EXERCISE MACHINE ALTERNATIVE LOAD SYSTEM DESIGN

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Abstract*. Conventional equipments for muscular training and physiotherapy use passive load systems. In other words, they work without aid of external forces. This class of equipment models uses masses for resistance generation that slide for guides being usually pulled by cables, chains or belts. Such systems present some inconveniences, as for example: cables that break up during the use; discreet increments of load variation; contraction speed limitation at very low values; high inertia forces production and high friction forces production. This work seeks to the creation of an alternative resistance generation system for the skeletal muscle contraction to be applied in conventional machines of muscular training and physiotherapy. The proposed system uses a group spring-follower-cam to produce the resistance and it doesn't use cables, belts or chains. The cam has the function of accomplishing the biomechanical resistance adjustment, allowing the appropriate training speeds to each workout. The mechanism inertia forces effect is annulled by the cam geometry, requesting spring force more or less as the case, at the work speed projected. This system proposes a substantial safety increase, an infinitesimal load variation, a low friction production, a low inertia forces production and a better biomechanical adjustment for any wanted speed contraction, maintaining the current systems production costs. In this work, it is presented the mathematical system modeling and the numeric solution for the cam profile. This profile will be implemented in system modeling, through software ADAM'S, for mechanism optimization and later construction.*

Keywords: *cam, spring, exercise machine, physiotherapy, muscular training.*

1. INTRODUCTION

The importance of equipments used to muscular conditioning and rehabilitation increase at proportion of social and scientific interest by health improvement and human life quality.

The end of seventy decade was marked by the growth of a world movement to valorization of the life quality with new habits cultivation and behaviors took, and still take, millions of people to start and to maintain physical activities. In this way, the economical interest in products and services related to this area also motivated the scientific progress.

The objective this work is to contribute with the development of the conventional equipment used to muscular work for sports, esthetic or physiotherapy purposes, expanding its functionality and improving safety and control.

Will be projected and build the simple device, easy to be used and to adapt to the conventional fitness equipment. Mechanical elements such as cables, chains, belts, weight stacks and plates won't be used.

The new proposed system, besides the simplicity, it intends to provide the accomplishment of exercise variations before impossible in conventional equipment.

The conventional systems, in general, use the gravity acceleration acting on masses to produce an extra resistance to the movement of skeletal muscles. This resistance produces an increase of capacities and size of these muscles. The biomechanical and the physiology study the nature of these skeletal muscles adaptation phenomena and they suggest forms of optimizing the muscular training and physiotherapy.

When masses are used for extra resistance generation to the skeletal muscles movement, the action of the inherent accelerations increases significant inertia forces to the load system.

These force commit the exercise biomechanical adjustment, condemning the conventional machines only work with reasonable precision in very low acceleration way, that allow inertia forces be controlled.

In this article, biomechanics and physiologics aspects of development and training of skeletal muscles that have relevance for the development of this work are approached first.

2. PHYSIOLOGIC ASPECTS

Three main types of muscles exist: skeletal muscle or striated muscle; flat muscle (also known by involuntary muscle, because it is not under the conscious control); and the specialized heart muscle. Here we will just maintain our interest on the skeletal muscle.

The muscle is the only tissue capable to develop actively stress. This characteristic allows to the skeletal muscle to accomplish the important functions of maintaining correct posture of the body, to move members and to absorb shocks.

A single muscle fiber is a cylindrical, elongated cell. The membrane that surrounds the myofibril is called plasmalemma and the specialized cytoplasm receives the sarcoplasm designation. The sarcoplasm of each myofibril contains countless nuclei and mitochondria. Each myofiber is formed by a network of myofibrils that are aligned parallel each other. The myofibrils, formed by the disposition in series of the sarcomeres, it contains two types of protein filaments whose organization produces the characteristic grooved pattern that checks to this muscle the designation of skeletal or grooved: the thick myosin filaments and the fine actin filaments. The myosin filaments projections, called crossed bridges, form physical links with the actin filaments during muscular contraction, with the number of those links being proportional to the force production and energy expenditure. The figure 1 shows the muscle fiber structures.

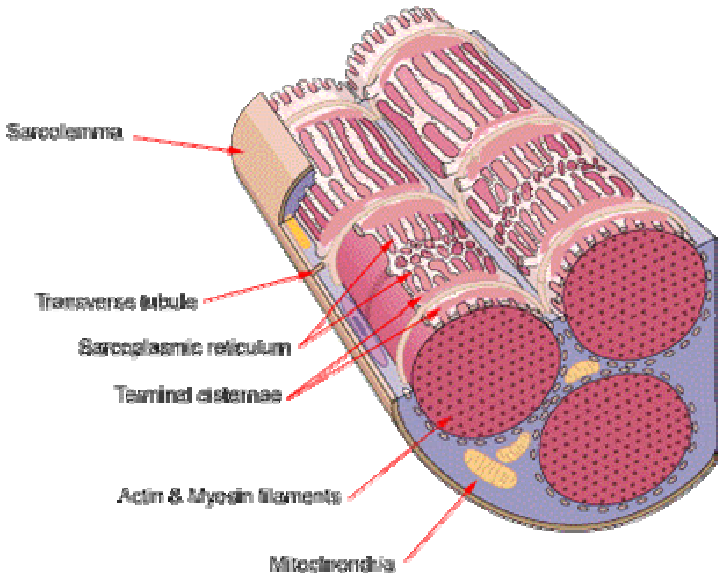

Figure 1. The grooved muscle fiber and the sarcomeres structures.

By crossed bridges theory and the muscular fiber structural transverse the force flow produced by muscular fiber be proportional to it a section area and it prolongation capacity is proportional to amount of prolongation sarcomeres disposed in series (Hall S, 1999).

3. BIOMECHANICS ASPECTS

According two muscular conditioning bases: the gradual load base (Gallagher and Delorme, 1949), where the progressively increase of loads on the skeletal muscles provokes an adaptation that produces, a forces increase and the hypertrophy of those muscles and the specificity base (McCafferty and Horvath, 1977) that establishes that not only the load, but also the way it is applied, cause adaptations in the skeletal muscles that going beyond of increasing forces and hypertrophy, extending to the other aspects like: muscular contraction type; movement pattern; movement area; muscular fibers recruitment; metabolism; biomechanics adaptation; flexibility; movement speed and fatigues. Then, is natural to suppose that any apparatus used the coadjutant in skeletal muscles conditioning should allow the loads to be increase the most gradual possible way and be precisely adjusted to the pattern of the movement.

On the other hand, the forces applied by the skeletal muscle against the resistance, always involving the member body movement around an articulation or fulcrum, doesn't stay constant during the same cyclical movement when the resistance is maintained constant (Zatsiorsky, 2004), varying according to factors like: muscle transverse section area; fibers density per transverse section area unit; mechanical lever efficiency through the articulation; speed and acceleration of the movement.

The resistance is usually generated by masses in workout conventional machines, inertia force of significant and variable magnitude associated to the cyclical movement accelerations, turning the exercise biomechanical adjustment more difficult.

Being desirable to request the muscle with a stress proportional to its capacity of generate force in each instant and in each articulation angle, a workout machine should allow this adjustment. The figure 2 shows, as example, the bicep’s work and the torque level relative the load applied.

It is known that during the movement against the resistance, the subject can feels (feedback) that the load is altering and acts to interfere voluntarily in the process, accelerating or the movement to increase the involved force. That is known as Training of Compensatory Acceleration and it can be useful to alter the muscular stress or movement speed for the specific training objective to be reached (Zatisiorsky, 2004).

The magnitude of inertia forces, possible speeds and moving accelerations will always be inversely proportional to the employed loads. In other words, as larger loads the smaller possible accelerations and training speeds.

In cases whose training objective is to qualify the subject to move loads similar those used in training, the beginning of the specificity is assisted. However, in cases that functional movement speed is higher, a workout to increase force should be accomplished in speeds similar to the intended movement one.

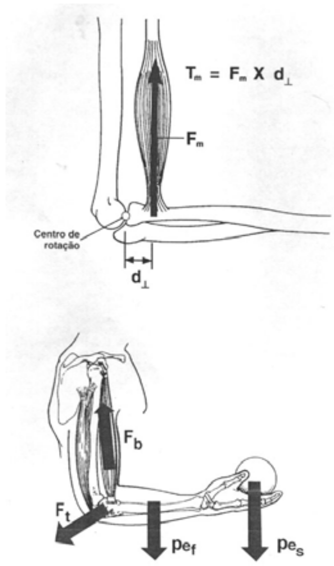

Figure 2. Elbow articulation mechanical characteristics showing the biceps’s work.

In these cases the inertia forces effects, mainly in movement direction changes, are not desirable and they hinder the biomechanic training adjustment.

The goal of this work is to obtain a mechanical system capable to produce dynamic resistance proportional to the skeletal muscles capacity and for an articulation torque produced with possibility to apply movement speed variations, for a defined speeds profile.

4. MECHANISM PROPOSAL

The proposed mechanism has, besides solving the exercise biomechanics adaptation problems, to solve some constructive problems found in the conventional machines as: lacks of an infinitesimal load adjustment; high value of friction forces, mainly in machines that uses cables, pulleys and chains; lack of safety due to breaking of traction elements, that always happens during the exercise and presence of great number of movable parts exposed to the user's contact.

The project should still be easy and economical to industrialize. Therefore, the system has to be applicable in a simple way to the workout and physiotherapy machines.

For the mechanism designed, some restrictions were imposed as: reduced number of components; total movable mass reduced; simple operation; possibility of simplified and automated construction with reduced cost.

With base in these restrictions and the desirable biomechanics adjustment and control characteristics, the mechanism was idealized, as shown in Fig. (3) with, basically three main components: Cam, follower and spring.

The mechanism should be capable to offer dynamic resistance to a specific movement accomplished by the user, in such a way that this resistance is proportional to the user’s capacity to maintain the movement for a defined acceleration and speed profile.

As sees previously, the human movements accomplished by the systems muscle-bone-tendon they happen around an articulation and, therefore, the resistance to the same ones can be offered as a torque around an axis.

The production of this resistant torque, proportional to the capacity of the articulation motor skeletal muscle, the elastic force of the spring will be used controlled by the profile of the cam that, at the same time, varies the spring length, the elastic force normal component direction line distance with relationship to the cam rotation center and the radius of the cam with relationship to the follower contact point.

As can be observed in figure 3, as bigger as α angle, greater the distance between the elastic force normal component direction and the cam center of rotation, increasing resistant torque value. And as bigger as α value, greater the variation of cam radius with regard to its proper angular displacement and bigger the displacement of spring, what also increases the resistant torque.

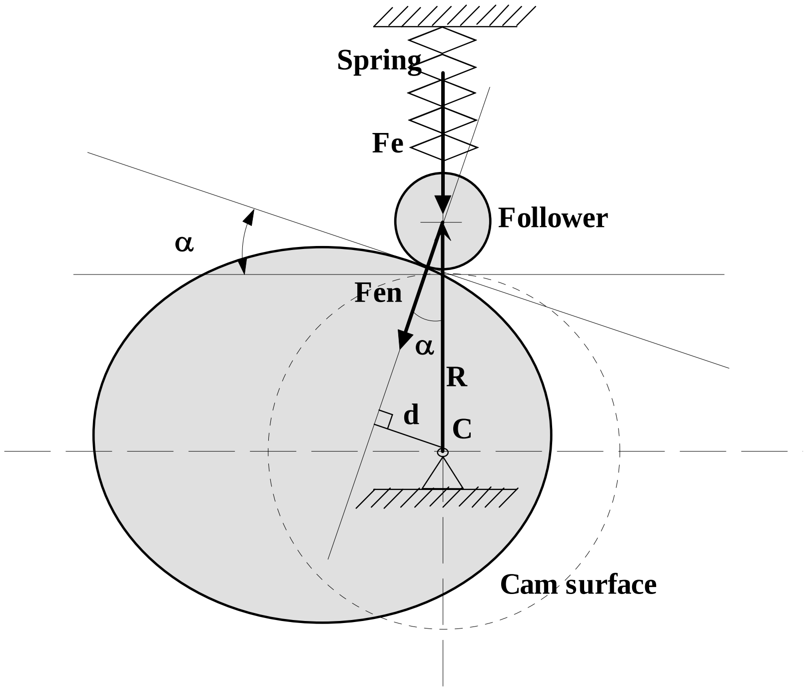

Figure 3. Scheme of the mechanism designed.

On the other hand, any reduction of α value causes contrary effect. In such a way, being (*Tm (θ)*) the torque that skeletal muscle can supply at each angular position (θ) and (*Tr*) the resistant torque produced by the mechanism, also at each angular position (θ), it can be written:

$$Tm = Tr \tag{1}$$

Where (*Tm)* is gotten through the experimental tests in a individuals group, measuring the maximum torque produced in joint by the motor muscle in each angular position and (*Tr)* can be calculated as follows, disrespected, for the time being, the torques produced by mechanism inertia:

$$Tr = Fe.\cos\alpha.R.\sin\alpha \tag{2}$$

Where (*Fe)* is the elastic force accumulated by the spring displacement, given by:

$$Fe = Fe(o) + K\Delta y \tag{3}$$

Being (ΔR) equal cam radius variation for each cam angular displacement around its axle and being (Δy) equal (ΔR) in the particular case of this model, where the elastic force direction passes for the cam rotation center, through this equation could be calculated a (α) value for each (θ) cam angular position and, therefore, a cam radius for each same angular position.

The (α) angle is known as cam pressure angle and was intended to use its geometry study in this work to design one cam such that, to keep its movement as a definitive pattern was necessary the application of one determined torque vector. It is important to consider the pressure angle value in the project of cam-roller follower. It must be kept as minor as possible and its maximum value until today is arbitrarily established at 30°.

For the cam roller follower system shown in Figure (4), the pressure angle OCA is called (α) and the cam center, "O". One assumes the cam is stopped and the follower turns clockwise from C position until C' according to a small $\Delta\theta$ angle. Then:

$$\alpha' = tg^{-1}\frac{C'E}{CE} \tag{4}$$

When (Δθ) goes to zero, OCE e ACC' angles go to 90º. At the same time the segment CD goes to CF arc length, equal to (R Δθ) and both, CD e CF go to CE. Therefore,

$$\lim_{d\theta \to 0} \alpha' = tg^{-1}\left(\frac{1}{R}\frac{dR}{d\theta}\right) \tag{5}$$

As all the sides of α e α' become respectively perpendicular when (Δθ) goes to zero, α' becomes equal α. Therefore,

$$\alpha' = tg^{-1}\left(\frac{1}{R}\frac{dR}{D\theta}\right) \tag{6}$$

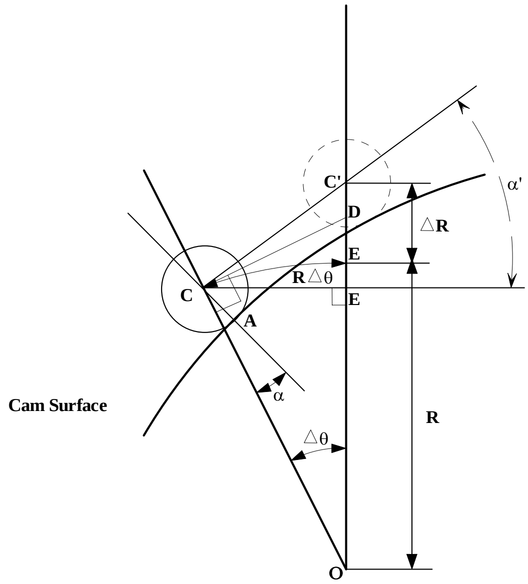

Figure 4. Relative movement between follower and cam through the pressure angle.

When the pressure angle value is used how given by Eq. (6) into Eq (2) the cam synthesis problem becomes solved using determined spring initial force value and its constant, as well as a cam radius initial value (R) for de initial cam position in respect to follower. However, as the spring deflection (ΔR or dR) is closely related to α angle formulation, get to transcendental problem of difficult analytical solution.

An alternative form to solution these problem was used an iterative algorithm in MATLAB for the cam profile synthesis, varying the α value and regulating initial values for the spring elastic constant, spring pre-load, initial cam radius (R(0) at θ=0) and pressure angle α, bringing up to date de cam radius values for each angular position θ where α was approached.

For the tests of this work the biceps joint was chosen. A torque mean characteristic curve produced for the muscle in this joint was generated by polynomial approach using the gotten values experimentally. This curve is used by the algorithm in the cam synthesis itself.

The Figure (5) shows the cam profiles generated by the algorithm. A profile generated without taking in account the torques produced by mechanism inertia and another one considering the torques due to the inertia of mechanism movement itself. Assuming *T (i)* as being the sum of torques produced by cam-follower-spring mechanism displacement submitted to the accelerations imposed by the subject movement and implementing its value in the Eq. (5) it is had:

$$Tr = Fe.\cos\alpha.R.\sin\alpha + T(i) \tag{7}$$

Can be observed that if the (*Tr*) value is given by the muscle capacity to produce force in each joint position, then, when it will have positive acceleration that occurs in the transition of eccentric contraction for concentric contraction and the (*T(i)*) values will be positive, the torque produced by the spring ($Fe.\cos\alpha.R.\sin\alpha$) has to be lesser, what implies in lesser values of α. On the other hand, in the concentric phase transition to eccentric phase, the movement accelerations values are negative, as well as the values of (*T(i)*), what means that ($Fe.\cos\alpha.R.\sin\alpha$) values will have of being bigger to keep equality. This implies in bigger values of α. In the intermediate phase, where the speed is constant, (*T(i)*) values will be null.

The Figure 6 shows the algorithm flowchart development to the generation of the cam profile.

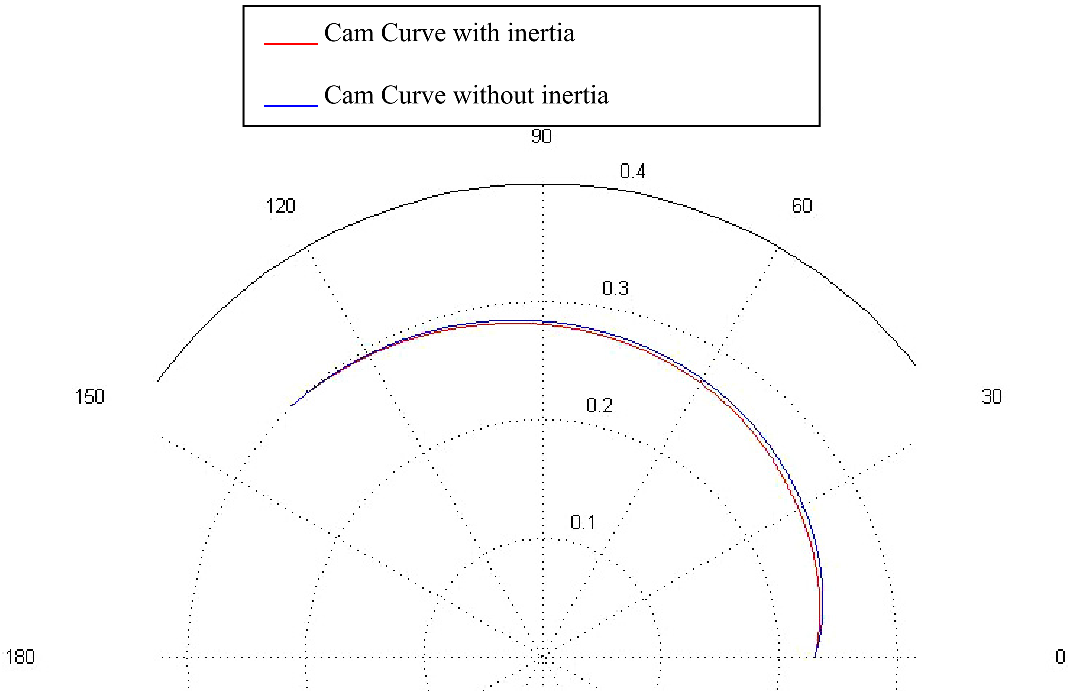

Figure 5. Cam profiles generated by the algorithm.

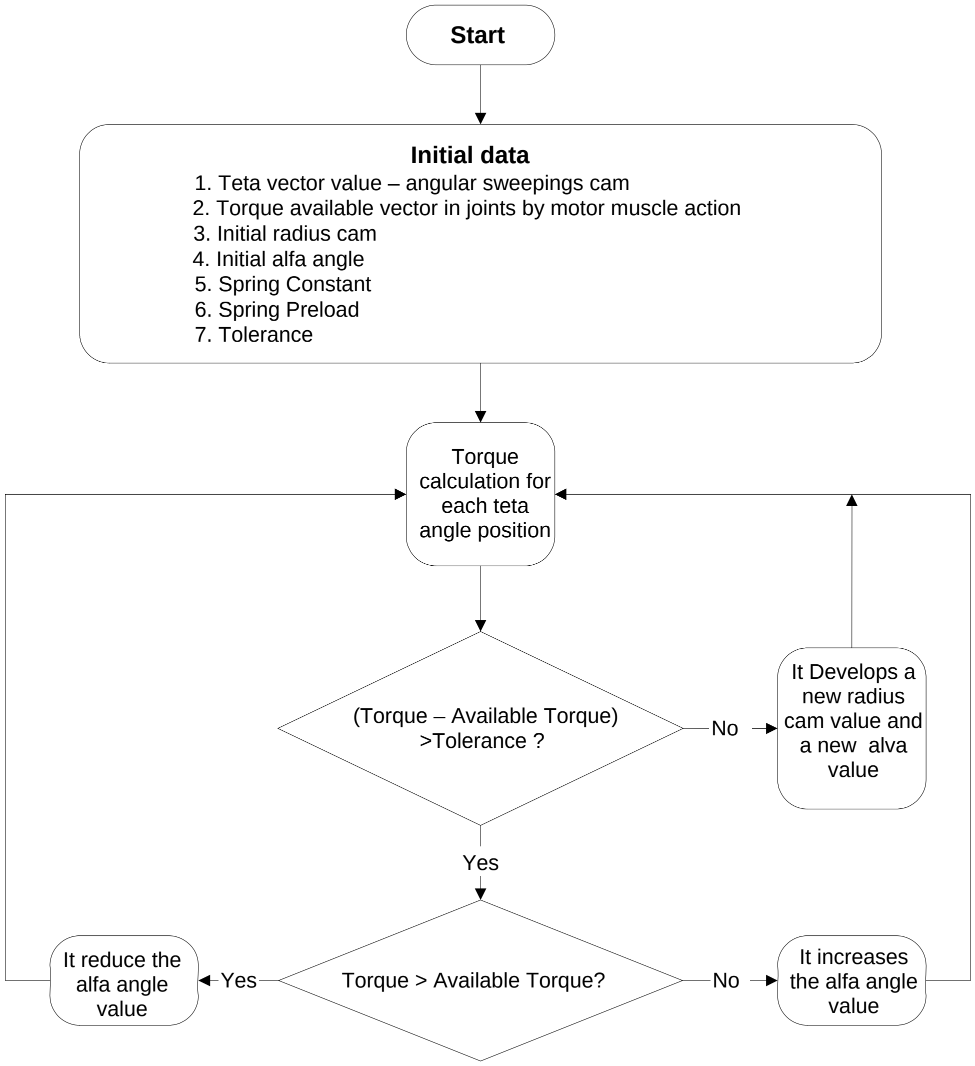

Figure 6. Cam synthesis algorithm flowchart

5. MECHANISM PROTOTYPE

The biceps curve it is necessary to the development of the real cam profile. This curve was obtained using a designed and manufacture device. This device use a resistance generation in different angles as shown at fig. (7). The angular variation can be done by a graduate piece in that is fixed a load cell of the capacity 200 Kgf, as show at fig. (8). The device was designed to obtain the biceps curve to left and right arms.

The Figure 9 shows the signal of the biceps curve o the particular angle. The device structure, show at Fig. 7, will be used at the designed and manufactured load system.

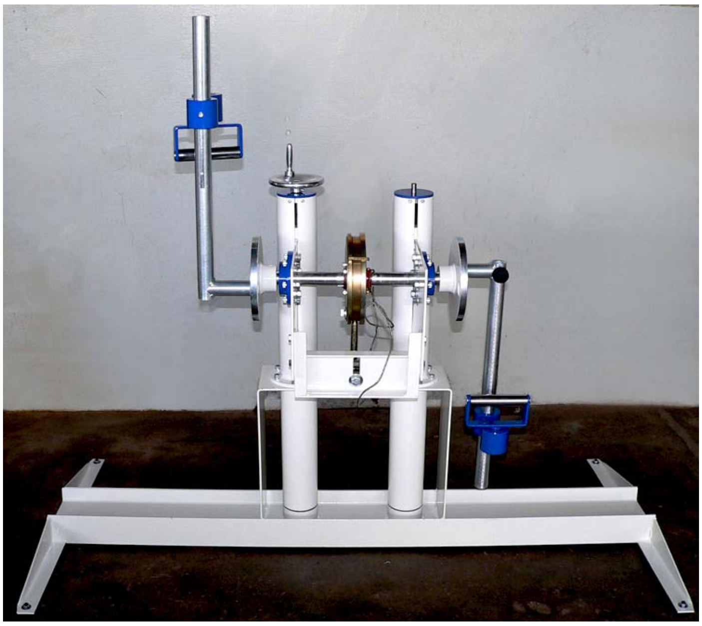

Figure 7. Device manufactured to obtain the biceps curve and to be used with the system load designed.

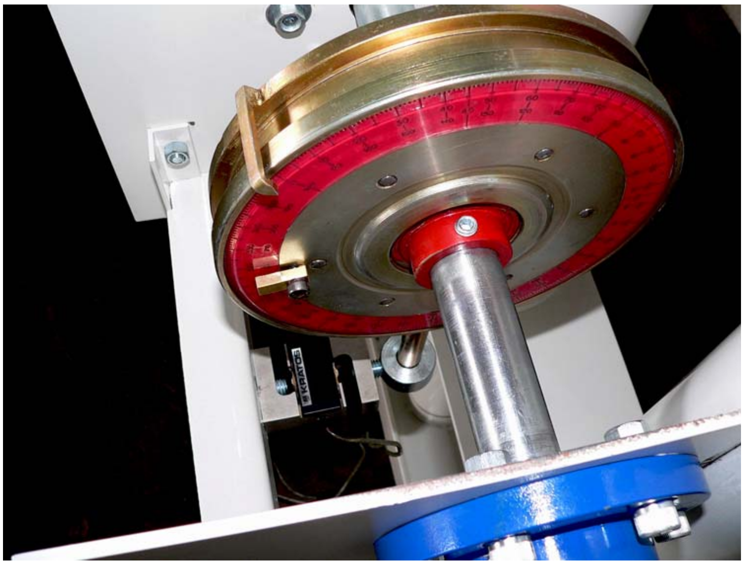

Figure 8. Detail of measure disk and of angle adjusted to biceps curve. It can be seen the load cell attached in the base piece.

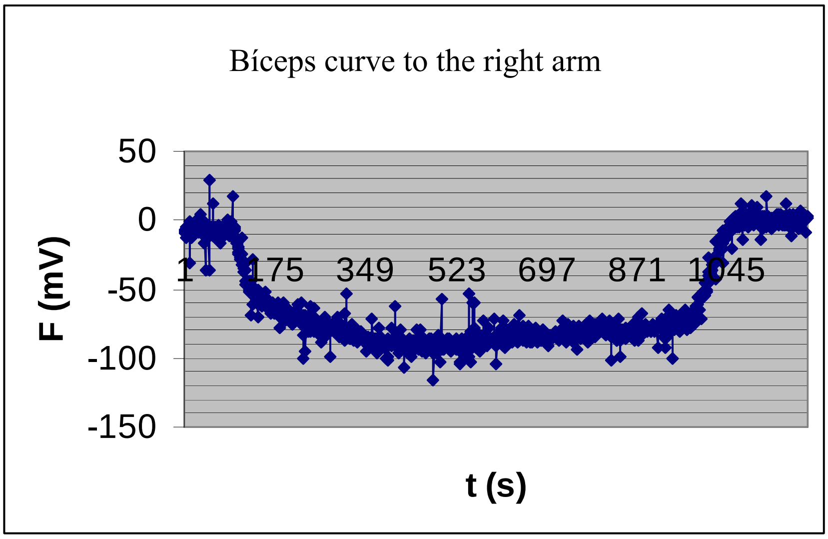

Figure 9. Signal force versus time to biceps right for particular angle. In this curve, the load level is showed in milivolts.

6. CONCLUSIONS

The mechanism was projected to prevent the inertia effect, first substituting masses by the spring-cam-follower system of lesser inertia and second, modifying the cam profile to increase or to diminish the resistant torque generate by the spring according the direction of inertia forces in a specific exercise. In such a way the resistant torque is kept proportional to the muscle capacity during all the movement, since that the accelerations and speeds are kept in accordance with the predetermined movement pattern.

For this system, this pattern can involve high speeds and accelerations in athletic or physiotherapy training that match better to each case.

Another advantage would be the reduction of injuries risk in transition of eccentric phase to the concentric phase of movement.

In the current state of this work, the synthesized cam profiles are being implemented in a simulation using ADAMS® software, so that the mechanism can be optimized and be adapted to an already constructed prototype, aiming at to the validation of the considered model.

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