International Journal of Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: 10.31695/IJASRE.2023.9.12.1

Volume 9, Issue 12
December - 2023

Ergonomic Design and Development of Guided Pulling Apparatus for outdoor Gyms

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ABSTRACT

Records of weightlifting date back to Ancient Greece, with stone weights named after Milo of Croton, a six-time Olympic champion athlete. This article proposes the development of an innovative guided pulling apparatus, focusing on the effectiveness and safety of upper-body training. The central goal is to replace the use of external masses with the user's body mass, triggering muscle hypertrophy. The device, suitable for outdoor gyms due to the chosen materials and ease of handling, offers personalized options. Users can choose to lift their entire body weight or reduce the load using movable pulleys on a second apparatus, both under guidance. These processes follow Isaac Newton's fundamental laws, along with the principles of Archimedean pulleys and rollers. The article addresses not only the mechanics of the apparatus but also crucial ergonomic concepts. Emphasis is placed on the importance of rules and procedures to promote health and avoid improper postures during exercise. The development includes an analysis of materials, weights, and prices, ensuring a solid foundation for the project. The comprehensive structure of the article covers everything from building a robust metal frame to implementing a traction system with pulleys and steel cables, evenly distributing resistance. Notably, it includes a damping mechanism, prioritizing the safety of practitioners. By offering guided movements, the apparatus not only reduces the rate of injuries and future complications but also ensures desired results efficiently. This project represents a significant advancement in strength training, combining the tradition of ancient weights with modern principles of physics and ergonomics.

Key Words: Damping Mechanism, Newton's Laws, Traction System, Upper-Body, Weightlifting.

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1. INTRODUCTION

The pursuit of enhanced health and fitness often involves various approaches, such as engaging in sports or regular walking. While these activities can yield positive outcomes, individuals aiming to specifically increase lean muscle mass may find weightlifting and calisthenics to be more effective. Unlike conventional sports like soccer, which naturally engage muscles with limited efficiency and significant calorie expenditure, weightlifting and calisthenics offer a comprehensive muscle engagement strategy. This approach aims to maximize muscle gain while minimizing energy expenditure, thereby enhancing efficiency in achieving fitness goals.

The historical roots of weightlifting trace back to Ancient Greece, where early records of weightlifting involve figures like Milo of Croton, a six-time Olympic champion [1]. In parallel, calisthenics, derived from the Greek words '*kallos*' and '*sthenos*' meaning beauty and strength, respectively, seeks to combine strength and aesthetics, emphasizing the sculpting of the body's forms and curves. This method has evolved and is now incorporated into diverse modalities such as functional training, crossfit, and street workout, catering not just to athletes but also to the general population [2].

2. LITERATURE SURVEY

In the market, there is a wide variety of gym equipment that employs various mechanical principles. At the most basic level, each machine has the function of performing a single task: causing the user to activate muscles through repetitive and constant physical or mechanical movements, aiming to break muscle fibers.

Various models can perform this function using pulleys, levers, pulls, or, in the simplest model, free movement, where the exercise is executed only with body weight. Some examples of exercises that can be performed on such machines include back pulley, front pulley, closed grip pulley, and supinated pull. In general, training methods manipulate variables in different ways, providing mechanical and metabolic stimuli in distinct magnitudes [3].

The application of Newton's Laws in weightlifting and calisthenics aims to achieve uniform movements, emphasizing the pursuit of balance. Considering Newton's first and second laws, it is possible to understand the effects of applied forces.

The first law, known as the law of inertia, highlights that objects in equilibrium do not accelerate due to the balance of acting forces. To initiate acceleration, an unbalanced force capable of altering direction, velocity, or both is required [4].

The second law, or the fundamental principle of dynamics, reveals that acceleration depends on mass and resultant force. The resultant force is the product of mass and acceleration, indicating that increasing force implies increased acceleration, while increasing mass results in decreased acceleration [4].

When calculating the energy generated during exercises on the machine, it is essential to consider gravitational potential energy. Disregarding friction, this energy is converted into calorie burning.

Damping is a physical phenomenon observed in mechanical systems that experience the dissipation of mechanical energy in the form of heat, noise, hysteresis, or dry friction [5]. In a mechanical system, when work is being done, the presence of a non-conservative force implies the loss of mechanical energy, resulting in damping occurrence [6].

There are different types of damping, with hysteric damping present in this project. This occurs when a material is deformed, absorbing and dissipating energy. The effect is attributed to friction between internal planes that slide or slip during deformations.

The chosen material to implement this damping is a damping spring, whose primary function is to attenuate a possible fall, prioritizing user well-being and prolonging the lifespan of the equipment.

Historical accounts indicate that pulleys were first used by Archimedes of Syracuse (287 B.C. – 212 B.C.) to move a ship [7]. Pulleys can be either movable or fixed, with a common combination of both types in this project.

DOI: 10.31695/IJASRE.2023.9.12.1

In a fixed pulley, the force applied is opposite to the object's movement, and the force is equal to that needed to lift the object without interference, using only human force. The strength of fixed pulleys lies in positioning an object in the desired location, changing only the object's lifting location. However, the drawback is that they do not alter the required force.

In contrast to fixed pulleys, movable ones are free, having translational and rotational movement. In the pulling motion, the force imposed by the user differs from the actual weight of the object, and both the object and the pulley assume higher positions.

The force needed to lift an object is halved for each movable pulley present in the system. The more movable pulleys, the less force is applied to move an object [8].

Although associated with the workplace, the concept and practices of ergonomics can be applied in virtually any environment. There are various concepts about what ergonomics is, but, in general, this science encompasses rules and procedures that promote health care, aiming to avoid incorrect postures and inadequate efforts.

Constantly maintaining incorrect postures can result in postural problems, affecting joints, muscles, among others.

Ergonomics brings several benefits, including reducing accident rates, decreasing health expenses, and increasing productivity, among others.

"Postural problems have been considered a serious public health issue, as they have a high incidence in the economically active population, temporarily or permanently incapacitating for professional activities" [9].

3. OBJECTIVE OF RESEARCH

This project aims to create a guided pull-up apparatus, focusing on enhancing upper limb training with an emphasis on effectiveness and safety. To achieve this goal, several steps will be taken. Initially, efforts will be dedicated to the design and construction of a robust metal frame to ensure stability and durability.

Next, a traction system will be implemented using pulleys and steel cables, aiming for a uniform distribution of resistance throughout the movement to ensure training effectiveness and minimize the risk of injuries. An important feature will be the incorporation of a mechanism for lifting the user's own mass, allowing for personalized resistance adjustments adaptable to each user's level.

To ensure the safety of practitioners, a system that dampens the fall will be developed. Thus, the resulting apparatus seeks to strengthen the upper limbs, offering an adaptable training experience and, above all, a secure one.

4. RESEARCH METHODOLOGY

The study was conducted through research across various sources of content related to weightlifting, health, and gym equipment. This approach allowed for the development of the project using specific tools and methods.

Based on e-commerce and neighboring city locksmiths, the following Table 1 displays the necessary materials, along with their masses and prices.

DOI: 10.31695/IJASRE.2023.9.12.1

Table 1 – Budget table for the required materials, weights, and prices

ITEM	QUANTITY	WEIGHT	UNIT PRICE (BRL)
Tube Oblong 98 x 50 x 2.00mm 1.5m in length	1	6 kg	R$ 25,00
Tube Schedule 3” 2m in length	2	11,2 kg	R$ 30,00
Rolled Steel Pulley 2” U-Channel 3/8” with Bearing	4	330 g	R$ 24,00
Coated Steel Cable 1/8” 2.8m in length	2	100 g	R$ 10,00
Shock Absorber	2	1,1 kg	R$ 100,00
Clamps	4	3 g	R$ 4,00
Pulley Handle	1	1 kg	R$ 60,00
Triangle Handle	1	1 kg	R$ 60,00
Bench	1	~	~
TOTAL		34,1 kg	R$ 537,00

4.1. Data Acquisition

4.1.1. Necessary Force

Using concepts from Physics, it is possible to calculate the minimum force for a person weighing 70kg to lift their own weight on the equipment. Next, Figure 1 displays the free-body diagram.

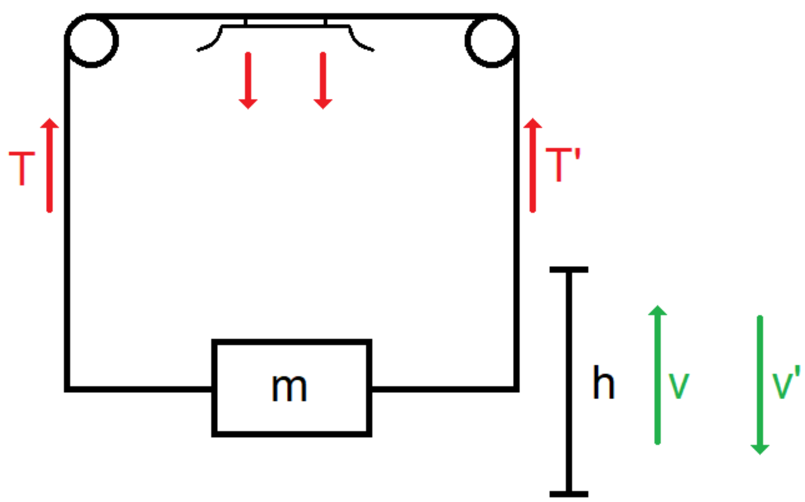


Figure 1 – Free-body diagram.

DOI: 10.31695/IJASRE.2023.9.12.1

Where T is the cable tension, m is the body mass, h is the displacement, and v is the speed at which the cables are pulled. Considering that the exercises will be done in an ideal scenario, the speed v will be given as a constant since $v = v'$, and they cancel each other out during the calculation. Next, Figure 2 displays the Cartesian plane of the free-body diagram.

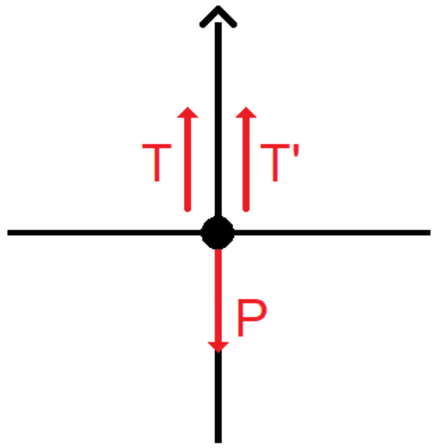


Figure 2 – Cartesian plane.

Where T is the rope tension, P is the body mass, and g is the acceleration due to gravity. Thus $\sum F_y = 0$, since $T + T' = P$, and the two forces balance each other. To determine the work done by these forces, we need to make the following relation:

$$W = \int F\, dh \qquad W' = \int F\, dh$$

$$W = Fh \qquad W' = F'h$$

$$W = Th \qquad W' = T'h$$

$$W = W' = (T + T')h$$

$$W = mgh$$

Resulting in the equation for gravitational potential energy. This time, let's take m as the mass of the user's body – in this example, it will be 70kg – and add the weight of the metal bar below the bench, then multiply by the acceleration due to gravity, at a displacement of 60cm. The resulting value is:

$$W = 76{,}075 \times 9{,}8 \times 0{,}6$$

$$W = 447{,}321 \text{ J}$$

Therefore, the work to perform a lift is around 447.321 J. As an alternative for beginners, a movable pulley can be added. This pulley will halve the necessary force, making the calculations and leveraging the same previous example. The resulting value is:

DOI: 10.31695/IJASRE.2023.9.12.1

$$W = \frac{76{,}075}{2^1} \times 9{,}8 \times 0{,}45$$

$$W = 167{,}745\ \mathrm{J}$$

Where the mass will be divided by 2 raised to the number of movable pulleys, and in the displacement, it will be necessary to pull twice as much as before. Thus, the bench will have a displacement of 15cm, and the bar 30cm, resulting in a total displacement of 45cm, and therefore a work of 167.745 J in a single lift.

4.2. Project Structure

Following in Figure 3, it displays the 3D sketch of the project, unifying the structures that will be mentioned below.

Figure 3 – 3D Project.

4.2.1. Bench Structure

The structure is designed in a unified manner, coupling the bench to a metal bar connected to two cylinders attached to the support structure – discussed in the next section. The bench's purpose is to provide support and stability to the body during exercise, prioritizing ergonomics and safety, especially to prevent wear and injuries to the back region. The bench materials can be metallic, considering an outdoor gym where there is more wear due to exposure to rain and sun. It can also be made with padding for greater comfort, but with lower resistance to natural elements.

The oblong metal bar aids in the dynamics of pull-up exercises, as the bars are connected by a steel cable, and pulling the upper one lifts the lower one. The ends of the bar are two cylinders that guide the bench upwards with the assistance of the upper bar. Their dimensions are:

- Height: 42cm;
- Diameter: 3.1/2 inches.

DOI: 10.31695/IJASRE.2023.9.12.1

There is also a solid internal bar in the center of the cylinders along the length of the tube diameter, which acts as a lock, supports, and guides the cylinders through the support structure.

The foot supports serve to provide stability during ascent, preventing excessive movement and aiming to achieve the best possible result. They are made of mild iron, welding one bar perpendicularly to another, forming a T shape, and finally securing it to the bench.

On this same bar, there will be a movable pulley at each end, which will function to reduce the applied force. Figure 4 shows the structure of the bench.

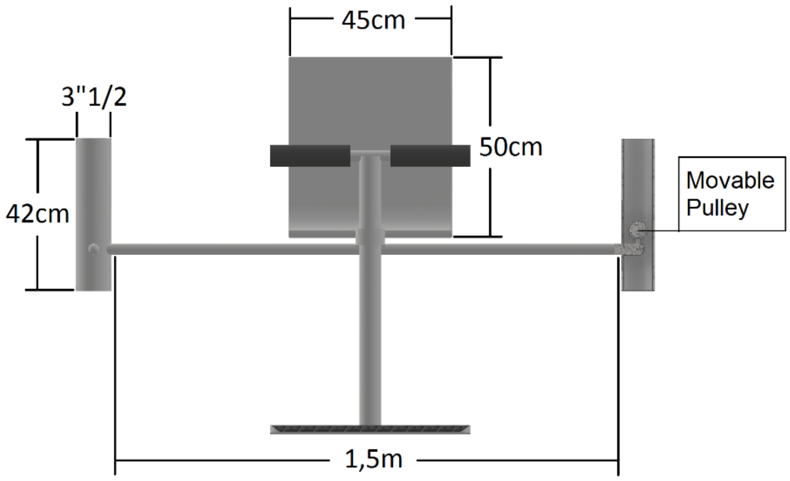


Figure 4 – Structure of the bench.

4.2.2 Support Structure

As the name suggests, its function is to support the entire structure and assist in the dynamics of the bars. It is assembled with metal tubes and is installed inside the bench system.

The dimensions of the tubes are:

- Height: 2m
- Diameter: 3 inches

The cuts are:

- Two cuts of 45 x 3cm at a height of 70cm (from the ground)
- Two cuts of 30 x 3cm at a height of 160cm (from the ground)

The cuts at the top are to lower the bar during the pull-up, providing stability in the movement and enhancing the aesthetic of the apparatus. A steel cable passes through the structure, and these cuts serve as the entry point for the cable.

The cuts at the bottom, on the other hand, cause the bench structure to rise when pulling the upper bar. The total displacement is 60cm – a value determined through measurements taken in the gym with a similar device. This measurement is obtained by measuring the arm fully extended upwards until the arm is in line with the chest, maintaining the elbow angle without changing and bringing them close to the chest – 30cm above and 30cm below. From a frontal view, the cuts on the left tube face to the right, and on the right tube, the cuts face to the left.

DOI: 10.31695/IJASRE.2023.9.12.1

In each of the support tubes, there is also a pulley attached inside through welding on each side. The pulleys serve to provide greater smoothness to the exercises, allowing the steel cable to be worked more smoothly. Additionally, there is a damping spring inside each tube to reduce the impact of collision in case of injury or exhaustion during exercises. Next, Figure 5 displays the support structure.

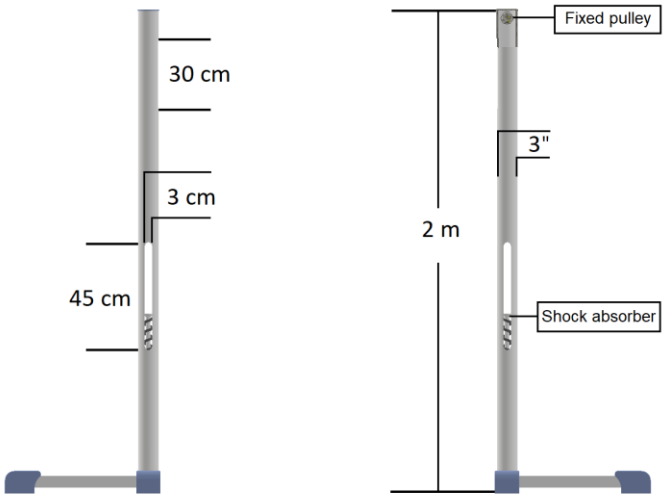


Figure 5 – Support Structure.

4.2.2. Bars and Their Structures

The auxiliary bar, located at the top and measuring 150cm, is used to provide greater stability in pulling the other bars and handles. It is positioned within the support structure so that when pulling the bars, they move uniformly without varying the angle. Without the auxiliary bar, the pull-up could have a higher number of errors, as it would be in a free position. Figure 6 below shows the auxiliary bar.

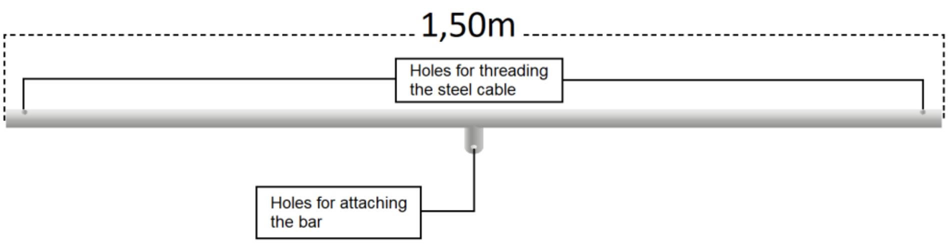


Figure 6 – Auxiliary Bar.

The bars designed for the exercises described in section 2 are:

- Pulley Bar Puller – a 1/14 hollow tube made of carbon steel with a length of 90cm and a thickness that is comfortable to the hand.

DOI: 10.31695/IJASRE.2023.9.12.1

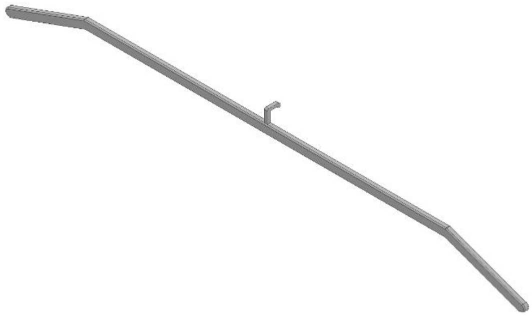


Figure 7 – Pulley Bar Puller.

- Triangle Puller – made of carbon steel with dimensions of 21.5 x 17.5 x 19.5 cm.

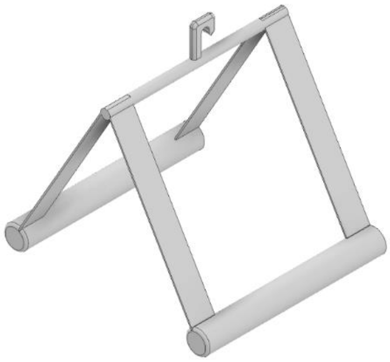


Figure 8 – Triangle Puller.

5. RESULT AND DISCUSSION

5.1. Caloric Expenditure

For pull-up exercises, one must consider the user's body mass added to the mass of the bench structure, as seen in the previous sections. The gravitational potential energy is given by:

$$W = mgh$$

As an example, let's assume the individual's mass is 70kg. Therefore, the energy expended by the individual is:

$$W = 447{,}321 \text{ J}$$

Converting Joules to calories, we have:

$$W = {}^{447{,}321}/_{4{,}184} = 106{,}91 \text{ cal}$$

This calculation considers only the ascent. In weightlifting, it is ideal for the times and speeds of ascent and descent to be equal. In other words, one repetition of the exercise has a caloric expenditure of 213.82 calories, considering both the ascent and descent.

Applying this expenditure to a generic set of 4x12 in a gym, the caloric expenditure per pull-up exercise is around:

$$4 \times 12 \times 213{,}82 = 10{,}26 \text{ kcal}$$

Here, 4 is the number of sets, 12 is the number of repetitions, and 213.82 is the caloric expenditure in a single repetition.

Similarly, for the machine with movable pulleys, the caloric expenditure is calculated as follows:

DOI: 10.31695/IJASRE.2023.9.12.1

$$W = 167{,}745\ \mathrm{J}$$

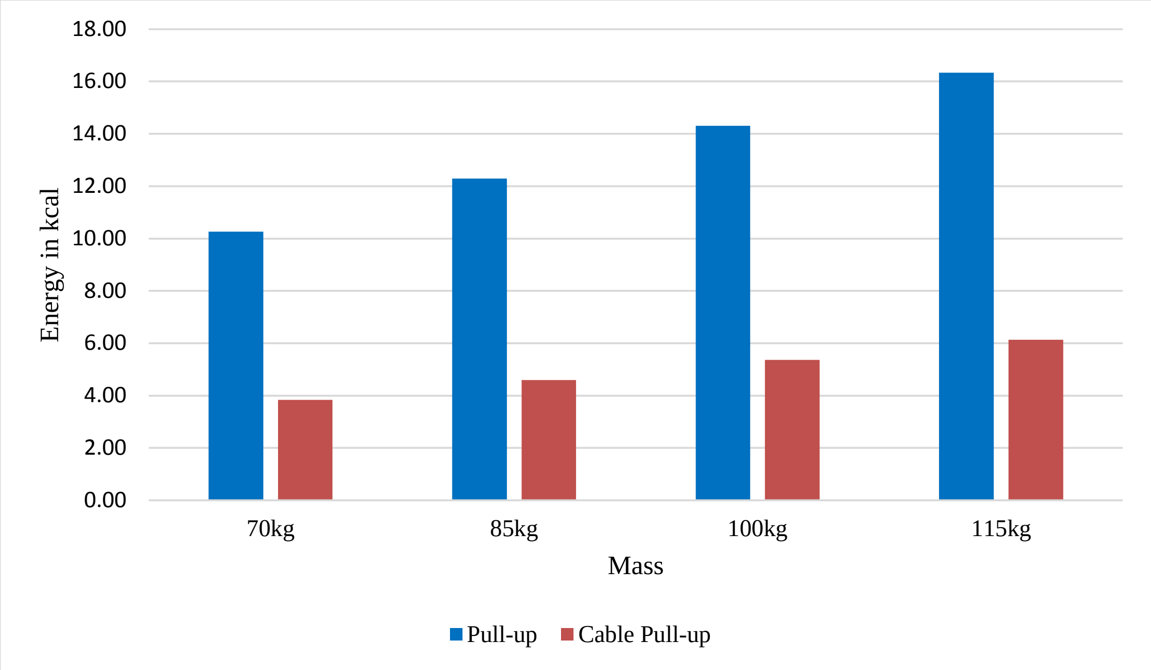
$$W = {}^{167{,}745}/_{4{,}184} \times 2 = 80{,}18\ \mathrm{cal}$$

$$4 \times 12 \times 80{,}18 = 3{,}84\ \mathrm{kcal}$$

Here, the total work done takes into account both the ascent and descent movements in the exercise.

5.2 Analysis in Graph

Below, Graph 1 displays the caloric expenditures in a series of exercises for individuals with different masses.



Graph 1 – Caloric Expenditure in a Series.

Applying the same principle as in section 5.1, calculations were performed to inform the user of the potential calories they could burn in a series of exercises. People with masses ranging from 70 to 115kg were used as a reference, providing an idea of how many calories the user will burn with or without movable pulleys.

5.2. Evaluation by a Biomechanics Specialist

When critically evaluating the pull-down machine, we received valuable contributions from Diego Moreira da Cunha Mata, a Physical Education professional specialized in biomechanics and posturology. He emphasizes that the machine's biomechanics are correct, providing an effective stimulus to the dorsal muscles and their auxiliaries. Careful analysis of the wrist positioning during the exercise highlights the machine's ability to offer more focused work in different areas of the dorsal muscles, adapting to the bar grip and individual needs.

A crucial point raised by Diego is the difference in weight used on the pull-down machine compared to the traditional one. He points out that by using body weight as the sole load, the machine provides more concentrated and consistent

DOI: 10.31695/IJASRE.2023.9.12.1

work, eliminating the instability often associated with excess weight in traditional pull-downs. This approach, according to Diego, results in a more controlled execution and more precise activation of the target muscles.

From the perspective of an experienced biomechanics professional, Diego categorically states that this project has solid foundations and arguments in its composition, thus validating the adopted approach. This validation by an expert reinforces the effectiveness of the pull-down machine as a valuable tool for muscular development and maintaining correct posture during exercise.

6. CONCLUSION

The current project utilizes mechanical and gravitational potential energy, making it possible to deduce the acting forces and the force that the user must apply to perform the exercises. Thus, the energy expenditure is associated with force. Although some exercises are limited to certain individuals, as the project is restricted to people who can lift their own body weight or half of it, simulations incorporating different masses in various types of exercises and adaptable materials show that the device is versatile. It can be used in both outdoor and indoor settings.

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DOI: 10.31695/IJASRE.2023.9.12.1