.

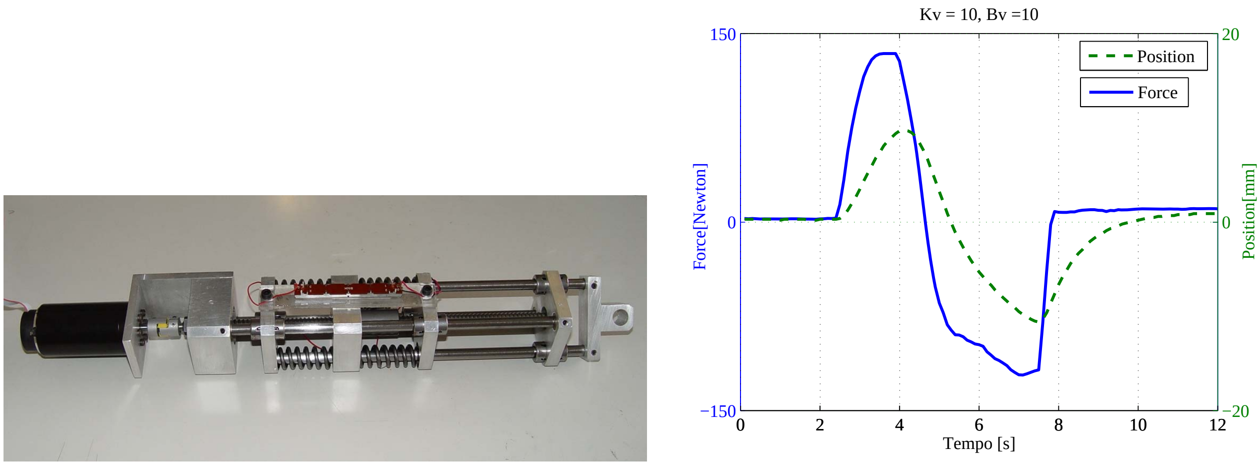
Table 1. Ranges of motion of the human ankle and the proposed AAFO.

Ankle Movement	Walking	Humam (max.)	AAFO (max.)
Plantarflexion	20^o	50^o	25^o
Dorsiflexion	15^o	20^o	15^o

An analysis of a typical human walking shows that the ankle cycle of movement can be divided into four parts: swing phase (SP), controlled plantarflexion (CP), controlled dorsiflexion (CD) and powered plantarflexion (PP). According to Au *et al.* (2006); Blaya and Herr (2004); Walsh *et al.* (2006), during each subphases the ankle joint presents a specific characteristic of stiffness and damping. For example, it is showed that the ankle joint behaves as a linear spring response during CP, where joint torque is proportional to joint position. These mechanical characteristics will be useful to specify the desired stiffness and damping for the SEA during the rehabilitation session.

The series elastic actuator was reproduced according to the device developed by Pratt and Williamson (1995) (details on how the device operate can be found in this reference and in Jardim and Siqueira (2009)). All SEA components are shown in Fig. 2, where can be noticed the six support parts, the effector, one DC motor (maxon RE40 150W), one elastic coupling, one ball screw, one nut, and bearings to support the ball screw. The elastic series is composed by four linear translational springs (two for each actuation direction) with total stiffness equal, approximately, to 78.9 N/mm in each direction, Fig. 2(a).

To test the ability of the SEA to simulate the behavior of a given impedance, the following experiment was considered: the device must behave with both virtual damping (Bv = 10 Ns/mm) and stiffness (Kv = 10 N/mm). The values of Kv and Bv are introduced in the C++ program which computes the desired position for the motor and send it to the driver, through an impedance control implementation (see Jardim and Siqueira (2009) for details). The actual force value is computed considering the voltage measured through the sliding potentiometer, which is attached to the parts supporting the elastic component. For these experiments, the SEA was connected to the ankle-foot orthosis and an oscillatory force was applied



(a) (b)

Figure 2. Series Elastic Actuator: (a) prototype and (b) spring-damper behavior.

in the ankle joint by the user, the results for the given behavior can be seen in Fig. 2(b), it is shown only the force acting on the SEA end-effector and its position. Note that, as expected, the spring-damper combination recovers with exponential decrement after load force is removed.

3. SERIOUS GAMES

Computer games are related directly to the act of playing and arouse fascination in people (Munguba *et al.*, 2003). However, Huizinga (1955) quote by Alves (2005) characterized the game as a cultural element which is composed of five characteristics: freedom, escape from real life, distinction from ordinary life, creating order and unpredictability. Also according to Alves (2005)these reflections are put into question the interpretation that, by playing, people are just having fun. The games that are not exclusively associated with or intended for entertainment are called Serious Games (Barnes *et al.*, 2009).

Serious games are receiving increasing attention as a result of successful game development industry, and because of the abundance of new technologies. These kind of games have been applied in many different areas such as education, corporate and military training, cultural training and health. You can adapt the concepts presented by Zyda (2005) applications for rehabilitation (health), and submit the following definition of serious games: mental competition done on a computer, according to specific rules and uses that as a form of entertainment achieving health goals (and rehabilitation). One advantage of this definition is that it overcomes the split between the developments accepted as serious and initiatives intended only for entertainment.

4. GAME-BASED FRAMEWORK

In this section we present the structure of the game-based framework for robotic rehabilitation. It consists basically in the integration between the interactive robots shown in previous sections and computer games developed in XNAC# platform. C# was the chosen language because it is an object-oriented language similar to Java language and with certain settings that come from C++, also it is the only one that works fine with XNA.

XNA (XNAś Not an Acronym) Game Studio Express is an Application Programming Interfaces (API) from the platform .Net developed by Microsoft to create games such for PC as Xbox 360 console. Although it is a recent technology, officially cast in 2006, it assembles all APIś form DirectX and Managed DirectX (MDX) and others, developed only for it. Further, it allows easy access to peripherals (keyboard, mouse e Xbox 360 gamepad), grafical hardware, audio control, network access and informations housing in archives or database (Lobao *et al.*, 2009).

The AAFO is controlled by EPOS (Easy-to-use Positioning) controllers from maxon motor. This digital amplifier can perform current, position or velocity control of the motor, with set-point values set through serial or CANopen interfaces. A set of real variables, including shaft position, velocity and motor current, can be measured using these interfaces. Also, this device can measure up to 2 analog inputs. Particularly, one of these analog input channels is used to obtain the spring deflection of the SEA, computed by the measurement of the voltage through a linear potentiometer connected between the nut support and the spring extremity. From the spring deflection, it is possible to estimate the actual torque in the ankle joint applied by the actuator and to perform the impedance control.

The basis of proposed framework for robotic rehabilitation is the communication between the EPOS controllers and XNA software. This communication is performed by the RobRehab library, specially developed for C# applications, taking as support the dll library for EPOS controller. RobRehab library provides to game developers a clear access to EPOS. Functions available by the framework are end-user ready so that the developers do not need to worry about any issue related to communication. Figure 3 shows the available diagram of game-based framework for robotic rehabilitation.

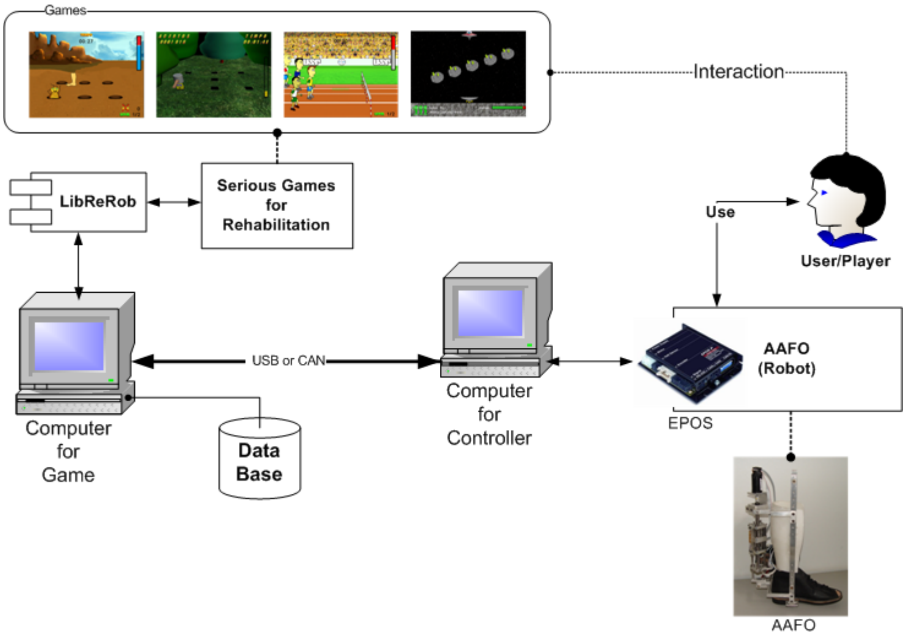


Figure 3. Diagram of the game-based framework for robotic rehabilitation.

5. GAMES DEVELOPMENT

The group which the project is targeted are people who have suffered stroke. The gait performance in a patient with stroke is characterized by a lower speed and timeless asymmetry with respect to the left and right sides if compared with healthy adults. Experimental data show that the speed of gait in stroke patients of different severities ranges from approximately 0.18 to 1.03 m /s, while adults of the same age is about 1.4m /s (Hsu *et al.*, 2003). The OTPA has only one degree of freedom in the ankle, which allows dorsiflexion and plantarflexion.

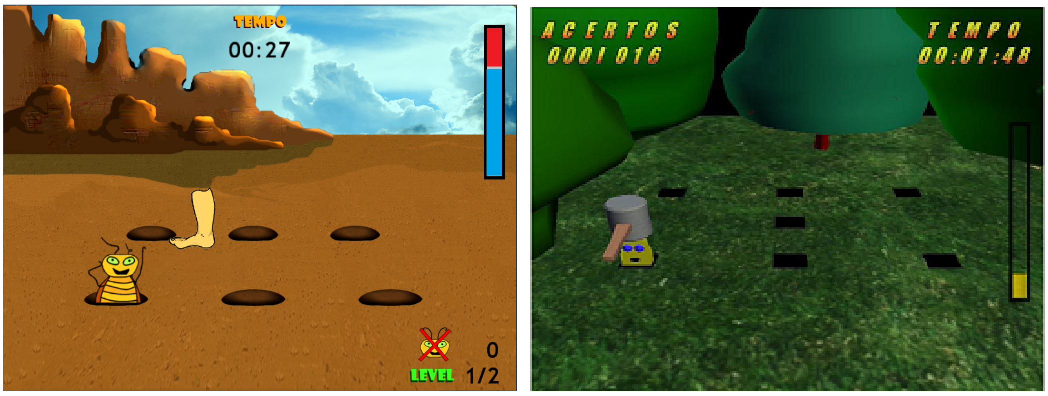
The drop foot is checked when there is damage to ankle extensor muscles. During the gait, with weak muscles, the foot contacts the ground during the support phase and, during the swing phase, the patient can not lift its foot off the ground and has to make a compensating movement with hip and knee (O'Sullivan and Schmitz, 2006). When there is an injury to the plantar flexors, at the moment of impulse during gait, after stroke patients have difficulty in playing forward the leg that is behind. In this case, a faster movement is performed with the hip. The virtual environment for rehabilitation will encourage such patients to perform the rehabilitation protocols proposed by therapists to strengthen both muscles. According to the protocols suggested by the involved therapists, the exercises should be conducted separately.

The success criterion for each movement is the force that the patient can exercise with the foot. The sessions will be carried out in three sets of twenty exercises, for both plantar flexion and dorsiflexion with intervals of one minute between each one. That is, the stent has its adjustable impedance, which may perform more or less resistance to movement of the ankle; when the patient reaches a minimum limit specified by the therapists (standard of 70% of the maximum force it can exert, but which can be adjustable), it will succeed.

Although the parameters are set by physical therapists, the rehabilitation environment will be adjustable, not restricted to the first criterion. The aim is to enable the important parameters such as strength, number of sets, number of repetitions per set, exercise speed and rest time to be adjustable according to the possible needs, making the system more versatile for future studies to be conducted with it.

5.1 Plantarflexion Game

In this section it is presented the concept and the final structure of a game, named Cockroach × Foot, designed for rehabilitation of the plantarflexion movements. The definition of the game was made to satisfy the protocol defined in the previous section. The most important information the protocol provides is that the movement's success is based on the strength that the patient can reach, since it interferes directly in the control of the game. The other parameters such as repetitions, number of sets and rest time are easily adaptable in the game. The game consists of little creatures that appear on the screen and must be disposed of by a foot, controlled by the user, as the patient reaches the strength stipulated. In



(a) (b)

Figure 4. Plantarflexion games. (a) Cockroach × Foot, 2D configuration, (b) Cockroach × Foot, 3D configuration.

the game scene, there is a bar that measures that force. The bar goes up as the force rises and falls with the decrease of strength performed by the user. The purpose of the bar is giving feedback while he plays, so he can know how hard it still must do to accomplish the movement.

The foot placement is done through the mouse and it just steps when its area intersects the creature area and the power held by the user is greater than or equal to that needed. Taking into account that many stroke patients also have difficulty moving the arms and may be unable to handle the mouse, it was added to set the option not to use it. In this case, we implemented an algorithm in which the foot is positioned automatically on the creature to prevent that even reaching the necessary strength, the patient does not meet the goal of the game due to a possible physical disability in upper limbs. The game ends when the patient can successfully perform the series of suggested exercises or when it goes beyond the maximum time given for their achievement. Figure 4 shows the two configurations already implemented, regarding 2D (Figure 4(a)) and 3D environments (Figure 4(b)).

Figure 5 shows the results obtained from a volunteer playing the Cockroach × Foot game and wearing the AAFO. The figure shows the force applied by the user on the AAFO sole and the desired force the player has to reach to obtain success. It is also shown the time instants when the cockroach appears (blue line), when the cockroach is supposed to disappears (green line) and when the cockroach is hit by the player (red line). Note that the applied force is reaches the desired value at this points.

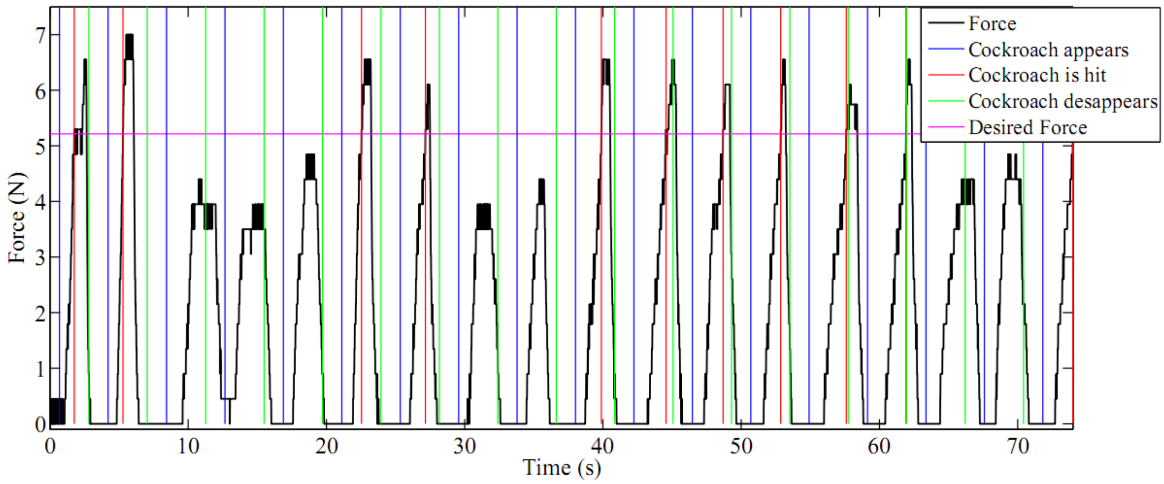
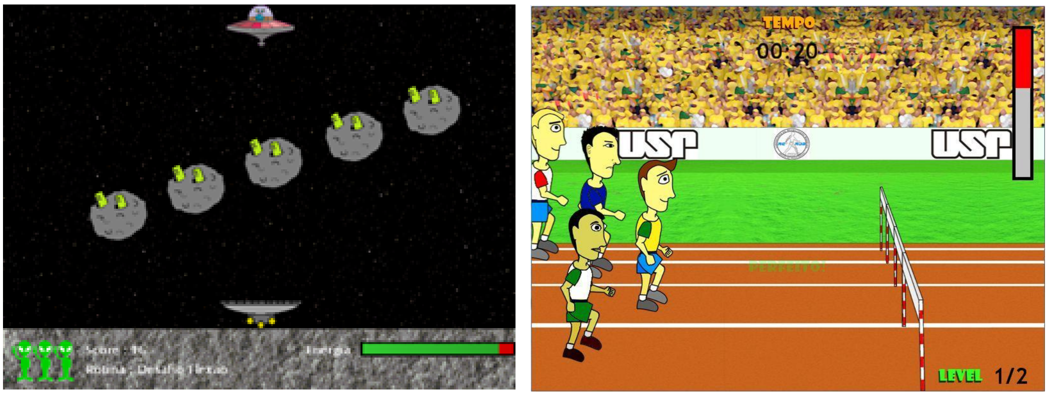


Figure 5. Applied force by the volunteer playing the Cockroach × Foot game.

5.2 Dorsiflexion Game

Following the protocols defined before, in this section two games are developed for rehabilitation of the dorsiflexion movements. The first game, named Space Ship, is based on a ship that is in space and aims to escape from meteors that could hit it. To increase the difficulty level, the energy decreases with time, and when approaching zero, the tank must be replenished. Thus, the user is encouraged to force the movement of the ankle in dorsiflexion, and when they need refueling, he is forced to make his challenge.

As explained before, when power is needed, the patient must perform a force beyond the maximum amount it can to reach the refueling station. Therefore, it is encouraged to increase its maximum force. Notice in Figure 6(a) that the maximum and minimum positions obtained by the ankle coincide with the limits of the screen. Also, note that the central refueling is beyond this limit. This position is within 5 % of the challenge.



(a) (b)

Figure 6. Dorsiflexion games. (a) Space Ship, (b) The Athlete.

The second game, named The Athlete and shown in Figure 6(b), consists in a running competition where the patient is one of the runners. The objective is to jump the bars which appear during the running. To do so, the patients must perform the dorsiflexion movement and reach the force specified by the therapist as a percentage of their maximum force. If the desired force is not reached within a predefined time after the bar comes into view, the bar falls when the athlete passes through it. Again, there is a bar on the screen showing the actual force the patient is applying to the orthosis.

6. CONCLUSIONS

In this paper we proposed a set of computational games for robotic rehabilitation of ankle movements. The games were evaluated using an active ankle foot orthosis, designed to perform dorsiflexion and plantarflexion movements of ankle joint. The device is driven by a series elastic actuator, which can be controlled to provide specific impedance behavior. The complete system uses the game-based framework for robotic rehabilitation developed in our laboratory, consisting in the integration between rehabilitation robots and computer games developed in XNAC# platform. The results show the proposed games can effectively be applied for robotic rehabilitation, giving to the patients visual and motor feedback, and increasing the motivation to complete the rehabilitation program.

7. ACKNOWLEDGEMENTS

This work was supported by CNPq (Scientific Initiation scholarship) and FAPESP (grants no. 2008/09530-4 and 2009/15945-5).

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