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A CONTINUOUS PASSIVE MOTION AQUATIC DEVICE

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Abstract. *This paper describes the development of a continuous passive motion aquatic device applied to human lower limb rehabilitation. The intention of this work is to help patients and health professional during rehabilitation sessions using the aquatic environment. First this paper presents a review about the continuous passive motion device developed and the robotics devices applied to rehabilitation in the aquatic environment. After, the mathematical model of proposed device as well as the prototype and the preliminaries experimental tests are presented. Finally, this paper presents the conclusions and the suggestions for future works.*

Keywords: *robotics, aquatic, rehabilitation, lower limb, continuous passive motion.*

1. INTRODUCTION

Human being always seeks to perfect any and all indispensable activity in his life, seeking to accomplish them in the shorter term, with less effort, with a higher quality of life and maximum safety. With the developments of civilization, more and more studies of machines and robots have appeared that are able to perform partially or totally activities before realized by the man.

The technology of robotic devices in medical applications is increasingly on the rise, and this integration of engineering and medical sciences is enabling the development of techniques and processes that only tend to increase the quality of life of those people who, for example, have a locomotion problem, often caused by accidents or illness. These robotic devices allow the practice of specific tasks to be reproduced several times, in a controlled and reliable way, and it is being shown in the literature as a determinant factor for the facilitation of cortical reorganization, with consequent increase of the motor capacity and improvement of the performance of the functional activities (Krebs et al., 2007).

To assist the work of health professionals and patient recovery/rehabilitation, companies have invested heavily in the development of robotic devices. These devices for rehabilitation allow the creation of new methods for relearning of the movements of the human limbs, assisting health professionals.

The method of Continuous Passive Movement (CPM) by definition is a movement produced by an external force, which is performed in a joint, part of the body, or tissue, starting from a complete immobilization spectrum for continuous, uninterrupted movement (Callegaro, 2010).

The main clinical use of CPM today is to avoid arthrofibrosis following trauma or joint surgery that are prone to stiffness, such as the knee, elbow, and hand joints (O'Driscoll and J. G. Nicholas, 2000). Another applications of CPM are: total knee arthroplasty; arthrotomy and drainage for acute septic arthritis; rigid internal fixation of a metaphysical osteotomy (e.g., knee arthritis); surgical release of the extra-articular contractures of the joints; knee ligamentoplasty; persistent limitation of joint movement; reconstruction of a chronic ligament laceration using tendon graft; surgical repair in an acute laceration of a ligament; joint stiffness and total prosthetic joint replacement.

The CPM is a therapeutic modality that, correctly indicated and used within a safe range of motion, helps to reduce edema, the range of postoperative movement, post-trauma of joint injuries and avascular cartilage healing. Controlled exercises immediately after surgical procedures stimulate the production of synovial fluid. This is important in the nutrition and healing of cartilage and avoids post-traumatic arthrosis, preventing joint contracture, without pain and stress to the healing tissue (Hebert et al., 2003).

Karolczak (2006) reports that immobilization causes muscle changes as well as a decrease in muscle fiber area, consequently reducing strength capacity and altering the percentage of prevailing fibers, leading to an increase in the number of fast contracting fibers. This generates functional changes in the mechanical properties of the muscle and the ability of the muscle to withstand fatigue.

Studies have shown that the use of CPM has been effective for rehabilitation and it can then be stated that CPM is effective in preventing stiffness, since it is applied immediately after surgery and sustained until the edema subsides (O'Driscoll and J. G. Nicholas, 2000). CPM presents very satisfactory results, with a reduction in hospital stay (Callegaro, 2010) and reduction of rehabilitation time (Ferreira and Martins, 2013).

Thus, this paper proposes the development of a continuous passive motion aquatic device to aid in the rehabilitation of the lower limb. To achieve the objectives of this paper, a brief review of CPM devices and aquatic rehabilitation is first presented. After, the mathematical model of the proposed device is presented followed by the built prototype. Finally, the preliminary tests and the conclusions are presented.

2. CPM DEVICES AND AQUATIC ENVIRONMENT

2.1 CPM Devices

With the use of CPM, patients had a greater angle of initial flexion and rapid progression when applied postoperatively, improving short-term flexion and functional outcomes in the long term (Callegaro, 2010; O'Driscoll and Nicholas, 2000, Hebert et al., 2003). Thus, in Liao et al. (2016) was suggested the early use of CPM after surgery. In this way several authors and companies have proposed CPM devices.

In (Ver et al., 2015), an ankle-foot CPM device for mobilization of acute stroke patients was presented. The CPM device was combined with manual therapy and improved the ankle's passive range of motion better than manual therapy alone.

Sperb (2006) proposed a simplified continuous passive motion device built using commercially available parts, two servomotors, cable-driven transmission system, respecting the movement limits of the human lower limb.

Blanchard et al. (2001) patented a therapeutic movement device that can be used for physiotherapy of a patient's knee by moving his leg through several cycles of movement in a single treatment session with the possibility of different speeds.

Palhares (2006) presented a CPM device that allows adjustments according to the size of the patient's leg. In another patented device (Jacofsky and Lyman, 2009) were added rolls for prophylactic therapy for venous thrombosis together with a CPM device.

A CPM device for knee rehabilitation after total knee arthroplasty was proposed in (Umchid and Taraphongphan, 2016). This device has four operational modes that highlight the intermittent and progressive modes. These modes permit more safety to the patients.

2.2 Aquatic environment

Aquatic rehabilitation, through the use of therapeutic exercises and using the physical principles of water and its physiological effects, aims to provide healing and prevention of diseases, as well as health promotion.

The improvements provided by immersion are scientifically proven. They are provided through the physiological changes that occur due to the physical properties of water, the main ones being: hydrostatic pressure, fluctuation, relative density and temperature. Aquatic rehabilitation provides innumerable advantages to patients, whether or not they have functional independence, maintaining and/or restoring range of motion, resulting in improved muscle strength, pain reduction, cardiorespiratory fitness and increased aerobic capacity, improving blood circulation, balance locomotion and coordination, reducing spasticity, among other benefits (Fornazari, 2012).

Benefits such as reduced fear of falling, decreased pain, and greater ease of movement make the pool an excellent means to restore patient balance and coordination. The freedom of floating motion helps increase the range of motion without the friction resistance, which is so difficult to overcome on dry land. Flotation also provides weight relief. The weight relief obtained is dependent on the proportion of the body below the water level. If only the head and neck are out of the water, approximately 90% of body weight is relieved ((Fornazari, 2012). This makes it possible to begin re-training the gait much earlier than on land.

Applied in the water there are several equipment's used in gyms like: treadmills, bicycles, hydro jump and water skiing.

For aquatic rehabilitation, generally, are used floats. During the bibliographic review, only one robotic device for rehabilitation applied to water was found. The Robotic Gait Trainer Water (RGTW) is a hip-knee-ankle-foot orthoses with pneumatic actuators (Miyoshi et al., 2008). The control software was developed based on the angular movements of a healthy individual's hip and knee while walking in the water. Three-dimensional and electromyography activities were recorded in nine healthy volunteers and the results showed that electromyography activities decreased when using the RGTW providing less effort in the patient's leg.

Thus, one of the main objectives of aquatic physiotherapy is pain relief, due to the support given in the fluctuation, which decreases body weight sensation and joint compression (Pieniazek, 2015).

3. MATHEMATICAL MODEL OF THE PROPOSED DEVICE

This section presents the mathematical modeling of the device proposed in this paper. The modeling was done to determine the dimensions of the structure considering the position and orientation of the patient's lower limb. The dimensions and kinesiology of the lower limb were obtained from (Kapandji, 2010; Gonçalves et al., 2015; Rodacki, 2004; Winter, 2009). The principles of trigonometry (Sullivan, 2012), fluid mechanics (White, 1998), free-body diagram (Hibbeler, 2015) and robotics (Tsai, 1999) were used for the calculation.

3.1 Kinematics Modeling

Figure 1 represents the geometric model of the proposed device in its initial configuration.

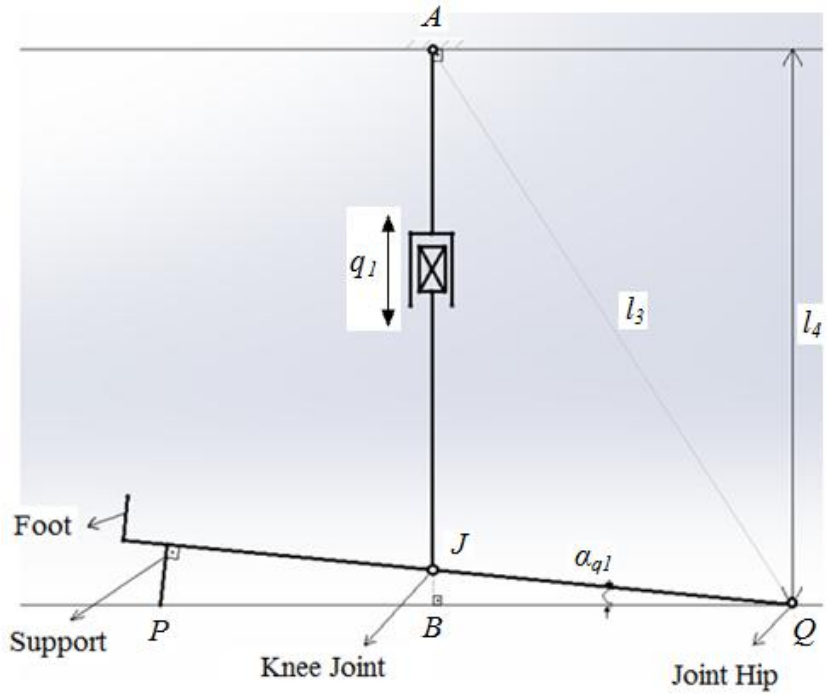

Figure 1. Initial position of the lower limb.

The kinematics modeling allows to relate the q_1 displacement with the parameters of hip movement, α_q, and knee movement, α_j. The solution can be obtained using trigonometric and the parameters defined in Fig. 2. q_1 represents the cable length used to actuate the proposed CPM device.

The distance between the pulley (motor position), point *A*, and the base of CPM device is constant and defined by l_4. The distance l_2 represents the constant length of the support. The lengths of the thigh, l_c, and the leg, l_p, are constant for the same patient.

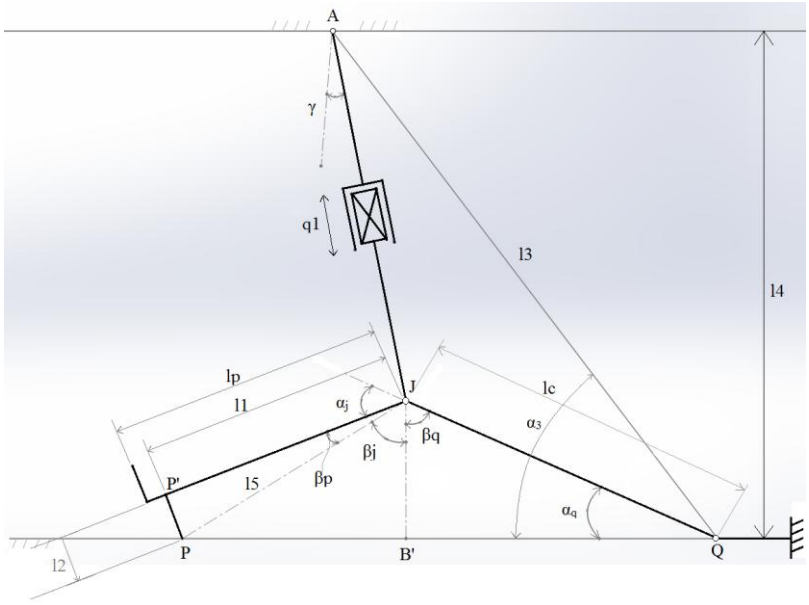

Figure 2. Parameters used in the kinematics modeling.

The length q_1 of the drive cable can be obtained by (1) from Fig. 2.

$$q1 = \sqrt{l_c^2 + l_3^2 - 2.l_c.l_3.\cos(\alpha_3 - \alpha_q)} \tag{1}$$

where:

$$\alpha_3 = \tan^{-1}\left(\frac{l_4}{l_c.\cos\alpha_{q_i}}\right) \tag{2}$$

$$l_3 = \sqrt{l_4^2 + \left(l_c.\cos\alpha_{q_i}\right)^2} \tag{3}$$

The inclination of the drive cable, γ, can be also obtained by trigonometry from Fig. 2 and is given by (4).

$$\gamma = \tan^{-1}\left[\frac{l_c\left(\cos\alpha_{q_i} - \cos\alpha_q\right)}{l_4 - l_c.\sin\alpha_q}\right] \tag{4}$$

The direct kinematics model can also be obtained, that is, if we know the variation of the cable length, q_1, we can obtain the angular variation of the hip, α_q from (5).

$$\alpha_q = \alpha_3 - \cos^{-1}\left(\frac{l_c^2 + l_3^2 - q_1^2}{2.l_c.l_3}\right) \tag{5}$$

3.2 Static Model

Figure 3 represents the lower limb with the appropriate loads and dimensional parameters for writing the static model. *Q* represents the position of the hip, *J* the knee, *P* the position in which the support remains in contact with the horizontal and q_1 the variable that describes the movement of the knee, as described in the kinematics model.

The weight of the thigh W_c and the leg W_p are on their center of mass G_c and G_p, Fig. 3. The weight of support, being small when compared with another weights was neglected. It should be noted that the weight of the foot is considered together with the leg.

An extra weight, W, applied to the knee, was considered to be on the side of the leg to predicting the needed aid for the knee to return to the initial position.

The thigh, F_{F_c}, and leg, F_{F_p}, buoyancy are considered to be acting on the center of mass of the thigh and leg, respectively, Fig. 3.

Considering also that the patient's hip may have some movement resistance, it is considered a resistive torque, τ_Q, in the static modeling.

Thus, considering the working forces in Fig. 3 we can determine the joints forces using the free-body diagram, Figs. 4 and 5.

The foot support can slide freely horizontally and we considered only a reaction in the vertical direction, F_{PY}, Fig. 5.

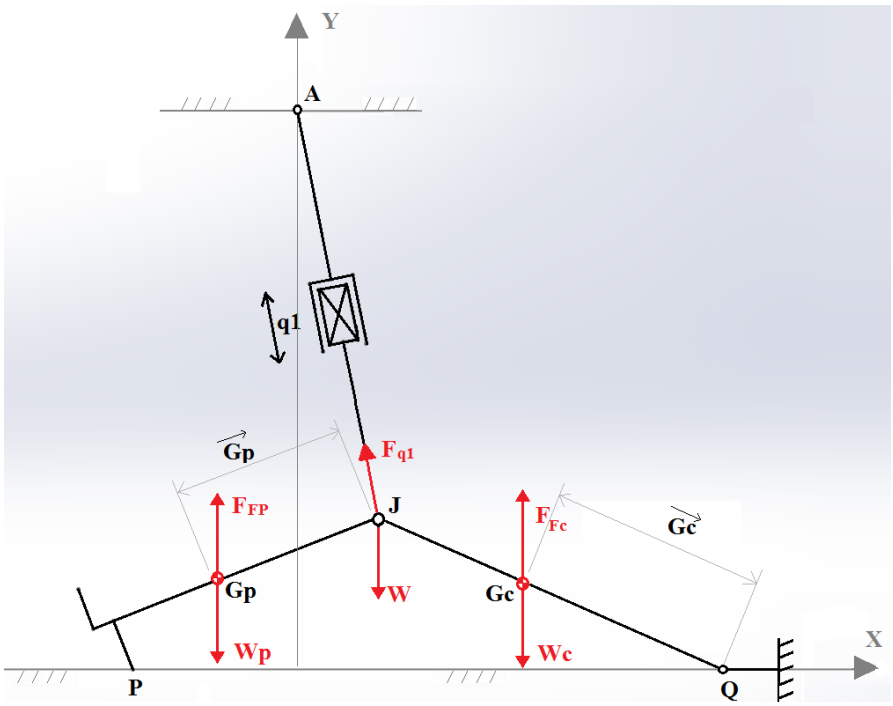

Figure 3. Parameters used in the Static modeling.

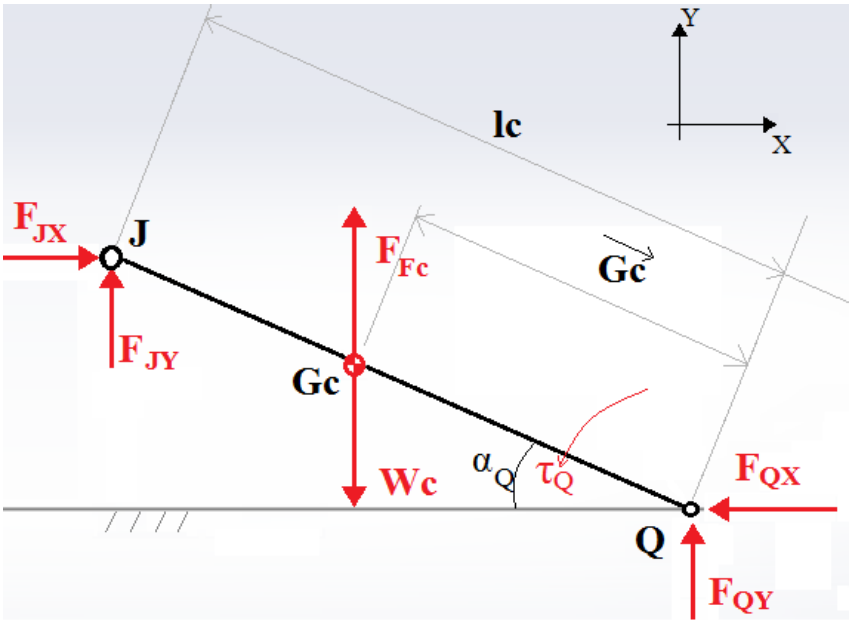

Figure 4. Free-body diagram of the thigh.

F_{Q_x} and F_{Q_Y} are the forces acting on the hip in the X and Y directions, respectively, Fig. 4. F_{J_x} and F_{J_Y} are the forces acting on the knee in the X and Y directions, respectively, Fig. 4.

From the free-body diagram and the equations of the static equilibrium of the thigh and leg, Fig. 4 and 5, we can obtain the forces exerted on the hip, knee and to move the knee, F_{q1}.

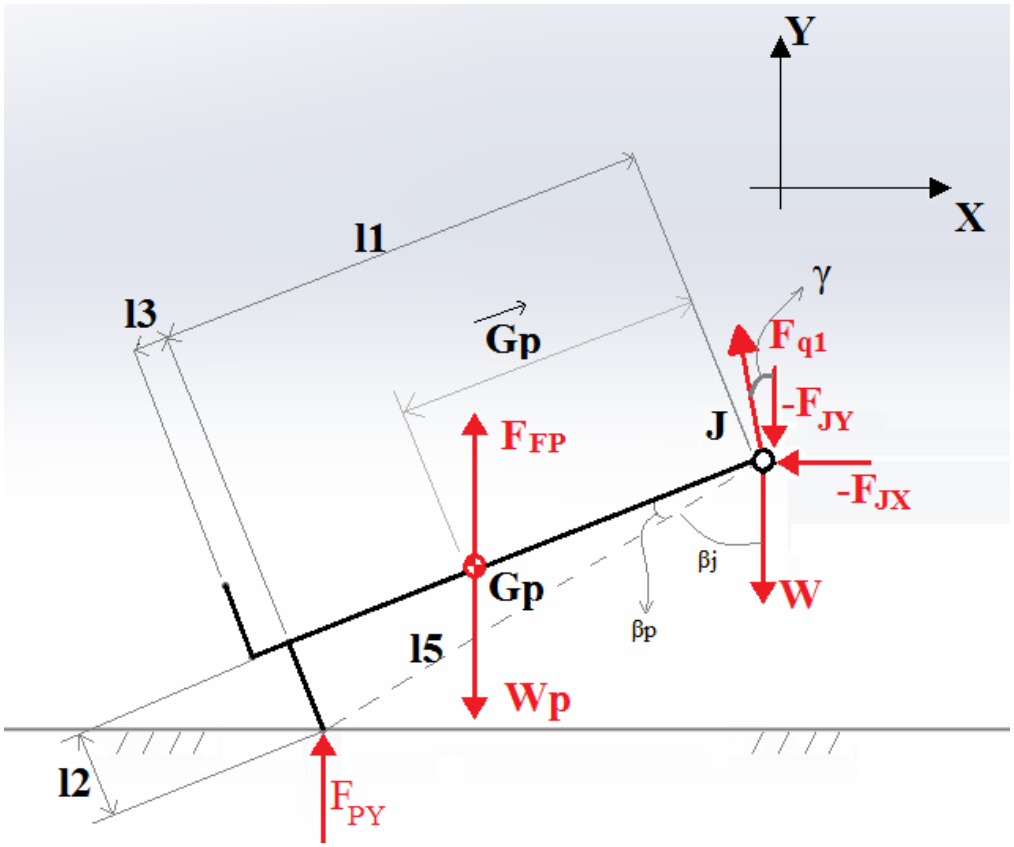

Figure 5. Free-body diagram of the leg.

$$F_{q_1} = \frac{1}{l_c.\cos(\gamma+\alpha_q)} \left\{\tau_q + (W_c - F_{F_c}).\overrightarrow{G_c}.\cos\alpha_q + W.l_c.\cos\alpha_q + (W_p - F_{F_P}).[l_5.\sin\beta_J - \vec{G}_P.\sin(\beta_J + \beta_P)]\frac{l_c.\cos\alpha_q}{l_5.\sin\beta_J}\right\} \quad \text{with } \cos(\gamma+\alpha_q) \neq 0 \tag{6}$$

$$F_{J_Y} = -F_{q_1}.\cos\gamma - W - \frac{(W_P - F_{F_P})[l_5.\sin\beta_J + \overrightarrow{G_P}.\sin(\beta_J+\beta_P)]}{l_5.\sin\beta_J} \tag{7}$$

$$F_{J_X} = -F_{q_1}.\sin\gamma \tag{8}$$

$$F_{Q_X} = F_{J_X} \tag{9}$$

$$F_{Q_Y} = W_c - F_{F_C} - F_{J_Y} \tag{10}$$

$$F_{P_Y} = F_{J_Y} + W + W_P - F_{F_P} - F_{q_1}.\cos\gamma \tag{11}$$

4. PROTOTYPE

The project of our CPM device was based on the paper (Sperb, 2006) and in the study of kinesiology of lower limb (Kapandji, 2010; Gonçalves et al., 2015; Rodacki, 2004; Winter, 2009).

Figure 6 shows the 3D model and the Fig. 7 shows the built prototype. The CPM device was built using only plastic materials, due to its underwater application.

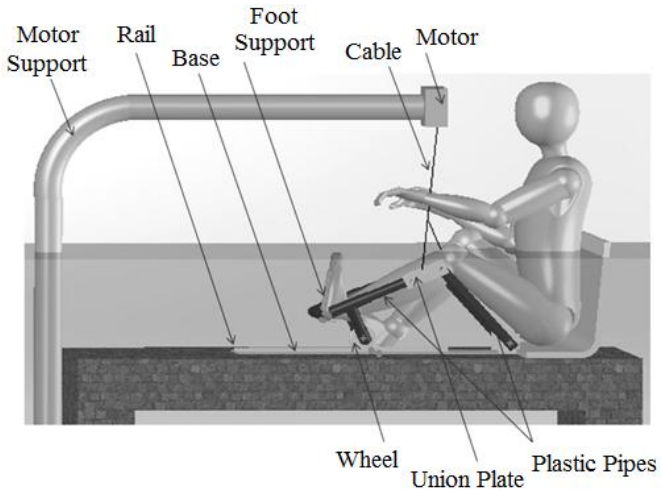

Figure 6. 3D CPM device model.

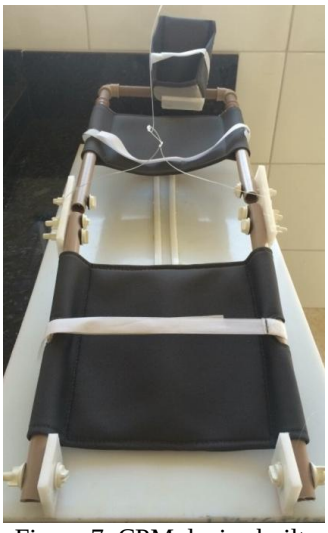

Figure 7. CPM device built.

Figure 8 shows preliminary experimental tests. The built prototype was able to move the lower limb of a healthy subject in function of the knee joints limits.

Figure 8. Experimental test with the CPM device built.

It is worth mentioning that the proposed device is for the aquatic environment. It is up to the health professional to make the use of this device possible according to the patient's trauma. For example, patients who have suffered an open fracture and are using external fixators will not be able to do this type of rehabilitation, since the fixation of the structure to the patient becomes unfeasible. Patients with cutaneous openings also should avoid using this device, since the water can be a contaminating medium.

5. CONCLUSION

To the best of our knowledge, this is the first work that applies one continuous passive movement device in the aquatic environment.

This paper presented a continuous passive movement device developed to be applied in the aquatic environment to lower limb rehabilitation. The preliminary experimental tests showed that the device can move the lower limb in function of the mathematical model developed.

As future work will be implemented the control system and tests will be performed on healthy patients and with knee injuries.

6. ACKNOWLEDGEMENTS

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