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Design of Exercise Device for Older Adults

Diseño de Dispositivo para Ejercitación de Adultos Mayores

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ABSTRACT

Older adults should perform physical activity to improve cardiorespiratory functions. Aerobic exercises improve cardiovascular function, decrease basal heart rate and blood pressure, and improve mood and energy. To facilitate the execution of aerobic physical activity in older adults, the objective of this research was to design an exercise device for older adults. Starting from design specifications such as comfort, size, weight, resistance, and cost, we developed the detailed design of a horizontal bicycle. The designed device, thanks to its horizontally disposed structure, its adequate resistance to pedaling, its dimensioning based on anthropometric measurements of the Chilean population, and the disposition of sensors for heart rate and oxygen saturation, is suitable for older adults. Its weight and size also make it convenient for use inside the home, and the use of materials, components, and manufacturing processes available nationally and within the cheapest options, increases the possibility of access by older adults.

KEYWORDS: Exercise, lower limbs, horizontal bicycle, older adult, physiological variables.

RESUMEN

Es fundamental que los adultos mayores realicen actividad física para mejorar las funciones cardiorrespiratorias, particularmente los ejercicios aeróbicos mejoran la función cardiovascular, disminuyen la frecuencia cardíaca basal y la tensión arterial, además de mejorar su estado de ánimo y energía. Con la finalidad de facilitar la ejecución de actividad física del tipo aeróbica en adultos mayores, se planteó el objetivo de este trabajo, centrado en diseñar un dispositivo para su ejercitación. Partiendo de especificaciones de diseño como comodidad, tamaño, peso, resistencia y costo, se desarrolló el diseño de detalle de una bicicleta horizontal. El dispositivo diseñado, gracias a la disposición horizontal de la estructura, la resistencia adecuada al pedaleo, su dimensionamiento con base a medidas antropométricas de población chilena, y la disposición de sensores para *heart rate and oxygen saturation*, es adecuado para adultos mayores. Además, su peso y tamaño lo hacen conveniente para el uso dentro de las viviendas, del mismo modo, el uso de los materiales, componentes y proceso de manufactura disponibles nacionalmente y dentro de las opciones más económicas, aumentan la posibilidad de acceso por parte de los adultos mayores.

PALABRAS CLAVE: Ejercitación, miembros inferiores, bicicleta horizontal, adulto mayor, variables fisiológicas.

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INTRODUCTION

A condition of the human body is to be prepared to move, and moreover, it needs to do so. However, the practice of physical activity in the population is becoming less and less frequent, leading to sedentary lifestyles; which, together with inadequate eating habits cause the increase of different pathologies (obesity, cardiovascular diseases, metabolic syndrome, among others), is in some cases a public health problem^[1]. Of course, older adults are included in this spectrum.

The Undersecretariat of Public Health^[2] in the 'Manual of geriatrics for physicians' emphasizes that the Chilean population has progressively entered a phase of accelerated aging, with the country projected to become the oldest in the continent in the next 20 years. This demographic aging, from a public health perspective, represents an unprecedented challenge for health policies. The great challenge is associated with taking charge of disease prevention in this age group, especially those that can lead to dependency.

Functionality is the ability to perform an action or activity within the range considered normal. Loss of functionality among the elderly may be an indicator of mortality, longer hospital stay, or the need for institutionalization, hence the need to establish strategies aimed at maintaining functionality as a central axis of active life expectancy^[2]. Considering this situation, it is necessary to promote strategies for health promotion, prevention, and better control of chronic diseases.

In light of this scenario, the objective of this work was to design a device for the exercise of older adults, to promote physical activity, and, therefore, to maintain functionality and its benefits in the quality of life. The device can be considered in the rehabilitation process of the elderly as well, following the indication of medical specialists and/or kinesiologists, basically for functional recovery.

Specifically, we worked on the design of an exercise machine for the lower extremities of older adults, considering that these correspond to the largest muscle groups and that this exercise favors the maintenance of mobility, improving muscle strength and power, as well as avoiding bone mass reduction^[2]. The design also considered incorporating sensors to read the users' physiological parameters; to monitor their behavior before, during, and at the end of the exercise; to improve performance, prevent injuries or inconveniences; and adapt to the physical and health conditions of each patient.

The World Health Organization emphasizes that older adults should perform physical activity to improve cardiorespiratory functions^[3]. They particularly indicate that aerobic exercises maintained over time improve cardiovascular function, decrease basal heart rate, and blood pressure, improve the person's mood and energy to carrying out activities during daily life.

Static bicycles have been a fundamental element in the process of improving different medical pathologies in adults and older adults. Bouaziz *et al.*^[4] conducted a study that aimed to know the health benefits of cycloergometer training for older adults aged 70 years; this study delivered information on the positive effect on cardiovascular disease prevention and a significant improvement in metabolic responses. The author posits that cycling is a healthy form of resistance exercise. As it is a non-weight bearing activity, it has less impact on the joints, being less stressful for the body. It also does not require so much postural control, representing a good alternative for people with poor balance, and is feasible even for frail elderly people^[4].

Alberts *et al.*^[5] conducted an interesting study in which they demonstrated that pedaling in Parkinson's patients was highly beneficial and improved motor skills. Anderson *et al.*^[6] studied the neuropsychological effects of exercise with a stationary bicycle in older adults with diabetes mellitus, observing cognitive

improvement in these adults. Lake *et al.*^[7] used the ergometer among other equipment and activities to assess improvement in adults with Chronic Airflow Obstruction, documenting statistically significant changes of important functional improvements. Similarly, Barbosa *et al.*^[8] conducted a review of the application of rehabilitation techniques that contemplate the use of cycling leg exercise for individuals who have suffered cerebrovascular accidents, finding promising results. It was especially highlighted that cycling exercise is simple, repeatable, low cost and portable, as well as suitable for clinical and home environments.

Focusing on device design, Fidelis *et al.*^[9] designed and built a prototype 'bimodal' exercise bike for joint or independent upper and lower body exercise (Figure 1); its comfort, functionality, and ergonomics were evaluated. Ahmed (2012)^[10] developed a device to exercise arms and legs, with low-cost manufacturing, easy maintenance, and repair (Figure 2a); Belli and Fanget^[11] developed a cycloergometer for elderly people (Figure 2b), including its physiological and biomechanical evaluation. Focusing on the use of the SAP system, Rodriguez Ortega^[12] designed a new model of an upright exercise bike, planning in SAP the resources available to build the product, and using different product design methods.

Yepes *et al.*^[13] developed a data acquisition system that allows therapists to set a minimum pedaling speed and analyze the strength and speed of pedaling for the lower limb rehabilitation process. Although the object of the design was not the mechanical structure, the adaptation of sensors for the therapeutic purpose was successfully realized. In the same vein, Muñoz^[14] provided data on the physiological variables to monitor.

Overall, the background review provided valuable information on the health benefits of cycle ergometer training, the design and selection of some device components, low-budget management, user interface

features, the use of monitoring instruments for physiological parameters, and material selection and procurement.



FIGURE 1. Prototype 'bimodal' exercise bike [9].

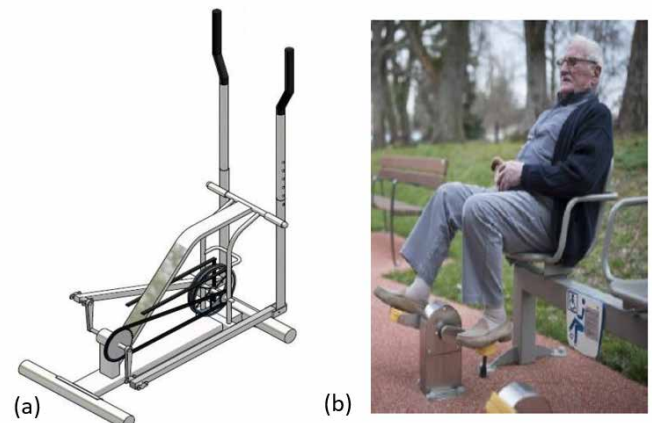


FIGURE 2. a) Arm and leg exercise device [10] b) Cycloergometer [11].

Regarding commercially available devices, there are some options oriented to rehabilitation, such as the mini bike with the possibility of pedaling hands and feet (Figure 3a)^[15], and the device to exercise legs and arms (Figure 3b)^[16], aimed at low-impact exercise for beginners and rehabilitation. Also available is the horizontal bike^[17] for general use with 8 levels of magnetic resistance, with an LED display that can be connected to a cell phone via Bluetooth (Figure 3c).

Although the options shown are available in the market, this work seeks to design an exercise machine

for the lower extremities, particularly for older adults, considering variables such as adequate resistance to pedaling (inertia disk) and its regulation, adjustment to anthropometric dimensions of Chileans considering the anthropometric study of the working population in Chile^[18], horizontal design and comfort (through seat adjustment).

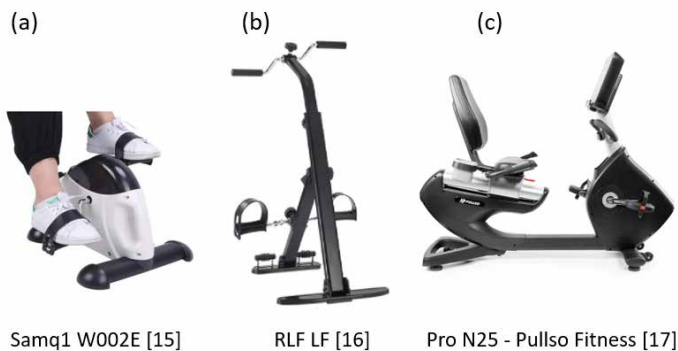


FIGURE 3. Commercially available devices.

It should be low-cost and easy to manufacture as well, so the structural materials, the different components, and the manufacturing process should be available nationally and correspond to standard dimensions and economic options. Other important aspects considered in the design are the facilities for placing devices to measure physiological variables (pulse oximeter and heart rate sensor) and that the device can be used in homes. For instance, device sizing will need to consider average access door size.

In addition, a pin was incorporated to separate the bicycle into two parts (making it modular), so that the user can use it in the way he/she feels most comfortable, complete, or just the front part. Also, the user can incorporate a seat of his/her preference, with the observation that in this case physiological variables cannot be measured. Although design scope did not contemplate implementation and programming of the sensors for physiological variables, general recommendations are given.

MATERIALS AND METHODS

The methodology used in the design process was based on the methodology proposed by Ullman^[19] and included the detection of needs and conceptual design, detail design, device modeling, and preliminary stress analysis. The details of each stage are presented below.

Needs assessment and conceptual design

To identify existing needs regarding the device to be developed, the recommendations of the Kinesiologist who is part of the project researchers were considered, along with the theoretical information reviewed on the benefits of pedaling in older adults^[20] and the traditional structure of pedaling devices^[21]. The needs raised in some of the background information reviewed^{[9] [10] [13] [14] [17]} were also important support.

Based on these needs, the design specifications shown and described in Table 1 were established. These specifications and all the information analyzed in the background study allowed the generation of three concepts that met the requirements, which are described below.

Concept 1 (Figure 4). The position of the person when performing the exercise is horizontal (1), positioning their feet on the pedals that produce a light grip (2). The resistance to pedaling is due to the friction provided by the shoe, whose intensity is regulated by a knob that offers different levels (3). During exercise, heart rate monitoring is done with sensors included in the handlebars (located next to the seat) (4), and respiratory rate and oxygen saturation are monitored by a pulse oximeter (5). All these measurements are performed on the upper extremities. A blood pressure monitor is present; however, this is not incorporated into the device. Physiological parameters appear on a screen positioned in front of the user. The device is also easy to move, as it has wheels. This concept gives the patient the option of sitting in the seat of the device or removing it and using a chair available in the center where they are located (5). However, using the

second option limits the measurement of physiological parameters since these are located on the handlebars anchored to the structure where the seat is located.

TABLE 1. Information of the patients analyzed.

Design specification	Description
Cost	The device must be affordable for users (older adults or their family) since the objective is to have it at home.
Supporting the user's weight	The device must withstand the stresses to which it will be subjected, for which the safety factor must be greater than 1.5, and the maximum displacements in the longitudinal elements must be less than $L/200$, i.e. $\Delta \leq L/200$; being Δ the value of the maximum displacement and L the length of the structure in that direction. This criterion, although taken from structural construction standards, guarantees both user comfort (by not feeling movements that could destabilize them) and the assurance that the bar will not exceed the elastic range during use.
Weight	The device should be easy to move, so its weight should be between 25 and 40 kg, which is the weight of commercially available devices. It should also include wheels to facilitate its movement.
Size	The dimensions of the device must allow its mobilization within the users' homes.
Resistance regulation	The device should offer different levels of exercise resistance as desired, to allow for more or less physical exertion when pedaling.
Comfort	The device must adapt correctly to the user, have a height adjustment, and adjust to the leg length.
Sensors	The device should include facilities to place basic sensors for physiological variables (heart rate, respiratory rate, and oxygen saturation).

Concept 2 (Figure 5). This concept has a vertical structure, that is, the bicycle saddle is higher than horizontal, allowing the legs to be positioned vertically at the time of exercise (1). Foot adjustment is made from the tips and the widest part, simultaneously (2). This device offers resistance by the magnetism that is regulated on a graduated knob which is manipulated by the user (3). Once the exercise is underway, heart rate is monitored by a clock (4), the respiratory rate and oxygen saturation by a pulse oximeter. As in Concept 1, for blood pressure measurement, a non-incorporated accessory is used, the tensiometer, which is performed when the user is at rest. Considering that the structure must be adapted to the measurements of the different users, it has distance adjustment from the saddle to the pedals. The device is easy to move, since it has wheels.



FIGURE 4. Main components (referential) of Concept 1.

Concept 3 (Figure 6). This concept consists of a horizontal structure (1). However, unlike Concept 1, this one does not have a built-in saddle, so the user must use a chair available in the facility where they are located to perform the exercise (6). Foot adjustment is made from the widest part of the foot and is a rigid component (2). During exercise, resistance to pedaling is performed by a friction system regulated by a non-graded knob operated by the user (3). In addition, heart

rate monitoring is performed by sensors built into the handlebars that are in front of the person (as on a common bicycle) (4), and measurement of respiratory rate and oxygen saturation is performed by two bracelets, one on each arm (5). Blood pressure is measured by an external blood pressure monitor, while the user is at rest. The device is easy to move as well since it has wheels.



FIGURE 5. Main components (referential) of Concept 2.

Selection of the concept to be developed. To select the concept with which to proceed in the following design stages, the Pugh Matrix tool was used^[19], also known as the decisional matrix, which makes a comparison between concepts using one as a base, called Datum. For this comparison, criteria were defined considering the previously established design specifications (Table 2), and each of these was assigned a score according to the level of importance, the sum being 100 points. The research team, based on the

defined needs, decided that the comfort, accessibility, and accuracy criteria should have greater weight, followed in importance by load support.



FIGURE 6. Main components (referential) of Concept 3.

To evaluate the solution alternatives, Concept 2 was used as Datum, comparing it with the other concepts using the Pugh matrix (Table 3), where different values were given: +1 when the concept meets the criterion better than the datum, 0 when the concept meets the criterion equally well as the datum, and -1 when the concept meets the criterion less well than the datum. Therefore, the outstanding concept to be developed was identified.

From Table 3 it is concluded that Concept 1 is the one that best satisfies the needs in comparison with the datum (greater than 0). Therefore, in the following stages we worked with this concept as a base. Figure 7 shows a schematic drawing of the selected concept.

TABLE 2. Comparison criteria for Pugh matrix.

Criteria	Description
Comfort	This refers to the fact that the device should be comfortable for the user.
Accessibility	The acquisition of the different components must provide a cost that allows an adequate value for the device.
Accuracy	The devices selected to measure physiological variables must be accurate.
Durability	The various components must have a long life.
Regulation	The device must allow for different levels of pedal resistance regulation.
Easy mobilization and positioning	Easy for the user to move and position the device.
Support	The device must support the weight of the user and the physical activity performed.

of materials for its manufacture, as well as technical information on some components for their acquisition in the market. The subsets defined were structure, transmission system, braking system, measurement of physiological variables, and ergonomic considerations. Each subset is detailed below.

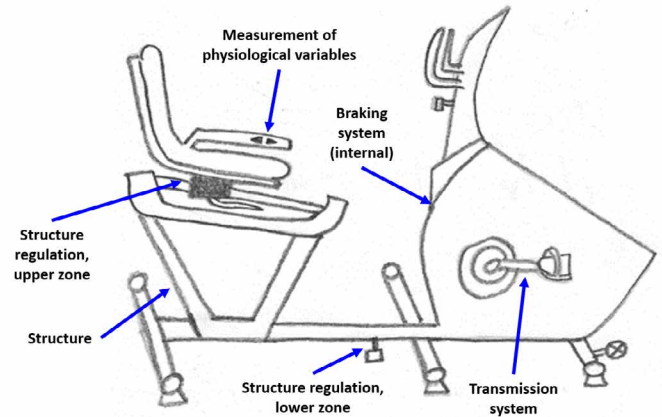


FIGURE 7. Schematic drawing of the selected concept (Concept 1).

TABLE 3. Pugh matrix for selected concepts.

Problem: To choose a concept for a lower limb exercise device for older adults.	Importance	Concept 1	Concept 2	Concept 3
Comfort	20	1	DATUM	0
Accessibility	20	1		1
Accuracy	20	0		0
Durability	10	-1		-1
Regulation	10	-1		-1
Easy mobilization and positioning	5	1		1
Support	15	1		0
Total		2		-2
Weighted total		40	5	

Structure

The structure is composed of elements that provide rigidity, stability, and support to the device. Three different sizes were considered for the rectangular profiles used according to the function that each one fulfills. Figure 8 shows the structure, where the two A36 steel profiles are shown, and the other profiles are made of 6061 aluminum. These materials were selected considering their structural use and wide availability in the national market, in different presentations and dimensions. Their suitability will also be verified through stress analysis.

The structure in the saddle area can be varied, using a pin, the distance to the ground and the pedals using a profile designed to move as shown in Figure 9, using the aluminum profile as a guide.

Detailed design

In this stage, the selected concept was refined by breaking the device down into subsets or groups, to provide information on the calculations and selection

The lower area can be adjusted or disassembled; the adjustment corresponds to the variation of the horizontal distance from the seat to the pedals, which

can be increased or decreased using a pin and holes in the base, as shown in Figure 10. Disassembly involves removing or separating the part of the structure that corresponds to the area where the person sits, leaving the device with only the transmission system. This gives the user the option of exercising using a chair available at the facility where the equipment is located; however, when this is done, the reading of physiological variables performed on the handlebars will be inoperative.

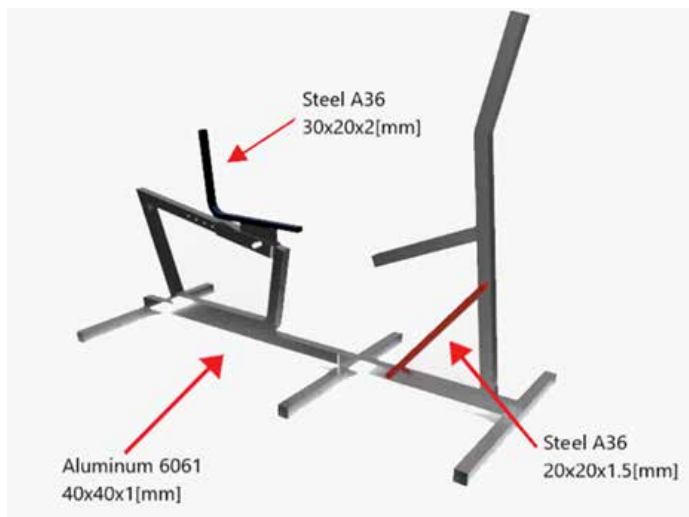


FIGURE 8. Representation of the device structure.

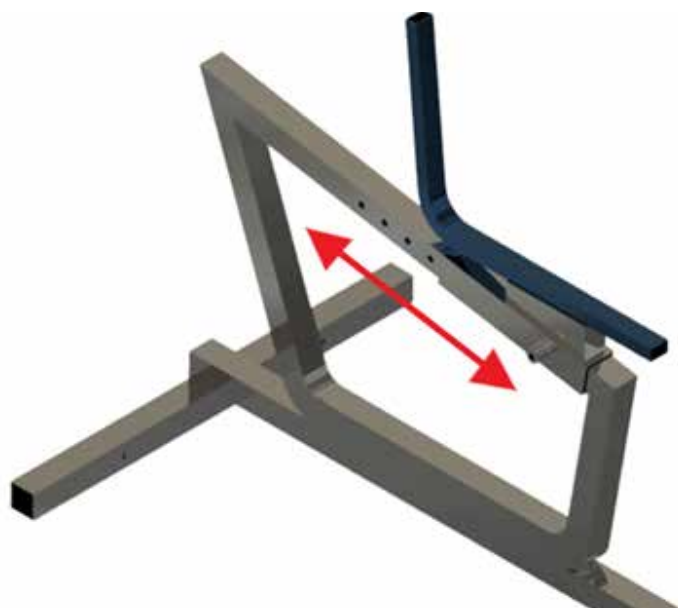


FIGURE 9. Structure regulation, upper zone.

Transmission system

The transmission system comprises the flywheel, two crank arms with their respective pedals, an axle,

a bushing, and two bearings with their respective supports (Figures 11 and 12). The movement is generated in the inertia disk, which has a mass of 6 kg (recommended for the selected user, the older adult^[22]). For the dimensions a commercially available flywheel^[23] was considered, making the verification of the mass and dimensions through the CAD model. The outer diameter was defined as 280 mm and the inner diameter (joint to bushing) as 30 mm. Table 4 includes the specifications of the transmission system elements that were selected, considering commercial availability and adaptation to the dimensions of the inertia disk.

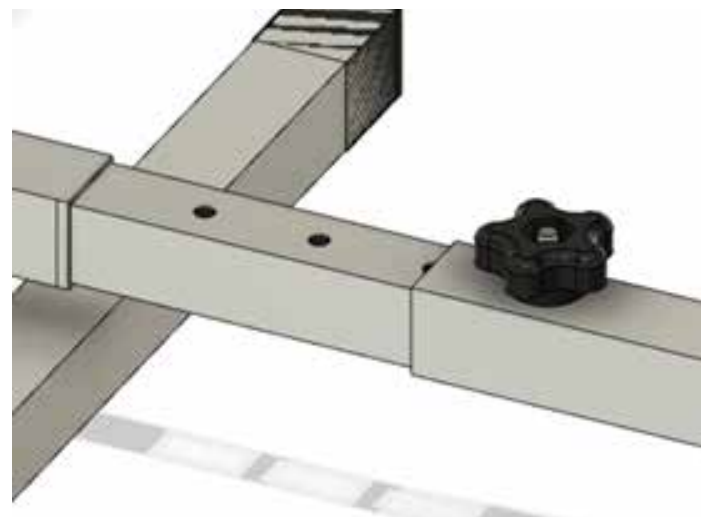


FIGURE 10. Structure regulation, lower zone.

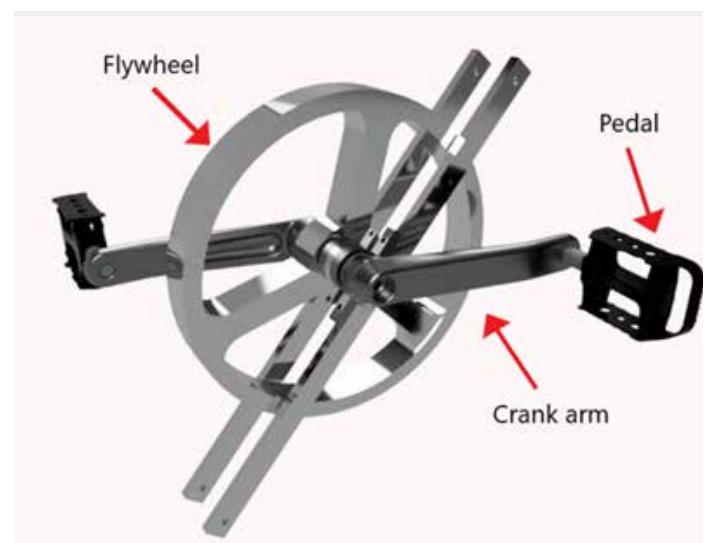


FIGURE 11. Device transmission system.

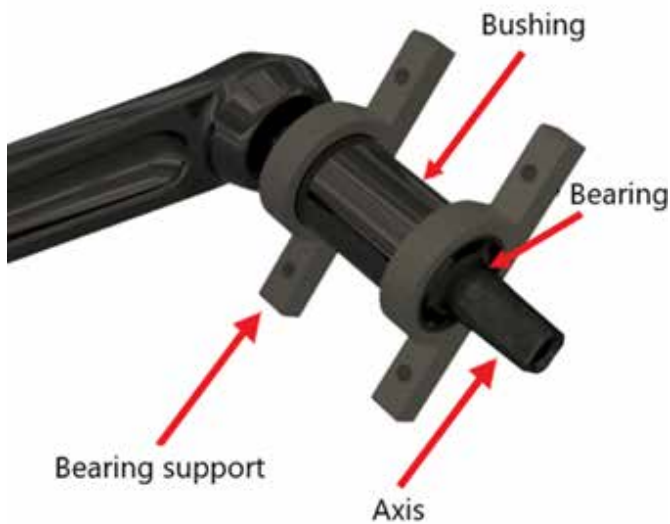


FIGURE 12. Enlarged view of the transmission system, without a flywheel.

TABLE 4. Transmission system element specifications.

Element	Provenance	Specifications
Flywheel	Commercially available. To be adapted according to drawing specifications.	ASTM A36 steel disc; outer diameter: 280 mm; inner diameter: 30 mm.
Bushing	To be manufactured according to drawing specifications.	ASTM A36 steel; inner diameter: 19 mm; outer diameter: 30 mm.
Bottom bracket	Commercially available.	Square type: 35x52x35 [mm].
2 cranks arm	Commercially available.	Universal, square union.
2 pedals	Commercially available.	Universal, square union.
2 bearings	Commercially available.	Ball-bearing; inner diameter: 16 mm; outer diameter: 21 mm.
2 bearing supports	To be manufactured according to drawing specifications.	Width: 10.5 mm. Compatible with 21 mm external diameter bearings.

Braking system

The braking system makes it possible to vary the resistance of the flywheel, i.e., the level of force that the

user must apply to make it rotate. All this is done using the different elements that compose it, as shown in Figure 13. These elements are commercially available, and their sizing and verification are shown below.

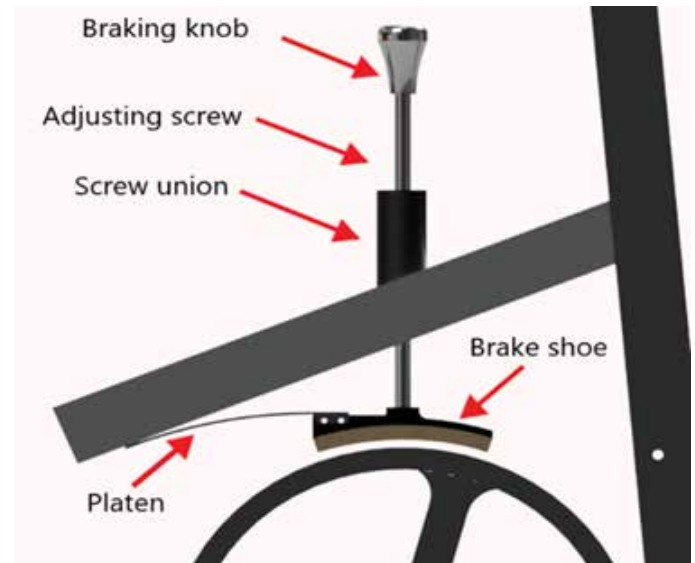


FIGURE 13. Braking system.

Brake structure analysis.

The braking of the device is carried out using a brake shoe, which acts directly on the flywheel, slowing it down using friction until it comes to a complete stop.

Taking^[24] as reference, Figure 14 shows a free body diagram of the brake shoe, to identify the forces acting at the moment of contact with the flywheel. The reactions R_x and R_y at point O correspond to the connection between the braking system and the structure. F_a is defined as the driving force, and F_n as the normal force, thus, clearing the unknowns of the static equilibrium equations concerning the axes presented in Figure 14, Equations (1), (2), and (3), and considering Equations (4) and (5), results in $F_n=115.45$ N, $F_a=115.12$ N, $R_x=25.4$ N, and $R_y= -0.32$ N, whose values represent the behavior when braking. The driving force is fundamental to determining the behavior of the brake plate, which is presented later.

$$F_a = \frac{F_n(a - e\mu)}{a} \quad (1)$$

$$R_y = F_a - F_n \quad (2)$$

$$R_x = -F_f \quad (3)$$

$$F_n = P_{max} r \theta w \quad (4)$$

$$F_f = \mu F_n \quad (5)$$

Where:

μ = Coefficient of friction of the brake shoe covering material (0.22 corresponding to wool felt covering^[25]).

P_{max} = Maximum allowable pressure of the brake shoe (35 KPa, corresponding to wool felt lining^[25]).

w = Brake shoe width (30 mm).

θ = Angle subtended in radians (short shoe, 45° ^[25]).

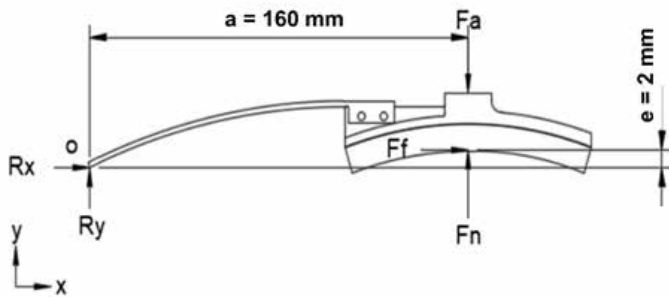


FIGURE 14. Brake shoe free body diagram.

Brake plate study

To analyze the brake plate, of cross-section 22×2 ^[mm], it was considered as a recessed and cantilevered beam, as can be seen in Figure 15, where the 115.12 N actuation force obtained in the previous section is incorporated.

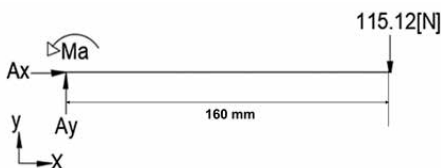


FIGURE 15. Brake plate free body diagram.

Using the equilibrium equations, $A_x=0$ N, $A_y=115.12$ N, and $M_a=18.42$ N were obtained, then the normal forces in the brake plate and the shear forces of the bolts that join it the structure were calculated, with Equations (6) and (7) respectively.

$$\sigma = \frac{M_{maximum deflector} * C}{I} \quad (6)$$

$$\tau = \frac{4 * Maximum shear force}{3 * Section area} \quad (7)$$

Where:

I = Moment of inertia of the section.

c = Distance between the neutral shaft and the end of the brake plate.

The section method was used to calculate the maximum bending moment and shear force acting on the brake plate. The maximum shear force was 115.12 N and the maximum bending moment, produced at the plate supports, was 18.4 Nm.

The normal stress obtained was 11.4 MPa, being the yield strength of ASTM A36 steel 250 MPa^[25]. Therefore, the plate supports the bending moment to which it is subjected. The maximum shear stress of the bolt was 5.43 MPa, being the selected bolt a class 4.8 DIN 601 bolt of 6 mm diameter, with minimum proof strength of 310 MPa and minimum yield strength of 340 MPa^[25], so it does not suffer any damage. Table 5 includes the specifications of the main components of the braking system.

Measurement of physiological variables

The reading of physiological parameters of older adults when using the bicycle is done in the handlebar area (Figure 16). These are elements that have sensors for the measurement of heart rate and respiratory rate. Oxygen

saturation is read by a pulse oximeter, which is attached to the handlebar through a "pulse oximeter holder" because the measurement is done on the index finger, this pulse oximeter holder will be manufactured with additive manufacturing. Once the heart rate sensor is incorporated, it must be connected to a microcomputer that processes the reading and then, through an HDMI connector, sends the results to the screen so that the user can see the respective values.

TABLE 5. Specifications of braking system elements.

Element	Provenance	Specifications
Brake shoe	Commercially available.	Material: Wool felt; dimensions: 100x30x10 [mm].
Brake plate	Commercially available.	Material: A36 steel; dimensions: 160 mm from pivot to adjusting screw shaft.
Adjustment screw	To be manufactured according to drawing specifications.	Material: A36 steel; dimensions: body 205 mm x 10 mm, with thread M10x1.5, length 50 mm, spaced 60 mm from one end.
Screw union	To be manufactured according to drawing specifications.	Material: A36 steel; dimensions: outer diameter: 30 mm; inner diameter: 10 mm, with internal thread M10x1.5.

Ergonomics considerations

To determine the dimensions that the device should have, anthropometric tables of the working population in Chile were used [18]. These dimensions are specified separately, an average for the female gender and another for the male gender, and the most critical dimension was used. The device was designed to be able to regulate the dimensions of the saddle, i.e., height

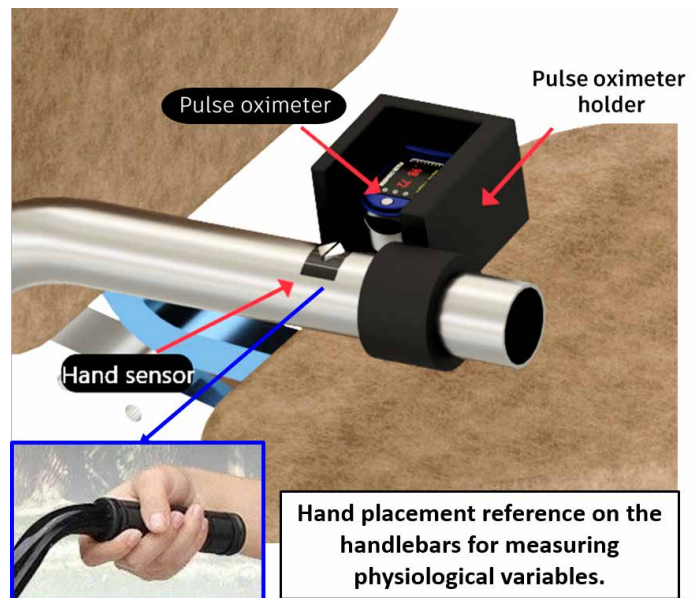


TABLE 16. Location of sensors to measure physiological variables.

and distance to the pedals, for which the parameters of [18] were used as upper and lower limits of regulation. Table 6 shows the dimensions considered. Although the device is being designed for older adults, where the possibility of reduction in height and muscle mass is high, these data are taken because they are the ones available; these dimensions can be adjusted when data are available for this age group specifically, though.

About the weight that the device must support and that should be considered for the calculations, the Chilean average was taken as a reference based on government statistics, specifically an average mass in men of 75 kg and women of 63 kg[26]. Starting from the highest mass, 75 kg, and because the source is not updated, the weight was increased by 10%, obtaining 83 kg.

Device modeling and preliminary stress analysis

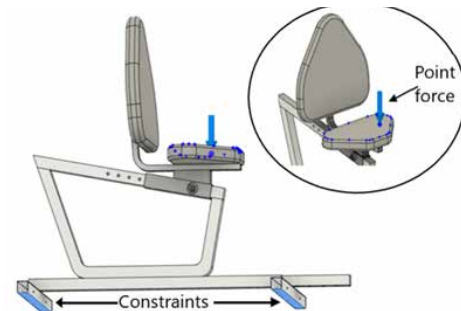
Figure 17 shows the device CAD model, designed according to the information presented in the previous sections. The model was developed using Fusion 360 © software and evaluated through the finite element method with ANSYS 2021 R1©.

TABLE 6. Dimensions considered for device design.

Variable	Dimension [mm]	Description
Height of the scapula to the seat (seat back dimension)	460	The vertical distance between the seat and the lower edge of the scapula or shoulder blade.
Maximum functional front reach	681	The maximum horizontal distance between the handlebars and the sagittal plane of the person.
Height from elbow to seat	244	The vertical distance from the seat surface to the lowest part of the elbow (elbow in 90° flexion).
Bideltoid width (width of the seat back)	475	The maximum distance measured between the left and right deltoid.
Width between elbows	487	The maximum horizontal distance between the inner lateral surfaces of the elbows.
Seat height	480 - 390	The vertical distance from the ground to the saddle.

**FIGURE 17. CAD model of the device.**

For the stress analysis of the structure, a static, linear-elastic model was considered, disregarding the cyclic loads resulting from the movement of the pedals. As acting loads, the user's weight applied vertically, eccentrically (away from the geometric center of the figure) and pointwise (see Figure 18) was considered. This represents the concentration of the entire load on one side of the body when performing the exercise. The point load is shown in Figure 18 with a blue arrow on one side of the saddle and has a magnitude of 814.23 N, representing the user's weight taken as a reference, a body mass of 83 kg. A fixed constraint was included in the lower profiles of the structure, simulating the contact of the device with the ground, and the condition of perfect contact or rigid bonding (bonded) was used in the union of all parts. Table 7 shows the mechanical properties of the elements involved in the study.

**FIGURE 18. Analysis specifications.**

Initially, the entire geometry was meshed. After performing several analyses without achieving convergence due to the complexity of the model, it was decided to analyze the parts in isolation. These were mainly areas that were perceived as critical in this first numerical approximation. Two substructures were evaluated; the saddle support bar structure (Figure 19) and the back support bar structure (Figure 20).

Figure 19 shows the lower profile of the saddle (6061-T6 aluminum material) together with the pin (DIN 4.8) and the seat base (A-36 steel). The load of 814.23 N (corresponding to the weight of the user) was applied but placed eccentrically on the saddle and a fixed constraint was included in the lower part of the structure, as shown in the figure.

TABLE 7. Mechanical properties of design elements.

Element	Material	Modulus of elasticity (E) [GPa]	Yield stress (Sy) [MPa]	Density (δ) [g/cm ³]	Poisson's ratio ν
Back support bar	Steel A36	210	250	7.85	0.30
Saddle support bar	Aluminum 6061-T6	68.9	241	2.70	0.29
Bolts	Carbon steel DIN 558 (4.8)	210	340	7.85	0.3

Regarding the back support bar structure, designed in A-36 steel, an unfavorable condition was considered, which is that the user applies all his weight on the backrest area (see Figure 20). This is equivalent to a pressure distributed in the area of 0.068 MPa. The restriction corresponds to a fixed support and is located in the area where this bar comes into contact with the saddle support structure.

For the saddle bar structure, 10-node tetrahedral elements were used. The von Mises stress and a stress variation of less than 2% were established as convergence parameters. From the analysis performed, the number of elements was set at 35421. Figure 21 shows the final mesh and Figure 22 the convergence graph.

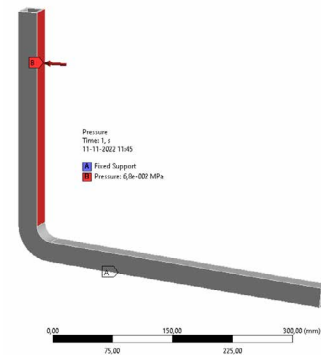


FIGURE 20. Back support bar structure, restrictions and loads evaluated.

Hexahedral solid elements of 8 nodes were used for the back support bar structure. The same criterion was used for convergence as for the saddle support bar structure, setting the number of elements at 8663. Figure 23 shows the final mesh, and Figure 24 shows the convergence graph.

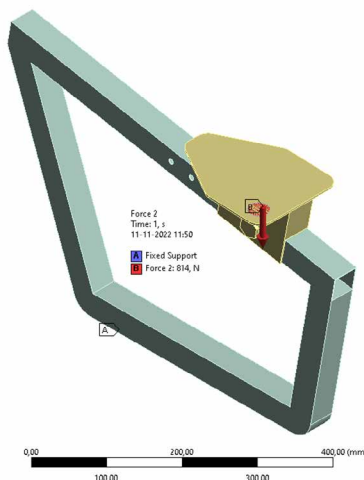


FIGURE 19. Saddle support bar structure, restrictions, and evaluated loads.



FIGURE 21. Meshing of tetrahedral elements of the saddle support bar structure.

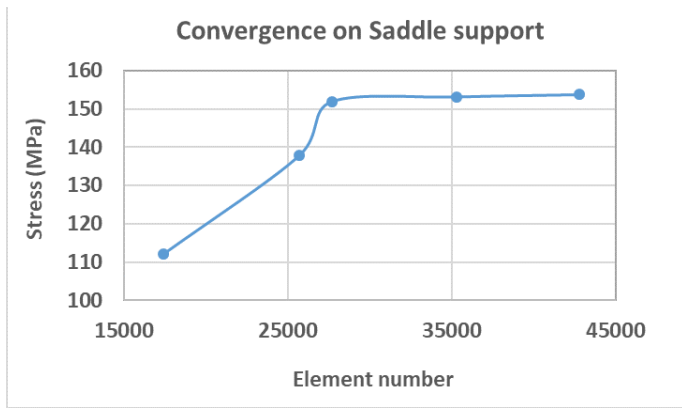


FIGURE 22. Convergence on saddle support.



FIGURE 23. Meshing of hexahedral elements of the back support bar structure.

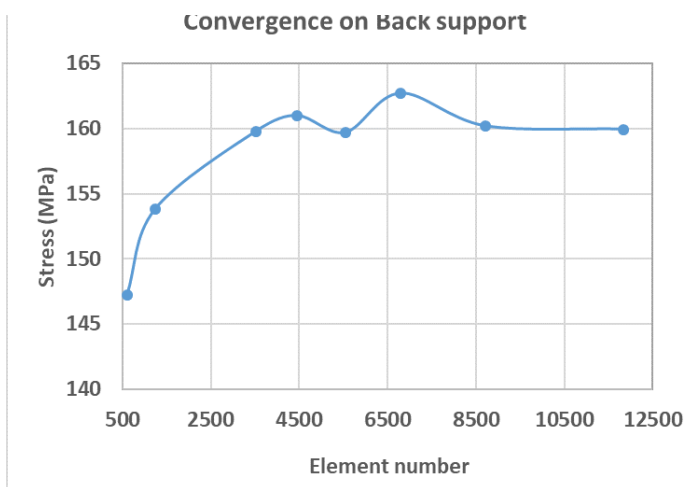


FIGURE 24. Convergence on back support

It should be noted that due to the relatively small mesh sizes, computational times were less than one minute per iteration, using an I9 processor with 128 GB RAM.

RESULTS AND DISCUSSION

Structural evaluation

In the structural evaluation, the von Mises stresses, a factor of safety, and maximum displacements were verified. Figure 25 shows the von Mises stress distribution of the saddle support bar structure, where a stress concentration is observed in the aluminum bar, mainly on the corners. A stress concentration is also observed at the load application point. Figure 26 shows the von Mises stress distribution of the back support bar structure. This time the stress concentration is evident in the area of change of direction of the bar. The maximum von Mises stress is 168 MPa.

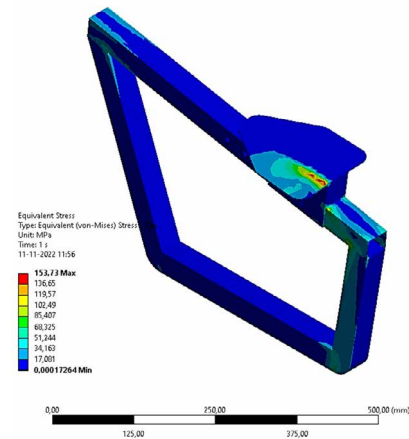


FIGURE 25. Saddle support bar structure. von Mises stress distribution (MPa).

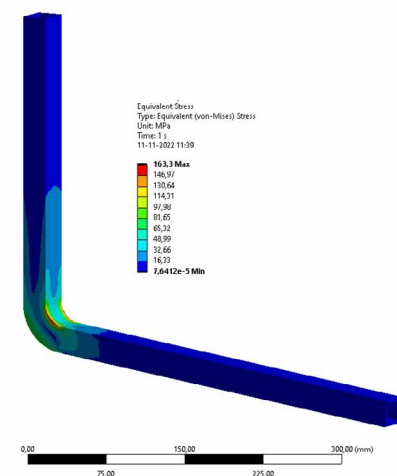


FIGURE 26. Back support bar structure. von Mises stress distribution (MPa).

Figures 27 and 28 show both structures, but this time with a distribution of safety factor values. The minimum safety factor read was 1.63, thus meeting the minimum established in the design specifications (Table 1) of 1.5.

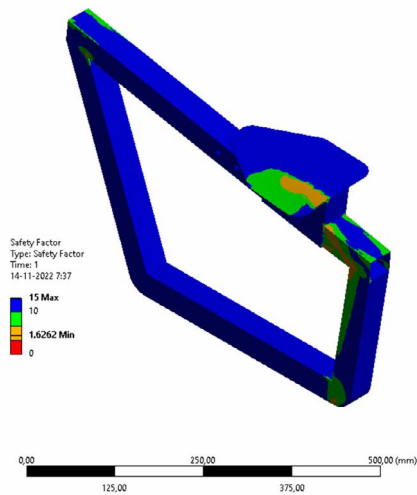


FIGURE 27. Saddle support bar structure. Safety factor distribution.

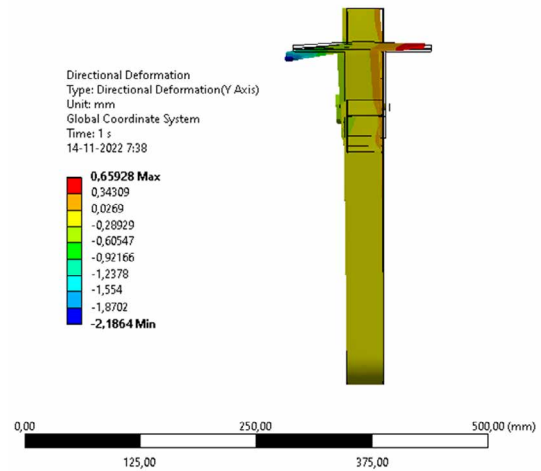


FIGURE 29. Saddle support bar structure. Displacements in the vertical direction (Y) (mm).

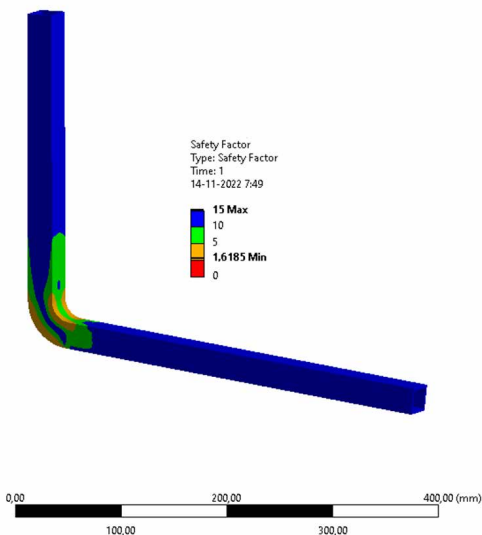


FIGURE 28. Back support bar structure. Safety factor distribution.

Regarding displacements that occur in the structure because of stresses, Figure 29 shows that the saddle support bar structure suffers a maximum displacement on its vertical line of 1.38 mm. This value is less than the quotient of the vertical length of the structure

between 200 ($\Delta/200 \leq 1.875$ mm). Figure 30 shows the distribution of displacements in the back support bar structure, where the maximum value of the displacement is again less than the established limit.

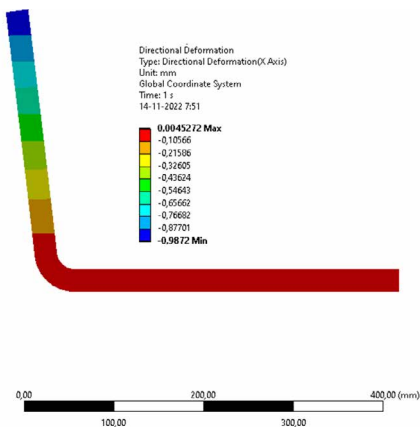


FIGURE 30. Back support bar structure. Displacements in the horizontal direction (X) (mm).

Final design and the established specifications

A summary of the results obtained for each design specification (Table 1) is presented below:

Supporting the user's weight. Through the preliminary stress analysis using the finite element method, it was

verified that the stresses to which the designed device will be subjected do not cause failure (safety factor higher than 1.5), therefore, it supports the user's weight.

Weight. The weight of the device is approximately 34 kg, which is within the range of commercially available devices between 25 and 45 kg. The profiles selected are mostly made of thin aluminum, which favors low weight. Wheels were incorporated for easy transportation.

Size. The device is within the average dimensions for this type of equipment, the main dimensions are shown in Figure 31. In addition, to size it, the average size of the access doors was considered, which allows the displacement inside the houses. A pin was also incorporated to separate the bicycle into two parts, making it modular so that the user can use it in the most comfortable way possible. Figure 32 shows the front part of the bicycle, which can be used with a chair that offers comfort to the user.

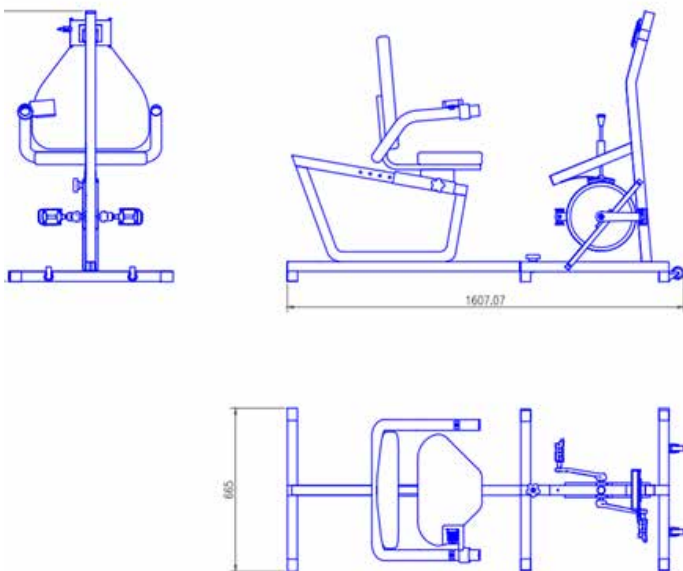


FIGURE 31. Main dimensions of the designed bicycle.

Resistance regulation. The bicycle has a braking knob and a regulating screw, which are manipulated by the user, and can control braking of the inertia disk, which leads to an increase or decrease in pedaling resistance.



FIGURE 32. Front part of the bicycle.

Ergonomics. To establish the main dimensions of the device and adapt it to the user, the dimensions specified in the anthropometric study of the working population in Chile^[18] were taken as a reference.

Sensors. The incorporation of sensors in the device for the measurement of physiological parameters was considered, specifically the heart rate sensor and pulse oximeter. The next phase of the project will include implementation and correct programming of the sensors by specialized personnel.

Cost. The cost is directly related to design and manufacturing. Regarding the design, it can be indicated that all the selected materials are commercially available and within the most economical options in the market.

CONCLUSIONS

The developed design complies with established design specifications, specifically through its horizontal design, adequate resistance to pedaling considering the selected inertia disk and the regulation system, adjustment to anthropometric dimensions of the working population in Chile, the comfort provided

through seat adjustment, the facilities for placing devices to measure physiological variables (saturation meter and heart rate sensor), and the consideration of the most economical options for materials, components, and manufacturing process.

In addition, from a strength point of view, the stresses on the structure generate stresses below the established limit.

The evaluation of the brake structure was performed using beam theory elements, which verified that the brake design components met the requirements.

The structural evaluation of the designed structures, carried out with the finite element method, showed that the values of stresses and displacements produced when the structure was subjected to a set of design loads were lower than the maximum allowable stresses and displacements established in the specifications.

The different materials and components selected in the detailed design are commercially available, and the cost of each one was also taken into consideration to offer a horizontal exercise bike for the elderly at a convenient cost.

A later stage of the project plan will include a detailed cost study and the manufacture of the designed device, so that it can be tested on older adults under the supervision of specialized personnel. This will also allow compared the device with others available commercially or proposed in other research.

Considering the importance of the ergonomic evaluation of the device, specialist personnel will be incorporated into the work team, to carry out the ergonomic evaluation using different available methods, and in this way endorse its use in the target age group.

Although the device is designed for use by older adults,

where the operating speed and loading cycles are not high, a dynamic study is planned to verify its behavior.

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AUTHOR CONTRIBUTIONS

D.G. conceptualized the project and designed the device. B.A. oversaw the general project, analyzed results, participated in all the writing stages of the manuscript (preparation of the original draft, review and edition of the different versions and the final document). G.M. participated giving guidance for the finite element analysis and support for the design of the device, and wrote, reviewed, and edited different versions of the manuscript. M.SM. participated giving guidance on the specifications of the device and carried out the design final analysis. All authors reviewed and approved the final version of the manuscript.

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