ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

CONCEPTUAL DESIGN OF ISOKINETIC DYNAMOMETER: MODELING AND SIMULATION

Fabíola da Silva Rosa
Laboratório de Engenharia Biomecânica, Universidade Federal de Santa Catarina, University Hospital, Campus Universitário, Trindade, Florianópolis/SC, Brasil.
fahbysr@gmail.com

Daniel Alejandro Ponce Saldias
Daniel Martins
Laboraty of Robotics, Federal University of Santa Catarina, Campus Universitário, Trindade, Florianópolis/SC, Brasil.
danielpo25@gmail.com, danielemc@gmail.com

Carlos Rodrigo de Mello Roesler
Ari Digiácomo Ocampo Moré
Laboratory of Biomechanical Engineering, Federal University of Santa Catarina, University Hospital, Campus Universitário, Trindade, Florianópolis/SC, Brasil.
rroesler@hu.ufsc.br, arimore@terra.com.br

Carlos Martin
Laboratory of Hardware LHW, GRUCON, Federal University of Santa Catarina, Campus Universitário, Trindade, Florianópolis/SC, Brasil.
cam@grucon.ufsc.br

Abstract. *The knowledge on the field of strength training and physiotherapy evolved a lot in recent decades, reaching up to develop machines that can monitor and perform the exercise so versatile and multifunctional: the isokinetic dynamometers (ID). Nowadays it can be identified some problems with ID, including: a) high cost, b) isokinetic impact, c) posture on the dynamometer do not simulate the posture on sports, d) difficulty in aligning the articular anatomic center of rotation to the center of rotation of the dynamometer. The objective of the present research is to model and simulate a new conception of ID that should to give support to performing solutions that satisfy problems related above. The ID was deployed by PRODIP methodology encompassing the phases of planning design, informational design, and conceptual design. Comparing the curves of actual measurements and theoretical curves of simulations obtained for each exercise mode, it can be conclude that despite some differences between the simulation results and theoretical, the objective of the present work was reached: the development of the new ID gave support to possible innovations based on problems related before.*

Keywords: *Robotic Dynamometer, Physiotherapy, Control, Mechatronics, Product Process Development*

1. INTRODUCTION

On the last decades the knowledge on strength training and physiotherapy evolved a lot, resulting in significant improvement on physical performance and muscle recovery from injury. In paralel it was developed and aply the robotic tecnology and machines automatization, mostly because of advance in microeletronic and signigicant increasing of aspects related to test quality and measuring instruments used on research by professionals from sports and rehabilitation (Aquino *et al.*, 2007). Thereat, it become possible to develop complex models of mechanical systems for special equipment to physical exercise. A group of machines, able to monitor and perform the exercise stands out for its versatility and multifunctionality: the isokinetic dynamometers (ID), also called robotic dynamometers (Figure 1), adapted from Wimpenny (2013)).

The ID are still not widespread due to high cost, limiting its use to advanced medical centers, sports studies and physical therapy (Aquino *et al.*, 2007; Keating and Matyas, 1996; Ozçakar *et al.*, 2005; Tunstall *et al.*, 2005).

Usually, the ID is used for clinical and sport evaluation, but rarely for the purpose of strength training. These devices allow to operate in two main functions: function evaluation and function exercise. The evaluation is very important for diagnostic to treat specific deficiencies preventively (Tunstall *et al.*, 2005). The evaluation aims to provide continuous information about the effects of exercise performed and the physical/technical condition of athlete or patient. Through it the process of training can be streamlined and quantified, since, thanks to the information may be provided better stimulus and get best results. The two functions (evaluation and exercise) are applied in high performance athletes and injured patients.

Figure 1. Models of isokinetic dynamometers

Nowadays it can be identified some problems with ID, including: a) high cost, b) isokinetic impact, c) posture on the dynamometer do not simulate the posture on sports, d) difficulty in aligning the articular anatomic center of rotation to the center of rotation of the dynamometer.

This work comes from the need for improvement of ID, considerating the problems associated with these devices. Thus, this research aims to model and simulate a new conception of ID that should to give support to performing solutions to satisfy problems related above. For this, it was performed a critical introduction to isokinetic dynamometers, provided by the explanation of its operation and utilities.

2. MATERIALS AND METHODS

To perform a introductory critical analysis of the ID, the study was monitored by experts in the use and performance of these devices. It was searched articles, patents of equipment to exercise and physical therapy, as well as literature related to ID's, physiotherapy, training and evaluation of force. The research was made on computer by selecting the full articles published until july 2012, reviewing journals in the areas of biomechanics, sports medicine and sports science, bioengineering, physiotherapy, orthopedics and sciences of motion. To find studies were used this keywords in english and portuguese: isokinetic, isokinetic evaluation, isokinetic dynamometry, isokinetic dynamometers, strength evaluation, rehabilitation, and muscle performance.

The new conception of ID was deployed by PRODIP methodology encompassing the phases of planning design, informational design, and conceptual design. Informational design consists on determination of user requirements, design requirements and design specifications. Conceptual design englobes functional sintesis, morphological matrix, choose of solutions principles and conception of product design.

This design methodology allow to develop a conception of system who suits the user requirements, enabling for example, experiment with different torque sensors and algorithms to perform isokinetic modes, passive, isometric and isotonic, thanks to the modularity and ease of system tests designed.

3. ISOKINETIC DYNAMOMETER'S STATE OF ART

3.1 Operation of Robotic Dynamometers

An ID responds very fast and accurately to movements and variations of speed and torque of the patient or athlete using a system of closed loop control. A block diagram of the dynamometer is shown in "Fig. 2" (adapted from Saldias (2009)) and consists of two interfaces (machine-operator and patient-machine) and four subsystems: control-command, drive, mechanisms, and measurement. These subsystems are explained below:

- **Control-command subsystem:** It performs the operator-machine interface. The operator can give instructions through a software manager to set each mode of exercise to be performed by the patient or athlete. This subsystem receives the simultaneous information from the measurement system and process it for maintaining of the dynamic characteristics and safety of the exercise. Here is also monitored the exercise of the patient or athlete and get printed

ISSN 2176-5480

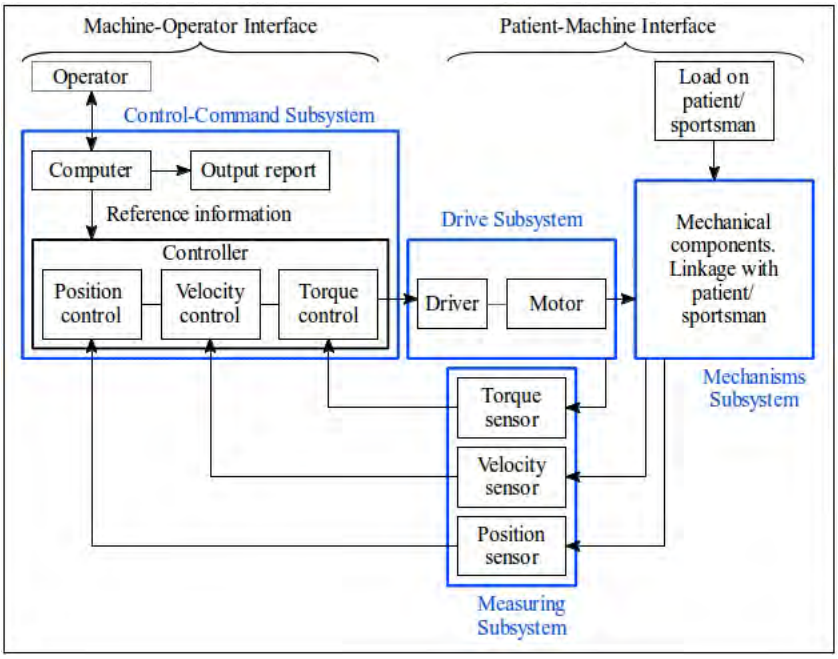


Figure 2. Block diagram of the ID.

reports and evaluations.

- **Drive subsystem:** It consists of a motor and its driver. The motor (hydraulic or electromechanical) provides resistance load as a function of force of the patient or athlete resultind in a smooth man-machine movement. The motor is connected to the mechanisms subsystem through a reducer. The driver or power amplifier is the component that manage and provide to motor the voltage and eletric current needed, using the reference in the control-command.

- **Mechanisms Subsystem:** It executes the patient-machine interface. It is composed by the mechanical and ergonomics components that allow the patient or athlete to perform the exercise and evaluation in a comfortable posture, enabling the isolated work of a single muscle group of interest.

- **Measurement subsystems**, which are basically three:

  (a) Torque measurement system: Strain gages are usually used in the effector. In moderns ID torque information is obtained by measuring the motor eletric current;

  (b) Speed sensor: It is usually used a tachogenerator. In modern models is used an encoder;

  (c) Position sensor: A resitive sensor is used often, but modern models use an encoder.

3.2 Functions of Robotic Dynamometers

The ID can provide two main functions: evaluation function and exercise function (Saldias, 2009). Both functions are applied in healthy athletes and in patients with injuries. Evaluation function serves as an indicator of the physical state of the sportsman, and monitors the evolution of injured tissues on patient to help to identify different pathologies (Blackburn *et al.*, 1982; Hoke, 1983; Wilk *et al.*, 1991). Exercise function means training to the athlete and physiotherapy to the patient. There is evidence of improvement on muscle strength in different populations after isokinetic training (Connelly and Vandervoort, 2000; Alaca *et al.*, 2002; Heitkamp *et al.*, 2001).

Many kinds of exercise and physical evaluation can be performed by ID as shown in “Fig. 3”. Evaluation function uses the basic modes and exercise function uses basic and advanced modes. A clinical advantage of the exercise function is that it offers multiple options of training strategies and exercises.

Basic modes are used by most patients. If it is not possible to perform one of the four basic exercises, it can be used "protocol" and "sequential" modes, classified as advanced modes.

The advanced mode "protocol" consists in an individual configuration organized by the physiotherapist or trainer. It involves basic modes with changes in moving, speed and strength ranges through the manager software. Many "protocols" could be stored in memory and screened (by name, date, etc.) to be repeated or modified. Some exercises of the "protocol" can be sequentially linked to create customized exercises through advanced mode "sequential".

Dynamic characteristics of the basic modes, seen in “Fig. 3”, are presented in “Tab. 1” and explained below.

ISSN 2176-5480

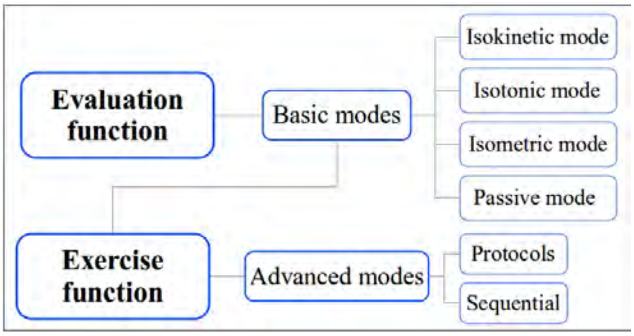


Figure 3. The two main functions of ID with their respective modes.

Table 1. Basic modes and dynamic characteristics.

	Basic modes			
	Isometric	Isotonic	Passive	Isokinetic
Position θ	**constant**	variable	variable	variable
Speed $\dot{\theta}$	null	variable	**constant**	**constant**
Acceleration $\ddot{\theta}$	null	variable	null	null
Torque τ	variable	**constant**	variable	variable

3.2.1 Isometric Mode

Based on immobility or null displacement, isometric mode consists in to do the maximum voluntary muscle activation against an invincible resistance (González and Gorostiga, 1997). When exercising, isometric muscle contractions can occur in many constant angular positions, within ranges of movimentation predetermined by the physiotherapist or trainer.

Some trainers qualify isometric mode as a training method that ease the growth of muscle volume, focused on the special training of muscle hypertrophy. From the physiotherapist point of view, isometric mode has defined therapeutic applications, as members stabilization, start the motor control of the patient, specific muscular strengthening, muscle stiffness remotion, and allow the work contraction/relaxation and maintenance/relaxation of the muscle (Isokinetics, 2013).

3.2.2 Isotonic Mode

Isotonic mode, also known as anisometric concentric with free loads, is the cheapest, simple and customary method to measure the force, although its relative inaccuracy can provide partial measurement values above the maximum strength. The typical force value measured with this mode is the maximum dynamic (González and Gorostiga, 1997).

During this exercise, it varies the speed that load is moved, depending on the ability of the patient/athlete and the speed-limit in maximum security programmed on isokinetic dynamometer (Chattanooga, 1995). In therapeutic use, the execution of this exercise not only allows a gain in muscle strength, but also a progressive neuromuscular response (Isokinetics, 2013). In strength training, it is equivalent to do exercises on gym machines with constant loads.

3.2.3 Passive Mode

It is also known as continuous passive movement (CPM), this mode is used on patients in postoperative or in patients who had muscle ou physical injuries and look for rehabilitation. Thus, the passive mode is classified as therapeutic. During this exercise patient is submitted to a movement, with low and constant speed, on articulation of interest.

The benefits of the passive mode are: increase of soft tissue elasticity, short time to become familiar with the equipment and muscle motor control (Chattanooga, 1995).

3.2.4 Isokinetic Mode

The isokinetic mode consists of performing muscular contractions, concentric and eccentric with a predefined speed that remains constant during the main part of movement (González and Gorostiga, 1997), except on initial and final stages. The isokinetic term must be reserved, therefore, to designate a type of muscular action that accompanies a constant angular movement on one articulation (Shinzato *et al.*, 1996). The isokinetic contraction can only be realized by special electromechanics equipments, with a control system, which the isokinetic machine responds in form of resistance directly proportional to the force exercised by the person.

The indications for performing this kind of assessment and exercise, refers to the agonist/antagonist muscular balance

ISSN 2176-5480

(muscle performing the movement/muscle opposing the movement), and the difference between the muscular groups agonists from one side compared to their contralateral side (agonists muscles on the left side compared to the right). The clinical applications of this mode are, for exemple: Resistance Exercises, Submaximal and Maximal Resistance, Resistance Training or Endurance Training and Motion Control of the Patient in addition to physical assessment.

3.3 Problems in ID

Nowadays, some problems related to the ID are known, whose consideration is primordial to the future improvement of these equipments. The mais problems are:

- High cost: The isokinetic allows to perform evaluation, training and physiotherapy, but these equipments are less known due the high cost, limiting its use to medical centers and studies.
- Usually the evaluation is done with machines and/or available equipments in distinct places from the training. The continuous monitoring is impaired.
- The isokinetic dynamometer usually does not copy the performed movement on some real sport training (Figure 4), and that, during the evaluation, the athlete keeps a different posture from training posture. There are not curves of isokinetic tests for exercises that copy specifics sports movements (with closed kinematic chain, involving kinetic energy in several articulations), nor interpretation methods for these curves. According Terreri *et al.* (2001), due the fact of the isokinetic equipment not performing the specific movement of a determined sport modality, the effort realized does not involve the kinetic energy in several articulations, but of a single articulation, while the rest of the body without displacement.

Figure 4. Difference between the positions of assessment and training.

- The isokinetic evaluation also present the overshoot. When a high acceleration happens before it reaches the constant speed stage of exercise, happens an impact (deceleration step) at the moment of reaching the isokinetic speed, because the mechanism "brakes" to decelerate and thus keeping the constant speed condition. The "overshoot" produces an oscillation at torque reading that may confuse the operator at the moment of reading the curve of the machine report.
- The big problem is the difficulty to position and align the anatomic rotation center with the dynamometer rotation center. Authors such Wimpenny (2013) indicate protocols with specific instructions to avoid this kind of problem. According Aquino *et al.* (2007), studies that uses the isokinetic dynamometry with several purposes often presents conflicting results, that is because differences at the subject positioning related to the evaluated articulations. The alignment process must be strict, since alignment errors may turn into low reliability and low repeatability reading data for the same patient or sportsman (Houweling and Hamzeh, 2010; Scoramuzza *et al.*, 2010).
- Other problems that were manifested on interviews with experts in the field during the execution of this work were: Appearance of looseness in bearings with short time of use, low robustness of the structure, patient/sportsman accommodation on the equipment bench, electronic problems due the environment humidity and ergonomic problems at shoulder and hip.

ISSN 2176-5480

Within this context, the development of a new design is proposed. This proposal consists in a mechatronic system for algorithm (and architectures) test that serves for the development of equipment technology applied to the performing of therapeutic and sports exercises.

This new design must allow to perform movements similar to the available exercises on ID, but in order to know better the technologies that will allow improving the current systems.

4. DESIGN OF ISOKINETIC DYNAMOMETER

To make the design, simulation and development of the basic prototype SMTE, should be put in motion the process of product development proposed by Back *et al.* (2008) until the stage of the preliminary design. This paper does not reach the detailed design phase. Thus, the structure of the project was:

- Project Planning: Here it was defined the problem, the research, the objectives and constraints of this work. - Informational Design: It was defined user needs based on the problems related to the ID mentioned above. Then teamed up these user needs into user requirements using technical language suitable for expressing quality attributes of the product. After that user requirements were changed, deployed and assigned to dimensions to them, emerging design requirements. Finally, the set of design requirements associated with service priorities have raised design specifications. In order to illustrate, the main basics design specifications are shown in "Tab. 2".

Table 2. Main Project Specifications for the development of ID.

Specifications list	Target values
Funcionality	
System must acquire angular speed	Dynamic zone: 0-300 ^{o}/s Resolution: 1^o/s
System must acquire angular position	Dynamic zone: 0-360 ^{o} Minimum resolution: 1^o
System must acquire torque	Minimum resolution: 0,01Nm
Data storage	1 Mbyte
System responde time	< 50ms
Four modes of physiotherapy and sportive exercises: Passive Mode, Isokinetic, Isotonic and Isometric.	
Passive mode	
Constant angular speed	
Continuous movement	
Isokinetic mode	
Constant angular speed	
Continuous movement	
Isotonic mode	
Constant torque	
Continuous movement	
Isometric mode	
Constant position	
Continuous movement	
Generalities	
Should be ergonomic	
Should be secure	
Shoul be strong	

- Conceptual Design: Englobes the development of principles of solution by functional synthesis, morphological matrix and choose of the bests principles of solution to product conception of ID.

5. MODELING AND SIMULATION

This step involves four steps which result in the plant model ID and the design of the simulation. The steps are:

- Physical sketch of system: Sketch that allows to visualize the interactions between system components. The sketch can be seen in "Fig. 5", and is composed of the electrical system and motor mechanic and effector system. In the engine's electrical system: ua is the armature voltage, ui is the induced voltage, Ra is the resistor, La is the inductance, and the current is going. In turn, the mechanical part of the engine: is the angular speed of the rotor, Bm is the friction of the

ISSN 2176-5480

bearings, and Jm is inertia of the rotor. The system effector: Bs is the friction coupling and reducer, Js is the inertia of the mechanical system, and is the angular position of the end-effector.

- Modeling by generalized circuit: Perform with tools of dynamic systems based on the power flows in each functional element of the system, such as inertia (kinetic energy storage), elasticity, rigidity (energy storage potential) and damping (sinks energy).
- Block diagram: Each functional element is converted to a transfer function as impedance or admittance.
- Simulation: We use a numerical simulation program with which one can obtain the response of plant design of DI in the time domain and the frequency domain behavior. For each basic mode, we implemented a PID control.

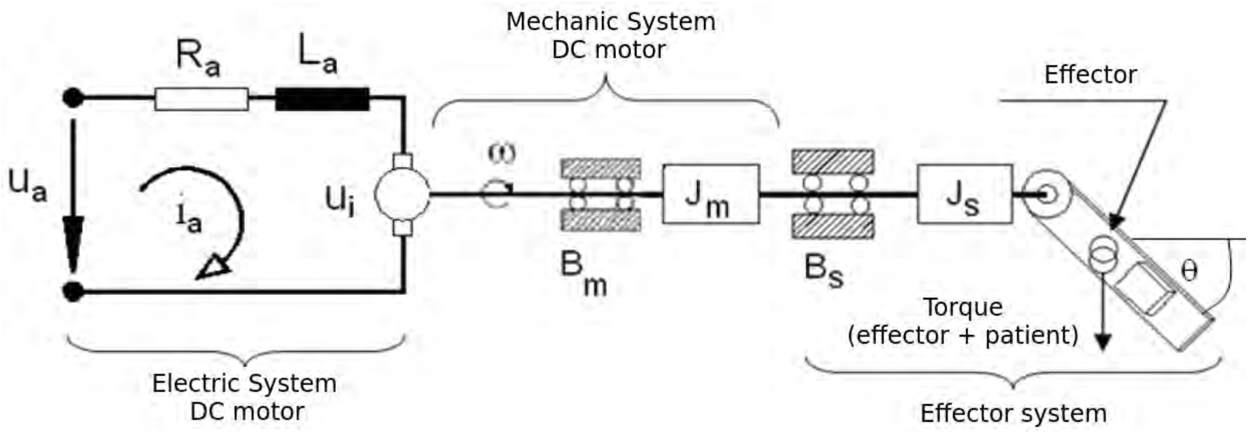
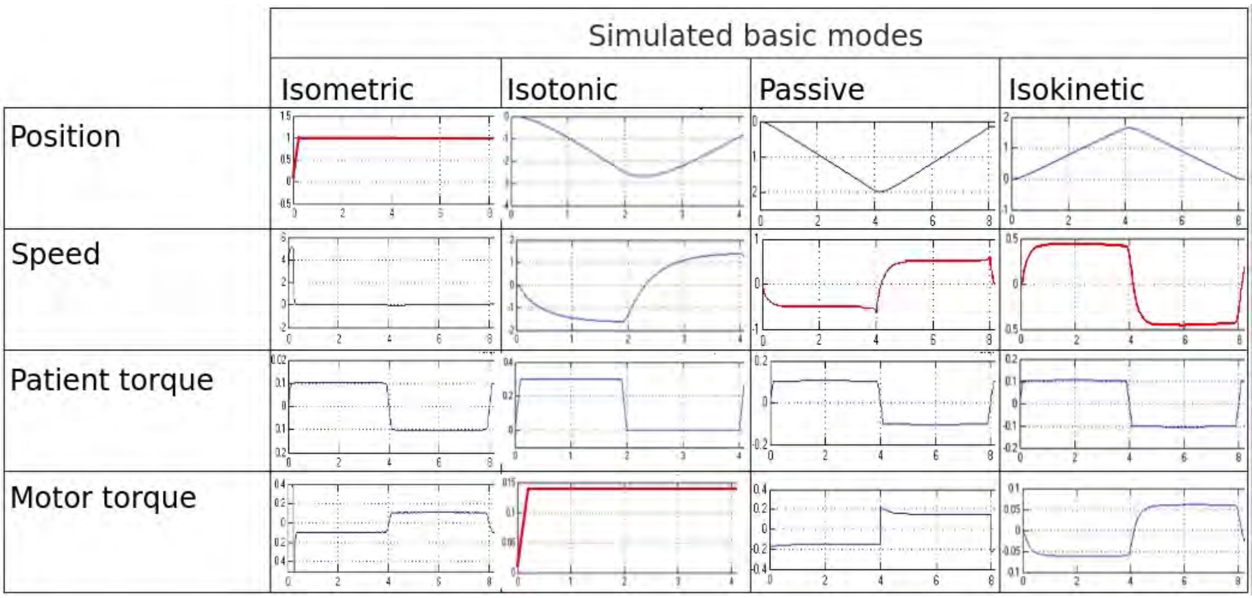


Figure 5. Physical sketch of new conception of ID.

6. RESULTS

The simulation results can be seen in “Tab. 3”, where the curves in red characterize the behavior of each basic mode. Comparing “Tab. 3” with “Tab. 1”, we see that the results are as expected. Thus, for isometric mode has a constant position throughout the movement, so as to have isotonic that the engine torque remains constant; into passive mode has a constant speed in the up and down movement; and the way we have the same behavior isokinetic curve that passive mode. Recalling that the difference between passive mode and isokinetic is: in the first case the motor torque is slightly higher than the torque of the person, and in the second case, the person wins the torque motor torque.

Table 3. Results of new ID conception simulation



7. CONCLUSIONS

The great value of the isokinetic evaluation consists in providing useful information to identify lesions and monitor the progress of treatment of patients and the sporting performance of athletes.

The design methodology used allowed to develop a project design system that met the needs of the user, allowing for example, experiment with different torque sensors and algorithms to perform isokinetic modes, passive, isotonic and isometric, thanks to the modularity and ease of testing of the system designed.

In the static torque operation, the operating region of electromechanical actuators is different from traditional, wherein the mechanical loads (but dynamic) are passive. In the case of active mechanical loads can characterize the dominance of mechanical load on the drive resulting in actual operation in static torque or quasi-static (resistive).

In accordance with the objectives of the work was acquired knowledge of biomechanics and ergonomics, which is to be applied also in future studies of control projects man-machine interface. Obtained training in practice in motor control DC loads under active biomechanical in nature, allowing the use of static torque, and realized that this feature engine adapts and facilitates control systems interaction man-machine.

On projects that can be developed from this work can be aimed possible innovations, such as an ID that enables performing exercises that simulate sports positions, reduce the cost, improve the control algorithm and use of pointers lasers to align the anatomical center of rotation with the rotation of the dynamometer percent.

8. REFERENCES

Alaca, R., Yilmaz, B., Goktepe, A. and Mohur, H., 2002. "Efficacy of isokinetic exercise on functional capacity and pain in patellofemoral pain syndrome." *J Gerontol A Biol Sci Med Sci*, Vol. 81, pp. 807–13.

Aquino, C.F., Vaz, D.V., Brício, R.S., Silva, P.L.P., Ocarino, J.M. and Fonseca, S.T., 2007. "Isokinetic dynamometry in sports and rehabilitation sciences." *Revista Brasileira de Ciência e Movimento*, Vol. 15.

Back, N., Ogliari, A., Dias, A. and Silva, J., 2008. *Projeto integrado de produtos*. Manole, São Paulo, 1st edition.

Blackburn, T.A., Eiland, W.G. and Banly, W.D., 1982. "An introduction to the plica." *J Orthop Sports Phys Ther*, Vol. 3, pp. 171–76.

Chattanooga, 1995. *Clinical Desk Reference*. Chattanooga Group, INC, KIN-COM, Tennessee, 1st edition.

Connelly, D. and Vandervoort, A., 2000. "Effects of isokinetic strength training on concentric and eccentric torque development in the ankle dorsiflexors of older adults." *J Gerontol A Biol Sci Med Sci*, Vol. 55, pp. B465–72.

González, J. and Gorostiga, E., 1997. *Fundamentos de treinamento da força, aplicação ao alto rendimento esportivo*. Artmed, Porto Alegre, 2nd edition.

Heitkamp, H., Horstmann, T., Mayer, F. and Weller, J., 2001. "Gin in strength and muscular balance after balance training." *Int J Sports Med*, Vol. 22, pp. 285–90.

Hoke, B., 1983. "The relationship between isokinetic testing and dynamic patellofemoral compression." *J Orthop Sports Phys Ther*, Vol. 4, pp. 150–55.

Houweling, T. and Hamzeh, M., 2010. "Does knee joint alignment with the axis of the isokinetic dynamometer affect peak torque?" *Isokinet Exerc Sci*, Vol. 18, pp. 217–21.

Isokinetics, 2013. "Isokinetics explained". Isokinetics 28 May 2013 <www.isokinetics.net>.

Keating, J.L. and Matyas, T.A., 1996. "The influence of subject and test design on dynamometric measurements of extremity muscles." *Physical Therapy*, Vol. 76, pp. 866–89.

Ozçakar, L., Inanici, F., Kaymak, B., Abali, G., Cetin, A. and Hasçelik, Z., 2005. "Quantification of the weakness and fatigue in thoracic outlet syndrome with isokinetic measurements." *Br J Sports Med*, Vol. 39, pp. 178–81.

Saldias, D.P., 2009. *Estudo introdutório e desenvolvimento experimental de sistemas automatizados para exercícios terapêuticos e esportivos*. Master's thesis, Universidade Federal de Santa Catarina, Florianópolis.

Scoramuzza, D., Axtell, R. and Thiel, R., 2010. "Effect of knee joint alignment on isokinetic torque production during leg extension and flexion exercise." *Med Sci Sports Exerc*, Vol. 22, pp. 190–8.

Shinzato, G., Vasconcelos, J., Ogawa, C. and Sampaio, I., 1996. "Protocolo de avaliação funcional de joelho em patologias ortopédicas." *Acta Fisiátrica*, Vol. 3, pp. 30–6.

Terreri, A., Júlia, G. and Marco, M., 2001. "Avaliação isocinética no joelho do atleta." *Revista brasileira de medicina do esporte*, Vol. 7, pp. 37–45.

Tunstall, H., Mullineaux, D.R. and Vernon, T., 2005. "Criterion validity of an isokinetic dynamometer to assess shoulder function in tennis players." *Sports Biomech*, Vol. 4, No. 1, pp. 101–11.

Wilk, K.E., Keirns, M.A. and Andrews, J.R., 1991. "Anterior cruciate ligament reconstruction rehabilitation: a six month follow up of isokinetic testing in recreational athletes." *Isokinet Exerc Sci*, Vol. 1, pp. 2–9.

Wimpenny, P., 2013. "Fundamentals explained basics." *Isokinetics Explained*.

ISSN 2176-5480

9. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.