# Sensors Selection and Detailed Mechanical Design on Developing a Mechatronic System for the Promotion of Physical Activity

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***Abstract*— The increase in the number of elderly people and people with motor limitations takes along concerns to health professionals. A way of helping health professionals and the elderly may be through the development of systems that allow people to maintain their mobility regardless of age and health problems that may arise. This paper presents the studies carried out in the development of a mechatronic system that aims to promote physical activity in people with motor limitations. The proposed mechatronic system consists of a stationary bike, however its architecture is completely different, besides including a game that aims to increase the motivation of its users, in order to make physical activity and rehabilitation more enjoyable. Briefly, this paper presents a description of the proposed solution, followed by an approach to the study of the dimensions of the model taking into account the anthropometric data, so that the system can be used by as many people as possible. Afterwards, a detailed mechanical design of the structure was carried out, as well as the selection of the encoders, sensors and actuators that could be used in the model to obtain the inputs supplied by the user.**

***Keywords- Serious Games; Rehabilitation; Modular Design; Sensors and Actuators.***

## I. INTRODUCTION

Aging and chronic diseases, such as obesity, Parkinson's, hypertension, arthritis, diabetes and even symptoms resulting from strokes are the main factors that force people to gradually lose their autonomy, making it more difficult for performing daily tasks such as bathing, dressing and walking. As many of the above diseases require rehabilitation, some researchers believe that active games (games involving physical activity) can increase adherence to treatment [1]. Over the years, several games have been developed with the purpose of promoting and improving the physical condition of the population in an effective and pleasant way. One of the first games of this type was Foot Craz in 1987 and since then several games have been released, however the device that more success had was the popular Wii console of Nintendo [2].

Nowadays, several equipment of this type is studied and commercialized, with special emphasis on games that use virtual reality through cameras, pressure platforms and simulators. Through the literature review, it was possible to find several studied and commercialized systems, among them: ReaKing, Physioland, Smartfloor, Physiosensing, Twall, GymTop USB, BOBO Balance and Trixter VR [3].

Recent research has integrated serious games as a valuable therapeutic tool in rehabilitation. In fact, virtual reality, especially in the form of serious games, combines therapeutic and recreational challenges. This strategy prevents boredom, making therapy less tiring and discouraging. Serious games can motivate patients to perform exercise and rehabilitation improving adherence to treatment. This ludic and challenging environment is the main aspect that differentiates virtual reality games from traditional physical rehabilitation programs [4].

Despite the wide variety of games on the market that aim to motivate the practice of physical exercise, it can be verified that there is a need to adapt them to allow their use by people with motor limitations. In fact, commercial games do not provide safety and comfort necessary for this people. To improve the practice of physical activity through this type of games by the elderly and/or physical impaired population, it is fundamental to develop rehabilitation games considering their safety and comfort [2].

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In order to achieve the main goals of this paper, the respective organization is as follows: in Section 2, the proposed solution is presented; it is also presented some aspects used in the 3D modeling, giving main emphasis to the modular principle that is intended to be implemented and to the study of the dimensions of the model taking into account the anthropometric data, that aims the use of the model by the largest number of people. In Section 3, a detailed mechanical design of the structure of the model is presented, analyzing the forces involved in the course of its use; a numerical analysis of the structure is also performed in this section. In Section 4, it is presented the review of the sensors, encoders and actuators that could be used; it also includes the analysis of the characteristics of each component and a brief comparison between them. Finally, Section 5 presents the conclusions.

## II. PROPOSED SYSTEM

The proposed model is presented in Figure 1 and consists of a stationary bike with a didactic component (simulation of a paramotor). This proposed 3D model resulted from an iterative process in which it was intended to choose the appropriated systems and to promote the desired versatility and functionality to the model. It was also intended that this 3D model presented an equipment that: occupied the minimum space as possible; had a chair with adjustment capability; allowed to adjust the loads for different workouts and to provide the necessary comfort and safety to be used by people with motor limitations [4].

Figure 1. The proposed solution.

### *A. Modules of the proposed model*

In order to occupy the smallest space possible, a modular system was adopted. In this way, it was easier to reduce the occupied space when it is fully assembled. Thus, it was decided to divide the system's model into 3 modules - chair module, pedal module and main module. This division into modules, besides allowing the disassembly and division of the equipment, allows the adaptation to any chair, wheelchairs included [2].

### *B. Study of the dimensions of the model taking into account the anthropometric data*

This project was aimed at obtaining a 3D model whose dimensions were adequate to any person.

First, it was necessary to define the length of the pedal crank arm. Research has reported that the ideal length of the crank arm can be between 145 and 180 mm [5] [6] [7]. Other studies in the same scope establish pedal performance analyzes according to the lengths of the pedal crank arms. A study carried out in these models shows that the difference is relatively small when using arms of lengths of 170 and 175 mm (commonly used lengths). The difference can be significant in competitive sports [8]. As in the case of the model under study, that it is not a competition sport, the used length is 175 mm.

This study of dimensions aims to allow anyone, in a wheelchair, to use the model, since the wheelchairs are not adjustable, contrary to what happens with the use of the chair module. For this it was also necessary to know the height of the seat of a wheelchair, which was considered 49.5 cm according to the researches carried out in [9]. Table I shows the dimensions for percentile 95 and 5 for both men and women to the following dimensions: buttock-heel length, seated vertical reach, vertical reach of apprehension and body depth maximum [9].

TABLE I. HUMAN DIMENSIONS STUDIED.

| | **Percentile** | **Buttock-heel length (cm)** | **Seated vertical range (cm)** | **Vertical reach of apprehension (cm)** | **Maximum body depth (cm)** |
|---|---|---|---|---|---|
| **Men** | 95 | 117,1 | 131,1 | 224,8 | 33 |
| **Women** | | 124,5 | 124,7 | 213,4 | |
| **Men** | 5 | 100,1 | 149,9 | 195,1 | 25,7 |
| **Women** | | 86,4 | 140,2 | 185,2 | |

In order to collect the data presented above, it was considered that the dimensions of wheelchair's users would be close to the dimensions of normal people, since the anthropometric study of people in wheelchairs is more difficult due to some variables, among them: the type of disability, the affected limbs or segments, the spread of paralysis, among others [9].

From the collected data, it was possible to verify the dimensions of the model being studied, taking into account some adjustments. The buttock-heel length varies according to the footwear and knee flexion in the execution of the exercise, so it was decided to reduce 5 cm to this length. In the case study, it can be verified that the handle will be below the maximum vertical seated range, because this measure goes from the seat to the tip of the middle finger with the arm stretched, while the handle will be reached with the hand closed and the arms will not be completely stretched. For this reason, a tolerance of approximately 20 cm this length is adopted. The vertical reach of apprehension is usually made with the individual without shoes, therefore a compensation of 3 cm will be performed in relation to this measure. Finally, it was considered that the horizontal perpendicular distance between the backrest of the

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wheelchair and the handle should be approximately 1/3 of the maximum body depth (horizontal distance between the most forward point of the body and the point farther back).

## III. DETAILED MECHANICAL DESIGN

The following computational tools were used: Autodesk Inventor 2017 and Autodesk Simulation Mechanical 2017 (CAD-CAE).

In order to be able to perform the simulation (CAE) stages, it was necessary to define the initial conditions and the boundaries.

### A. *Study of the forces applied to the structural components of the model*

Figure 2 shows the free body diagram of one of the arms of the model structure.

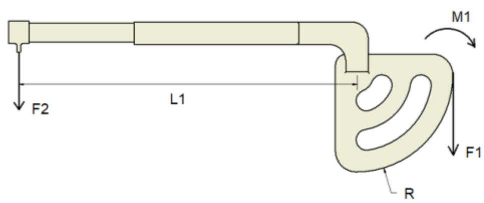


Figure 2. Free body diagram of one of the arms of the model (where F1 represents the load exerted by the weights and F2 represents the force exerted by the user)

For the arm completely stretched and the maximum load *F1* (the maximum force *F1* is half the maximum load of the weights, since this load is divided by two arms) the following values are considered:

- *L1* = 1,225 m
- *R* = 0,35 m
- *F1max* = 368 N

*M1* and *F2* are calculated as follows:

- Calculation of the torque produced by the force *F1*:

$$M1 = F1 \times R = 128{,}8 \text{ Nm} \tag{1}$$

- Calculation of the force *F2* that will be required to move the arm:

$$M1 = F2 \times L1 \tag{2}$$

$$F2 = M1/L1 = 105{,}1 \text{ N} \tag{3}$$

In the course of the game, the force exerted by the user will not be constant, since the direction of the force will change with the rotation of the arms. Figure 3 shows the variation of the position of the arms and their applied forces.

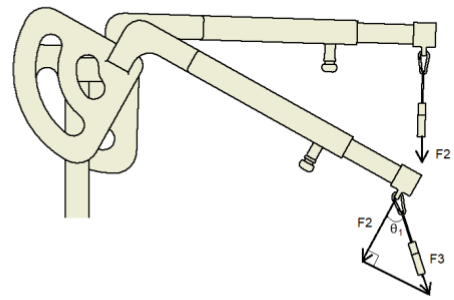


Figure 3. Variation of the position of the arms and their applied forces (where F1 represents the load exerted by the weights and F2 represents the force exerted by the user)

Calculation of F3, considering that the triangle from the Figure 3 is a triangle rectangle:

$$\cos \theta 1 = F2/F3 \tag{4}$$

$$F3 = F2/\cos \theta 1 \tag{5}$$

Figure 4 represents a graph showing the variation of the force *F3* with the variation of angle *θ1*.

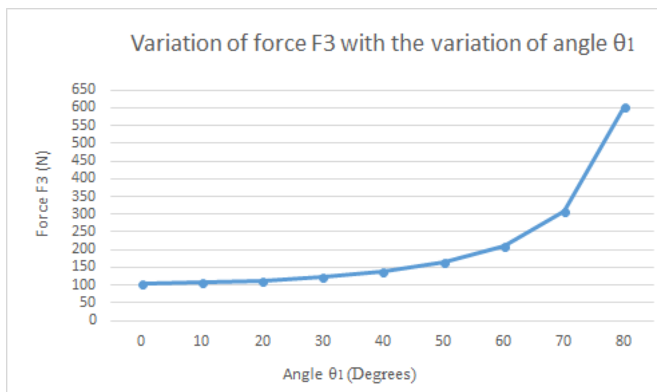


Figure 4. Variation of force F3 with the variation of angle θ1.

### B. *Numerical analysis and simulation of the model structure*

In order to verify and study the structure and its behavior, quickly and effectively for different geometries, a numerical analysis was chosen. For the numerical analysis, a finite element analysis software was used (Autodesk Simulation Mechanical 2017). The following are presented the pre-processing and the post-processing performed for the final form of the model.

#### 1) *Pre-Processing*

With regard to the simulation, the first step corresponds to the selection of the type of analysis. In this case, a linear static analysis was performed, because the structure presents

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linear behavioral materials, with the exception of the bushings, which, in this case, was neglected.

After defining the type of analysis, the model was discretized (mesh generation). The mesh initially presented was coarse generated, which allowed the first simulation to be faster and to identify the locations of the most critical zones. After the creation of the mesh, the boundary conditions were considered. In this case, it is intended a static model, so it was considered that the base of the structure was embedded with no rotation of the arms. Finally, the materials (AISI 1050 and AISI 304 [2]), the loads and the contacts were defined. In the case of loads, the forces previously obtained (Section III.A) were used for the situation where L1 = 1,225 m, F1 = 368 N and F2 = 105 N for the initial position. In the case of joints, it was considered that all the pieces were bonded. Figure 5 shows the pre-processing representation of the structure model.

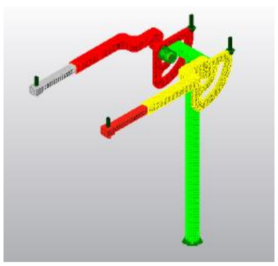

Figure 5. Pre-processing representation of the structure.

*2) Post Processing*

After the processing step - Solver execution - the results of the maximum displacements and the installed stress were obtained and verified. Figure 6 presents the maximum displacement, whereas Figure 7 presents the stress analysis by the criterion of Von Mises.

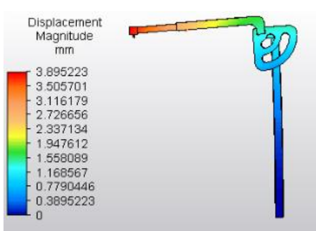


Figure 6. Displacement magnitude results.


Figure 7. Stress Von Mises results.

From the obtained results, it can be verified that the maximum displacement verified by the software was 3,90 mm. This value can be considered acceptable for the structure. Another important verified aspect was the maximum analyzed stress, in the structure, that presented a value of 40,16 MPa. In addition to these results, a mesh refinement was also carried out in the zone of higher tension. This refinement presented a result of around 42 MPa for the maximum tension. Comparing the maximum installed tension with the yielding tension of the material (415 MPa) it can be stated that the material is adequate for the required loads.

## IV. SELECTION OF SENSORS

In order to create the game, it is necessary to acquire some inputs: detection of the pedal velocity and detection of the position of the arms of the structure. To obtain this data, it is necessary to use encoders and sensors to measure the position and velocity. In the following section, there are presented the encoders and sensors that will be used for the detection of the pedal speed and the position of the arms of the structure.

### *A. Detection of position of the structure arms and the pedal speed*

For the detection of the position of the arms of the structure, incremental rotary encoders will be used. The incremental encoders are simpler and low-cost when compared to the absolute encoder. This type of encoder generates only pulses and does not have a different combination for each position. In this way, they are manufactured with a quantity of pulses per revolution. The higher the number of pulses per revolution, the higher the encoder resolution. The disadvantage of this type of encoder is in the reading of its data, because as it operates by pulses, the reading of a certain positioning needs an initial reference.

For the detection of the pedal speed it will be used a Reed Switch sensor. The Reed sensors are used as highly effective speed sensors in low speed applications (up to 1000 rpm). A Reed sensor consists of a switch having two ferromagnetic blades contained within a hermetically sealed tubular glass housing. Generally, the gas inside the glass is nitrogen that serves to eliminate the presence of oxygen and to ensure that the contacts do not oxidize. Reed switches are usually activated by a permanent magnet or an electromagnet. This type of sensor allows solutions for detection of proximity, speed, flow, among others. In this way, these sensors are versatile possessing different utilities and forms [10].

### *B. Selection of encoder for the rotation of the arms of the structure*

The following are encoders that can be used in the case under study

*1) Rotary Encoder 200 P/R (YUMO)*

Figure 8 presents an encoder with 200 pulses per revolution. This encoder produces electrical pulses that can be interpreted using a microcontroller to find the position of the input shaft. This allows the addiction of a feedback to the control system. Encoders of this type are often used in balancing robots. The encoder comes with a set screw coupling that will connect to any 4mm shaft [11]. Table II shows the specifications of the encoder 200 P/R.

Figure 8. Rotary Encoder 200 P/R (YUMO) [11].

TABLE II. SPECIFICATIONS OF ROTARY ENCODER 200 P/R [11]

| **Resolution** | 200 Pulse/Rotation |
|---|---|
| **Input Voltage** | 5 - 12VDC |
| **Maximum speed of rotation** | 5000 rpm |
| **Permissible radial load** | 5 N |
| **Permissible axial load** | 3 N |
| **Cable length** | 50 cm |
| **Shaft diameter** | 4 mm |

*2) Rotary encoder 1024 P/R (YUMO)*

Figure 9 presents an encoder with 1024 pulse per rotation; this encoder has an output gray code which can be interpreted using a microcontroller and find out how and in which direction the shaft is turning. This allows to add feedback to the control system. Encoders of this kind are often used in balancing robots and dead reckoning navigation but they can also be used as a precise input knob [12]. Table III shows the specifications of the encoder 1024 P/R.

Figure 9. Rotary encoder 1024 P/R (YUMO) [12].

TABLE III. SPECIFICATIONS OF ROTARY ENCODER 1024 P/R [12]

| **Resolution** | 1024 Pulse/Rotation |
|---|---|
| **Input Voltage** | 5 - 12VDC |
| **Maximum speed of rotation** | 6000 rpm |
| **Permissible radial load** | 5 N |
| **Permissible axial load** | 3 N |
| **Cable length** | 50cm |
| **Shaft diameter** | 5mm |

*3) Encoders comparison*

By the analysis of the two encoders presented it can be verified that any of them could be used, however, as the *1024 P/R* rotary encoder presents superior resolution it will give more accurate results.

## *C. Selection of encoder for the detection of the pedal speed*

In the following, there are presented sensors and actuators that can be used in the model being studied.

*1) 59150 Flange Mount Sensor and 57150 Actuator*

Figure 10 presents a flange mounting reed sensor (28.57mm x 19.05mm x 6.35mm) with a choice of normally open, normally open high voltage, normally closed or changeover contacts. The design of this sensor enables screw or adhesive mounting and the wires exit from top right-hand side. It is also available with left hand exit (59145 Series). It is capable of switching up to 265Vac/300Vdc at 10VA. The 59150 functions best with the matching actuator 57150-000 [13].

Figure 10. 59150 Flange Mount Sensor [13].

Table IV shows the types of sensors (normally open, normally open high voltage, normally closed or changeover contacts) and two sensitivity options for each one of them (These data are based on the use of an actuator 57150).

TABLE IV. SENSITIVITY OPTIONS FOR 59150 FLANGE MOUNT SENSOR WITH 57150 ACTUATOR [13].

| | | **S** | | **V** | |
|---|---|---|---|---|---|
| | **Switch Type** | ***Pull in AT Range*** | ***Activate distance - D mm average*** | ***Pull in AT Range*** | ***Activate distance - D mm average*** |
| 1 | Normally open | 12-18 | 13,5 | 27-33 | 9 |
| 2 | High Voltage | - | - | 27-33 | 9 |
| 3 | Change Over | 15-20 | 11 | - | - |
| 4 | Normally closed | 15-20 | 11 | - | - |

*2) 59025 Firecracker Reed Sensor and 57025 Actuator*

Figure 11 presents a Firecracker Reed Sensor (length=25.4mm and diameter=6.22mm). This sensor has a cylindrical shape with a choice of normally open, normally open high voltage, normally closed or changeover contacts. It is capable of switching up to 265Vac/300Vdc at 10VA. The 59025 Firecracker Reed Sensor is available with a range of sensitivity and cable length options. It functions best with the 57025 actuators [14].

Figure 11. 59025 Firecracker Reed Sensor [14].

Table V shows the types of sensors (normally open, normally open high voltage, normally closed or changeover contacts) and two sensitivity options for each one of them (These data are based on the use of an actuator 57025).

TABLE V. SENSITIVITY OPTIONS FOR FOR 59025 FIRECRACKER REED SENSOR WITH 57025 ACTUATOR [14]

| | | S | | V | |
|---|---|---|---|---|---|
| Switch Type | | ***Pull in AT Range*** | ***Activate distance - D mm average*** | ***Pull in AT Range*** | ***Activate distance - D mm average*** |
| 1 | Normally open | 12 to 18 | 7,9 | 27-33 | 4,2 |
| 2 | High Voltage | - | - | 27-33 | 4,2 |
| 3 | Change Over | 15 to 20 | 7,2 | - | |
| 4 | Normally closed | 15 to 20 | 7,2 | - | |

*3) Switch Reed sensors comparison*

One of the most important factors for the selection of a reed sensor and its actuator is the sensitivity. The sensitivity of the switch is the amount of magnetic field that is required to actuate the contact into an open or closed mode (Most reed switches have a sensitivity range of 10–30 AT, where 10 AT is more sensitive than 30 AT)

A check that can be made in terms of sensitivity is that for the same variations of sensitivity the distance in the set 59150 Flange Mount Sensor and 57150 Actuator is higher. In addition to the sensitivity, the ease of assembly and adjustment makes the set 59150 Flange Mount Sensor and 57150 Actuator more advantageous.

## V. CONCLUSIONS

With this work it was verified the evolution and growth of the serious games over the years, besides it was verified that it is necessary to adapt and create new equipment so that they can be used in physiotherapy and rehabilitation areas. Thus, the development of a mechatronic system was presented, whose main advantages are: being motivating, adjustable, appealing, comfortable and safe.

The system was divided into modules and a study of the dimensions of the model was carried out considering the anthropometric data. A detailed mechanical design study was also conducted.

Finally, it was analyzed the sensors and actuators in the market that could be implemented in the system, among them: Rotary Encoder 200 P / R (YUMO), Rotary encoder 1024 P / R (YUMO), 59150 Flange Mount Sensor, 57150 Actuator, 59025 Firecracker Reed Sensor and 57025 Actuator.

Future work may include: the development of the game scenario, the construction of a prototype for validation and the implementation of the studies performed.

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