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Vertical Load Lifting System Desing for Ergonomic Safety in Civil Construction

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ABSTRACT

As is well known, the handling of heavy loads is a constant in the construction industry and is one of the main risk factors for workers in this sector. This article presents the design of an industrial winch-type vertical load-lifting system to mitigate ergonomic risks in civil construction, using applied and experimental research with a quantitative approach through the DICREA methodology (Develop, Integrate, Construct, Reorganize, Elaborate, and Adapt). Furthermore, using Finite Element Analysis (FEA) in SolidWorks © software, a von Mises stress of 130 MPa was obtained; these results were compared with the data from the structural analysis report, which showed a maximum stress of 127.3 MPa. Furthermore, the scale prototype produced via 3D printing demonstrates the proper mechanical operation of the vertical load-lifting system, which was validated through a controlled load test. Finally, the results obtained demonstrate the design's feasibility from both a technical and operational standpoint; however, the calculated safety factors are higher than expected, so the use of different materials for each component is recommended. Despite this change, the design can perform its function and withstanding the maximum load specified. This design merges mechanical engineering with ergonomics and safety principles, system significantly aids construction workers, reducing health and safety risks by preventing potential accidents and injuries.

KEY WORDS: Civil construction, Ergonomics, Finite Element Analysis, Occupational health, Vertical lifting system.

INTRODUCTION

As is well known, the construction industry has a significant impact on economic and social development. This is due to its crucial role in creating the infrastructure necessary to meet the population's needs, such as housing. However, the main activities in this sector continue to be carried out manually, especially on construction sites that lack the resources to implement the use of large, specialized safety equipment, which puts the health and safety of workers at small- and medium-scale construction sites at risk.

Similarly, among the main construction activities that require the greatest physical effort are the constant transport of materials between different levels, manual handling of loads, and maintaining awkward postures. According to Chango, P. (2023), handling loads weighing more than 30 kg increases the likelihood of developing low back pain by up to 6.23 times; this is the most common musculoskeletal disorder among construction workers exposed to activities involving heavy physical labor.

In addition to the foregoing, injuries result from inflammatory or degenerative conditions affecting the muscles, joints, ligaments, nerves, and tendons, which are most commonly located in the lower back or lumbar spine (Chango, P., 2023). Consequently, manual material handling remains a significant issue in the construction industry, as it compromises the safety and, above all, the health of

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workers while they are performing their duties on-site.

Because this is not an isolated problem, various researchers have focused on studying and solving it. One such example is Barahona, who undertook the development of a cargo-lifting system for the industrial sector; by preparing a technical report, he designed the system and adapted it to address the specific challenges faced by a particular company.

According to Barahona, D. (2019), the final system exhibited optimal dynamic performance during the lifting and lowering of materials. Meanwhile, Gavillanes, F. (2014) designed and built a manual vertical stacker-type lift with a maximum load capacity of 300 kg; according to his research, the system he built is 65.10% less expensive than commercial alternatives.

Similarly, in Ecuador, a portable lift was designed using a winch and pulley system. Through a qualitative and applied approach, a three-dimensional model of the system was developed, and the mechanical forces, bending moments, and deflection were subsequently analyzed using simulations; as a result, Jiménez, J. (2023), asserts that implementing this design reduces the number of operators required to just two, instead of the 5 to 8 that would typically be needed.

However, in the article titled “Improved FMEA Risk Assessment Based on Load Sharing and Its Application to a Magnetic Lifting System,” in which an optimized Failure Mode and Effects Analysis (FMEA) method was applied to an industrial magnetic crane with movable pole faces; after conducting an analysis, Chang, C. (2025) mentions the identification of 12 major failure modes distributed across the transmission mechanism, magnetic system, and pole face, demonstrating that such an analysis is necessary to account for potential failures in this type of machinery.

Finally, Rodríguez, Y., in his article “Manual Load Handling as an Ergonomic Risk Factor for Lower Back Disorders in Construction,” states that 43% of construction workers believe they perform activities that increase their risk of musculoskeletal injuries due to the non-ergonomic postures, and they associate this with the physical exertion required to handle very heavy loads (Rodríguez, Y. (2021), which is why efforts are being made to address this issue.

In this context, the premise put forward by Muñoz, L. (2025)—who argues that proposing the use of ergonomic machines and tools in construction minimizes biomechanical risks for construction workers from an occupational health perspective— we have opted to use mechanical engineering to develop solutions that optimize the transport of construction materials without compromising the safety of those working on the job site.

Since occupational risks associated with handling heavy loads are directly related to the lack of adequate equipment, machinery, and tools to mitigate them, as noted by Rodríguez, Y. (2021), this project proposes the design of an industrial winch-type vertical load-lifting system for civil construction, through the application of mechanical engineering principles.

The proposal seeks to integrate criteria for structural strength, stability, and functionality, supported by the development of a calculation report and mechanical simulations, with the primary objective of validating its performance before implementing it in the construction industry, thereby strengthening occupational safety conditions by reducing employees’ exposure to excessive physical strain.

Therefore, the objective of this article is to design a portable, mechanically driven vertical load-lifting system. The goal is to optimize the transport of materials in civil construction, reduce the risk of injury, and ensure safety through the implementation of the DICREA methodology.

RESEARCH ELABORATIONS

In the construction industry, lower back injuries caused by poor posture when handling heavy loads are more common than they seem, according to the study by Gómez Salazar et al. (2025) titled “The Risk of Lifting Loads: Much More Than Biomechanics.” Tasks such as shoveling to fill a mixer and lifting bags of cement were found to pose a very high risk of musculoskeletal injury, especially to the spine and upper limbs.

In a similar study conducted by Chango P. (2023) which investigated musculoskeletal disorders of the lumbar spine in workers performing physical loading activities, low back pain was found to be the musculoskeletal disorder (MSD) with the highest incidence in the lumbar spine, occurring in 82% of workers exposed to physical loading activities. Meanwhile, physical exertion involving loads greater than 30 kg increases the likelihood of developing low back pain by up to 6.23 times.

State of art

A systematic literature review was conducted to prepare the study on art, following the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method. The data collection process was divided into four stages: identification, screening, eligibility, and inclusion, which are described below.

PRISMA methodology

First, scientific databases such as Scopus, Google Scholar, IEEExplore y Science direct were used for the initial search. Groups of keywords in English and Spanish were used, such as “folding crane construction,” “compact lifting system,” “manual transport of materials,” “folding crane construction,” and “small construction hoist 250 kg.”

Preliminary filters were then applied to narrow down the number of results. The exclusion criteria used were: articles not related to the civil construction sector, lifting systems intended for heavy industrial use, and documents published more than 10 years ago.

The documents that passed the initial screening were reviewed manually, examining their abstracts, methodology, and technical details. At this stage, articles on equipment that did not meet the portability requirement were eliminated, as were those mechanisms that did not provide relevant information regarding structural design or load assessment.

Finally, the documents that provide essential information for the project were selected; these will serve as a reference point to support the innovation and define the design criteria for the new mechanical lifting system.

Title	Objective	Methodology	Results	Reference
Musculoskeletal Disorders of the Lumbar Spine in	A Review of the Scientific Literature on Musculoskeletal Disorders	Qualitative literature review study using specific health descriptors in accordance	Low back pain stood out as the musculoskeletal disorder (MSD) with the highest	Chango P. (2023)

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Workers Who Perform Physical Lifting Tasks.	in Workers Exposed to Constant Loads.	with the PRISMA guidelines.	incidence among workers exposed to physically demanding tasks.	
Occupational Risk Assessment for Heavy Lifting Amon Laborer.	Assess ergonomic risks and their impact on the development of musculoskeletal disorders caused by handling heavy loads.	A descriptive study with a non-experimental design, using a correlational approach, and a cross-sectional design.	53% of blue-collar workers have never received any training or instruction in ergonomic risk prevention.	Gordillo Montero, J.(2024).
Analysis for Dynamic Characteristics in Load lifting system of the Crane.	Establish a three-dimensional dynamic model for a crane's load-lifting system. Compare the results among different lifting systems.	Dynamic Modeling and Numerical Simulation Using C Programming Language Code.	Advanced cranes with variable-frequency control performed better in the dynamic analysis.	Hanjun P. (2010)
Manual Handling of Loads as an Ergonomic Risk Factor for Lower Back Disorders in the Construction Industry	Analyze the ergonomic risks associated with manual handling of loads for construction workers.	This was an observational, descriptive, quantitative, non-experimental, cross-sectional study in which structured surveys were used.	57% of workers feel that companies pay little attention to how cargo is handled, since they only take action in the event of serious accidents.	Rodríguez Y. (2021)
Control of the beam pendulum dynamics in a tower crane with a slender boom carrying a distributed-mass load.	Development of a dynamic model of a tower crane that rotates a slender boom and moves a load with distributed mass.	The effects related to boom deflection, load oscillation, and load torsion are studied. Validated through numerous experiments	An equation is presented to predict the frequencies of the coupled system. In addition, a hybrid piecewise smoothing filter is proposed to filter out the oscillations.	J. Ye y J. Huang, (2023)
Ergonomic risk assessment in construction: Case study Ecuador	To standardize the ergonomic risks to which construction workers are exposed, by determining the level of ergonomic risk and the level of preventive action.	Using a probabilistic method based on the repeatability index, the five most frequent cases were selected to evaluate a total of 94 workers.	The construction industry is one of the most dangerous sectors, especially because of the awkward working positions that workers assume while performing various tasks.	Tandazo Oswaldo, et al. (2025)
Optimal trajectory generation for reducing structural stress in rotary cranes with multiaxial motion.	The goal is to eliminate load sway and mitigate dynamic structural stress in order to extend the equipment's service life.	It proposes a mathematical model for kinematic calculations and finite element analysis (FEA) in LS-DYNA, supported by experimental tests.	The three-stage design reduced the maximum structural stress on the boom, resulting in a 2.7-fold increase in mechanical service life against structural fatigue.	Kudara, K., et al. (2026)

Table 1) State of art

(Source: compiled by the author)

Methodology

This research is experimental and applied in nature, with a quantitative approach, as it seeks to design, analyze, and validate a system for transporting materials at small- and medium-scale construction sites.

The research is structured into several stages, including problem identification, information collection and analysis, definition of design requirements, proposal development, preparation of the calculation report, validation through simulations, construction of a scale model, and analysis of the results obtained.

To organize the project's development, the DICREA Methodology is proposed, which is based on action verbs related to the "Create" level of Bloom's taxonomy.

Develop the proposal, Integrate the system components, Build the prototype, Revise the design, Develop the improved proposal, Adapt the system for the next phases, Adapt the system for the next phases.

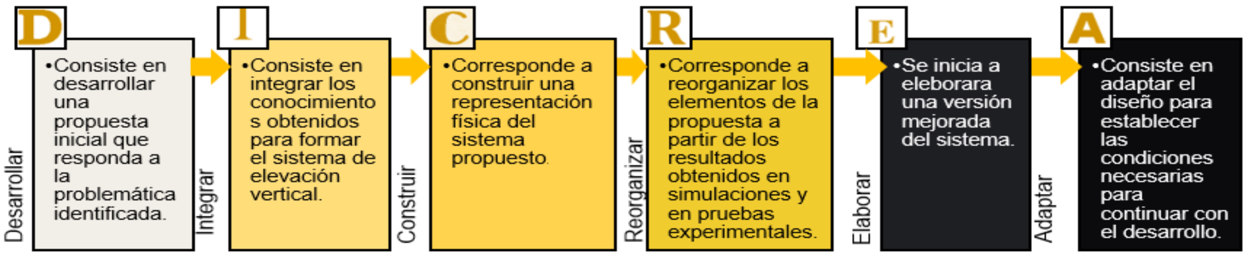

Figure 1) DICREA Methodology

(Source: compiled by the author)

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The first stage consists of designing an initial proposal that addresses the identified problem. The second stage consists of integrating the knowledge gained during the literature review, the defined requirements, and the components necessary to build the lifting system.

The third stage involves building a physical model of the proposed system. Once the prototype is built, the elements of the proposal are reorganized based on the results obtained from simulations and experimental tests.

In the fifth stage, work begins on developing an improved version of the system, incorporating the corrections identified during the simulations and prototype testing. The final stage consists of adapting the design from the first phase to establish the necessary conditions for continuing the for continuing the research.

SolidWorks software was used to develop the simulation because it allows users to create engineering drawings and perform simulations using Finite Element Analysis (FEA). This program employs various meshing tools and calculates how each element reacts to applied forces, making it possible to test a design's strength before it is manufactured, according to Dassault Systèmes SOLIDWORKS Corp. (n.d.)

Identification of the need

The construction industry requires the constant transport of materials between different levels of a job site. In small- and medium-scale construction projects, this work continues to be performed primarily by hand using ladders, scaffolding, or makeshift mechanisms with pulleys and hoists.

Manual handling of loads requires considerable physical effort and the adoption of awkward postures, which increases the likelihood of developing musculoskeletal disorders, especially injuries to the lower back. Furthermore, transporting materials to upper levels increases safety risks due to the potential of accidents related to lifting operations.

Consequently, the manual lifting of materials remains an issue in the construction industry, as it jeopardizes workers' safety and health while they are performing their duties on-site.

User Requirements

Among the user needs to be taken into account are: portability, since construction workers typically have to travel to different job sites; the design must be able to be easily moved over considerable distances.

In addition, the system must be easy for users to install and operate; in many cases, these users lack technical training or formal instruction. Therefore, the presented design is highly intuitive, and it requires no specialized knowledge simply reading the user manual is sufficient to begin operations.

The main factor to consider is market price; the design must be affordable for those working on small- and medium-sized construction projects, where budgets are often limited. Compared to existing market options, industrial cranes are much more robust but also quite expensive. The main competing option is hoists, however, these devices rely directly on the use of counterweights and a beam or structure to which they can be attached; likewise, their cost is lower, as is their load capacity.

Another factor to consider is the system's resistance to exposure to corrosive environments; therefore, the design incorporates corrosion-resistant materials to extend the equipment's service life.

CTQs represent the quality attributes that must meet customer expectations and ensure product conformance, while CTFs correspond to the functional characteristics that are essential for ensuring the proper operation of the system.

No.	CTQ	Descriptions
1	Weld Beads	A continuous weld with no visible defects.
2	Surface finish	No burrs or sharp edges.
3	Corrosion Protection	Uniform paint finish, free of flaking, and corrosion-resistant.
4	Assembly Quality	All parts are properly aligned and adjusted.
5	Equipment Identification	Safety labels, load capacity, and manufacturer information must be visible and legible.
6	Operational Ergonomics	Design of the crank, drive mechanisms, and operating elements that allow for comfortable, safe operation with as little physical effort as possible on the part of the operator.

Table 2) Table of CTQ

(Source: compiled by the author)

Functional Analysis

Defining the CTQs and CTFs made it possible to establish the critical characteristics that must be controlled during the design and manufacture of the vertical cargo lifting system. These criteria facilitate verification of the equipment's compliance with quality and functionality requirements.

No.	CTF	Descriptions
1	Shaft diameter	It withstands the operating torque.
2	Gear module	Compatible with other gears in the system.
3	Number of teeth	Maintains the designed gear ratio
4	Pulleys' Diameter	It ensures proper cable routing.
5	Drum diameter	Uniform cable winding.
6	Cable diameter	Sufficient capacity for the load.
7	Crank length	It provides the required torque.
8	Plate Thickness	Adequate structural strength.
9	Arm length	Lifting range set.
10	Bearing Position	Smooth rotation of the shaft.
11	Wheelbase	Proper transmission gear engagement.
12	Jib Position	Prevents the load from sliding backward.
13	Base Height	Ensures the stability of the equipment.
14	Maximum load capacity	Value indicated on the equipment's blueprint and nameplate.

Table 3) Table of CTF

(Source: compiled by the author)

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Quality Function Deployment

QFD (Quality Function Deployment) is a planning methodology. Its main objective is to identify customer/user needs in order to establish the technical requirements for a product; these specifications must be measurable for the creation or improvement of products.

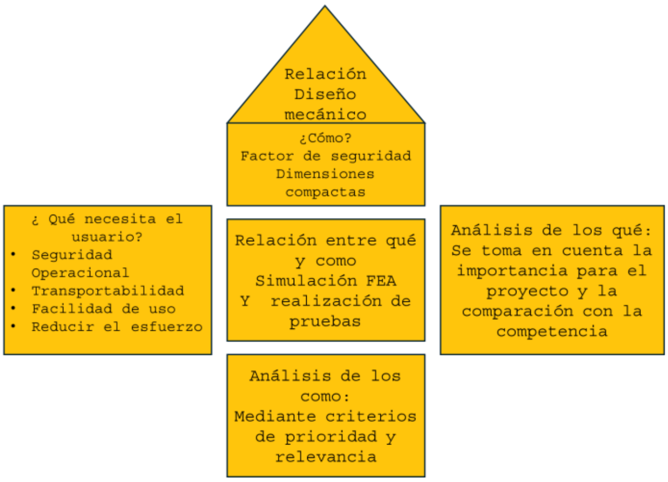

Figure 2) QFD

(Source: compiled by the author)

In order to understand the perceptions and actual needs of construction workers, we decided to develop a survey focused on materials handling at small- and medium-scale construction sites. This survey allows us to gather information on the main challenges, risks, and opportunities for improvement associated with this work.

The questionnaire was created with a quantitative and descriptive approach and was designed using Google Forms to reduce the time spent processing the collected data; it was administered exclusively to workers in the construction sector.

The study population consists of the 121,445 workers in the construction sector in the state of Hidalgo. INEGI (2023). The mathematical formula used to calculate the sample size is presented below:

$$n = \frac{121445 \cdot 1.96^2 \cdot 0.5 \cdot 0.5}{0.05^2(121445 - 1) + 1.96^2 \cdot 0.5 \cdot 0.5} = 383$$

This population was stratified according to the type of construction in the study area, in a statistical sample of 32 workers from the state of Hidalgo.

$$n_h = \frac{383}{12} = 31.91 \approx 32$$

After performing the stratification, a total sample of 32 completed surveys was obtained to determine whether the issue in question has a greater impact on the construction sector.

The results of the surveys are shown below.

The results of the survey showed that excessive physical exertion is the main problem, accounting for 77% of the responses, followed by low productivity at 19%. Together, these two issues account for 96% of the problems identified, which justifies the development of a folding crane to reduce workers' physical exertion and improve the efficiency of material handling on the construction site.

Figure 3) Question 4 of the survey

(Source: Google Forms)

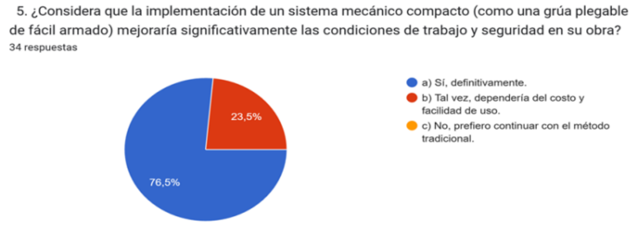

Figure 4) Question 4 of the survey

(Source: Google Forms)

Ishikawa diagram The Ishikawa diagram is a tool used to identify and solve quality problems by pinpointing the causes of a given problem; it is a highly versatile diagram that can be applied to any type of problem or area.

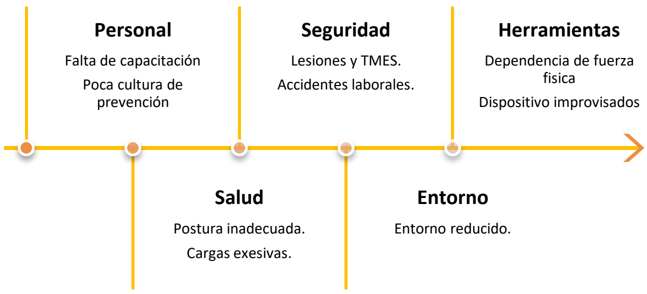

Figure 5) Ishikawa diagram

(Source: compiled by the author)

Problem tree

The problem tree is an analytical tool used to identify and graphically represent the central issue of a project, as well as the cause-and-effect relationships that give rise to it and its consequences. The following figure shows the problem tree.

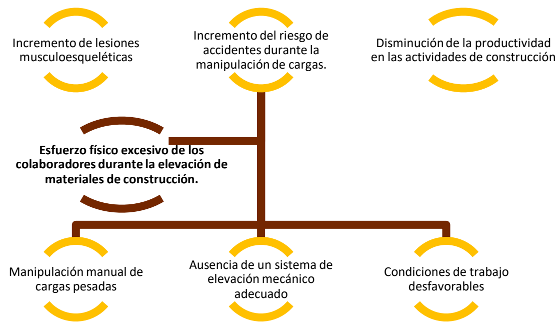

Figure 6) Problem tree

(Source: compiled by the author)

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Conceptual design

Benchmarking is a technique that involves comparing an organization's processes, products, and results with those of other companies or products in the industry. Its main objective is to identify opportunities for improvement through the analysis of best practices. (BBVA, 2026).

Benchmarking was used to compare various products currently on the market with the product to be developed in this project.

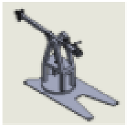
Safety	Capacity and Performance	Design and Functionality	Maintenance and Operating Costs	Image
Electromagnetic brake	Capacity: 1,000 kg at appropriate speed	Compact and easy to install; requires electricity	Simple maintenance; periodic inspection.	 *1-Ton Hoist, 1.6 Control Panel, Pulley-Type Hook. Source: Google Images*
Automatic braking system and overload protection.	High load capacity and excellent reliability in continuous use.	Robust industrial design, but not very portable.	Low maintenance, high cost.	 *CPV-F / VEGO: Source: Google Images*
ASTM A36 steel structure, mechanical braking system, load stability guide, and high safety factors.	Designed to meet the needs of small and medium-sized construction projects, optimizing vertical lifting.	Dismountable structure, easy transport, quick installation, and design optimized for tight spaces.	Easy-to-replace commercial components, simple preventive maintenance, and lower operating costs.	 *CAD design created in SolidWorks. Source: Created by the author*

Table 4) Benchmarking

(Source: compiled by the author)

Selection of Design Alternatives

To determine the appropriate operating mechanism for the vertical lifting system, three design alternatives were evaluated based on load capacity (250 kg), portability, transmission mechanism, cost, and ease of operation on small- and medium-scale construction sites.

Alternative A consists of a manual chain hoist with a rigid carbon steel frame; Alternative B features a mechanical hand-crank winch with spur gear transmission, a lightweight tubular structure, and a ratchet brake; while Alternative C proposes a winch with a single-phase electric motor and an aluminum chassis.

Criteria	Option A (Chain Hoist)	Option B (Mechanical Hand-Crank Winch)	Option C (Single-Phase Electric Winch)
Drive System	Manual, via endless chain	Manual, via crank and gears	Electric (Single-phase)
Portability and Weight	Low (Heavy frame)	High (Not too heavy and equipped with wheels for transport)	Medium (Depends on the power source)
Safety Mechanism	Integrated friction brake	Ratchet and locking system	Electromagnetic brake
Energy Dependence	Mechanical (No electricity or fuel)	Mechanical (No electricity or fuel)	Requires an electrical connection
Cost	Moderate	Accessible	High

Table 5) Table of Alternatives

(Source: compiled by the author)

The final selection was Alternative B: the manual mechanical winch with gear transmission and a folding frame. This decision directly addresses the need for equipment that is 100% mechanical and independent of electrical power sources, ensuring its operability at any location on the job site without increasing supply costs. Furthermore, its light weight and foldable design allow for optimal portability in confined spaces.

Furthermore, the incorporation of a gear-driven transmission system combined with an automatic locking mechanism provides precise control over the physical effort required by the operator and maximizes safety when hoisting the 250 kg load to a height of 20 meters. Its structural rigidity and the feasibility of manufacturing it using commercially available components establish Alternative B as the most viable and cost-effective option.

Alternative Selection Matrix

Rating: 1 = Poor, 3 = Acceptable, 5 = Very Good.

Evaluation Criteria	Option A (Chain Hoist)	Option B (Mechanical Winch)	Option C (Electric Winch)
Portability and Ergonomics	2	5	3
Energy Independence	5	5	1
Operational Safety	4	5	4
Manufacturing Costs and Access	3	5	2
Ease of Maintenance	3	4	2
TOTAL SCORE	17	24	12
Result	Rejected	Selected	Rejected

Table 5) Table of Alternatives

(Source: compiled by the author)

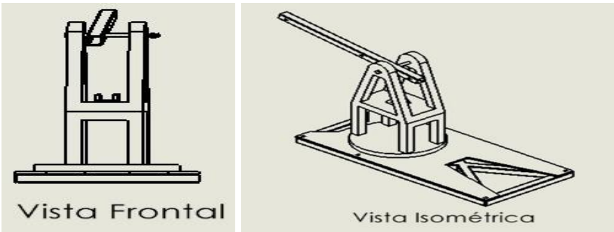


Figure 7) System views

(Source: compiled by the author)

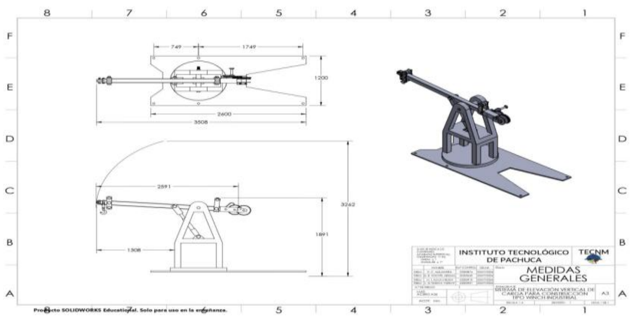


Figure 7) General Measures

(Source: compiled by the author)

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The bill of materials (BOM) is a tool used to identify and organize the components that make up the vertical cargo lifting system. The following is the bill of materials for the designed model.

No.	Part name	Description	Quantity
1	Base Frame	The mechanism's main support structure.	1
2	Base Plate	Mounting base for the assembly.	1
3	Boom Crane	Sliding bar for transmitting motion.	1
4	Jib Bolt	Eje de articulación de la pluma.	1
5	Boom Nut	Fastener for the boom bolt.	1
6	Gears A1, A2, A3	Main drive, driver, and driven gears.	5
7	Axle Leveler	Axle Leveler	2
8	Pulleys 1 and 2	Pulleys for primary and secondary power transmission.	5
9	Hook	Support or clamping bracket.	1
10	Connectors 1, 2, and 3	Mechanical coupling and joining elements.	5
11	Gears 3 and 4	Transmission intermediate and output gears.	4
12	Ratchet	One-way locking mechanism.	1
13	Claw	Lateral support for the mechanism.	1
14	Crank	Manual operation of the mechanism.	1
15	Boom Cylinder	Boom piston guide body.	1
16	Pulley Drum	Drum for winding the cable.	1
17	Piston rod	Sliding drive element.	1
18	Screws B18.2.3.6M, B18.2.3.6M, B18.2.3.6M, B18.2.4.5M	Hexagonal fastening screw.	11
19	B18.2.4.5M and B18.2.4.5M Nuts	Hexagonal fastening nut.	7

Table 5) List of Materials

(Source: compiled by the author)

Below is the assembly drawing created in SolidWorks, which allows each part to be identified by its corresponding number.

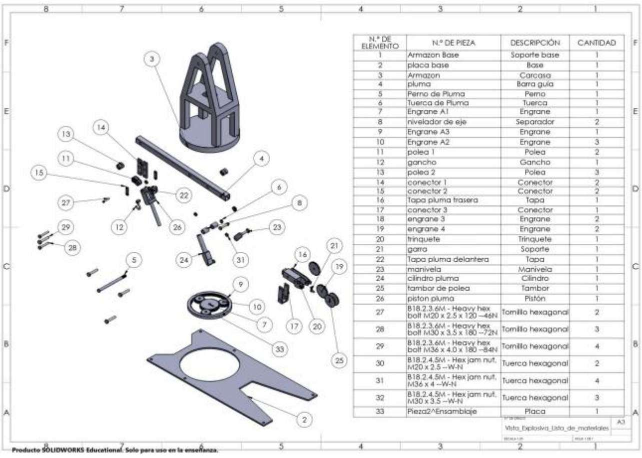

Figure 8) Bill of Materials, BOM

(Source: compiled by the author)

Engineering design

The material selected for the simulation model was ASTM A36 structural steel. This low-carbon steel was chosen for its tensile strength and yield strength ($S_y = 250\,MPa$), which provide an optimal strength-to-weight ratio for structural applications. Additionally, A36 exhibits excellent ductility, weldability, and machinability, allowing it to absorb cyclic loads and stress concentrations without experiencing sudden brittle failure. Its widespread availability, affordability, and reliability under severe operating conditions make it the standard choice for the manufacture of construction machinery and loading mechanisms (ASTM International, 2019).

Stability Analysis

Calculation of the Maximum Force (F_L)

$$F_L = m * g$$

$$F_L = 9.81\frac{m}{s^2} * 250\,kg = 2452.5\,N$$

Calculation of the Overturning Moment (M_V)

The overturning moment on the crane is caused by the suspended load multiplied by its perpendicular distance from the front wheel axis (fulcrum).

The lever arm of the load (d_L) relative to the front wheels is:

$$d_L = X_{carga} - X_{frenos}$$

$$d_L = 1.5\,m - 0.8\,m = 0.7\,m$$

Therefore, the overturning moment is:

$$M_V = F_L * d_L$$

$$M_V = 2452.5\,N * 0.7\,m = 1716.75\,Nm$$

Calculation of Required Resisting Moment (M_R)

For the crane to be stable, the Resisting Moment (M_R) generated by the weight of the rear structure and the counterweights must be greater than the Overturning Moment. In the design of lifting equipment, a minimum Overturning Safety Factor (FS_{vuelco}) of 1.5 is established.

$$M_R \geq M_V \cdot FS_{vuelco}$$

$$M_R \geq 1716.75\,Nm \cdot 1.5$$

$$M_R \geq 2575.1\,Nm$$

Sizing the Rear Counterweight (W_{cp})

To meet the calculated M_R, we will use a counterweight at the rear end. We will not include the weight of the mast's PTR profiles in the calculation to ensure a conservative estimate; in this way, we will rely entirely on the stability of the counterweight.

The sum of the distance from the mast to the front wheels plus the distance from the mast to the rear wheels is the lever arm of the counterweight (d_{cp}) relative to the front wheels.

$$d_{cp} = 0.8\,m + 0.7\,m$$

$$d_{cp} = 1.5\,m$$

The required force of the counterweight is:

$$F_{cp} = \frac{M_R}{d_{cp}}$$

$$F_{cp} = \frac{2575.1\,N \cdot m}{1.5\,m} = 1716.7\,N$$

To calculate the required kilograms, we convert the force to mass:

$$m_{cp} = \frac{1716.7\,N}{9.81\,m/s^2} \approx 175\,kg$$

Therefore, to ensure a safety factor of 1.5 against tipping when lifting the maximum rated load of 250 kg, approximately 175 kg of rear counterweight is required, which must be positioned at least 70 cm from the main mast.

Structural Safety Factor (Boom and Mast)

The main boom (the horizontal arm) of the crane acts as a cantilever beam supported by a mast pivot and a linear actuator. When subjected to a point load of 250 kg at its free end, this element will

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experience critical bending stresses. To ensure the correct selection of the structural profile—which guarantees that the chassis profile does not undergo plastic deformation—a safety factor of: has been selected.

$$FS = 3.0$$

Assuming a structural profile equivalent to that of the frame in order to maintain balance during manufacturing, a structural profile (($PTR\ 4" \times 4" \times 1/4"$) has been selected. The geometric and load parameters are:

- Elastic Section Modulus (Z)**:** $72{,}200\ mm^3$
- Wall thickness (t)**:** $6.35\ mm\ \left(\frac{1}{4}"\right)$
- Hinge bores: 4 $\emptyset 40\ mm$ (H7) bores distributed among the frame connection, actuator, and load hook.
- Material: A36 structural steel ($Sy = 250\ MPa$)
- Applied loads: Maximum payload of $250\ kg$ ($W \approx 2452.5N$) at the end, and an estimated actuator reaction force of $F_{max} = 9196.87\ N$

The crane frame (mast) acts as the main support structure, transferring loads from the actuator and the boom to the mobile base. Since this element is subjected to axial compressive loads, the analysis requires validation of critical buckling and a static analysis at the connection nodes.

A structural profile has been selected based on the dimensions in the manufacturing drawing and its properties. The structural profile is $PTR\ 3" \times 3" \times 1/4"$ made of A36 steel.

The geometric and load parameters are:

- Height of the main column ($\boldsymbol{L}$): $1700\ mm(1.7m)$
- Cross-sectional area of the PTR ($\boldsymbol{A}$)**:** $1550\ mm^2$
- Turning radius of the section (r): $35.7mm$
- Modulus of Elasticity of Steel (E)**:** $207\ GPa\ (207{,}000MPa)$
- Yield Strength (Sy)**:** $250\ MPa.$
- Estimated maximum compressive load (P_{max}): The worst-case scenario is considered, in which the mast absorbs the total reaction of the actuator plus the payload, with a conservative maximum estimate of $1700N$.

To determine whether the column behaves as a rigid body according to buckling theory, the first step is to calculate the actual slenderness ratio (S_r). Assuming an end condition constant $K = 1.0$ —which is the most conservative standard for bolted structures—we obtain the following result:

$$S_{r} = \frac{K \cdot L}{r} = \frac{1.0 \cdot 1700\ mm}{35.7\ mm} = 47.61$$

The next step is to calculate the transition slenderness ratio (C_c) for A36 steel in order to classify the column:

$$C_c = \sqrt{\frac{2\pi^2 E}{S_y}} = \sqrt{\frac{2\pi^2(207{,}000\ MPa)}{250\ MPa}} = 127.8$$

Since C_c is greater than ((127.8 > 47.61), the mast is classified as an intermediate column, which means it will fail due to creep rather than elastic instability.

To calculate the critical buckling load (P_{cr}) we will use J.B. Johnson's formula:

$$P_{cr} = A[S_y - \frac{S_{y^2}}{E4\pi 2} \cdot \frac{K \cdot L^2}{r}]$$

Substituting values:

$$P_{cr} = 1550[250 - \frac{(250)^2}{(207{,}000)4\pi 2}(47.61)^2]$$

$$P_{cr} = 360.6\ kN$$

The buckling safety factor (FS_p) is:

$$FS_p = \frac{P_{cr}}{P_{max}} = \frac{360.6\ kN}{11.7\ kN} = 30.8$$

The frame column is quite robust, meaning it would require more than 36 metric tons of force to cause it to buckle; this ensures the chassis's complete rigidity during civil engineering operations.

Main Pin (Shear and Crushing)

The boom pin serves as the main joint of the lifting system. The boom pin fully transmits the loads between the boom and the frame. Due to the nature of its kinematic function, this component is not subjected to axial stress; rather, it is subjected to surface contact pressures (crushing) and direct transverse shear forces.

Based on the manufacturing drawing, the following critical dimensions of the component are obtained:

- Smooth rod diameter (d): $40\ mm$
- Total rod length (L): $610.80\ mm$
- Equivalent material: A36 structural steel ($Sy = 250\ MPa, Sut = 400\ MPa$)
- Maximum applied force (F): $9196.87\ N$ (Maximum actuator load evaluated in Section 5.2.1, taken as the critical case for the pivot).

Steel cable (safety factor)

The pulley drum acts as a redirecting element for the hoisting cable, which means it changes the direction of the cable. The critical failure modes are wear due to contact pressure (radial pressure in the groove) and crushing stress on its own axis of rotation, since it is in direct contact with the steel cable under maximum tension.

In industrial machinery operating continuously (such as elevators), the ratio of the cable diameter to the pulley diameter (D/d_c) is typically greater than 20 to prevent bending fatigue in the steel wires.

That said, in this design, the ratio will be:

$$Ratio = \frac{D}{d_c} = \frac{18\ mm}{3\ mm} = 6.0$$

Although this ratio may seem unfavorable, it is entirely standard and justifiable for manual hoisting equipment, compact winches, or winches operating intermittently (i.e., at low speeds), where weight and space savings take precedence over the need for millions of cable life cycles. For this reason, it is recommended that the user manual specify a schedule for periodic visual inspection of the steel cable.

Simulations

To obtain a more comprehensive analysis of how the vertical load-lifting system operates, we chose to conduct a static finite element analysis in SolidWorks ©, in which we first verified the geometry of the assembly and assigned ASTM A36 steel to the structural

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components. The model utilized the material's mechanical properties—primarily the modulus of elasticity, Poisson's ratio, and yield strength—which are constants necessary for representing the stresses and strains present in the model.

Subsequently, the contact conditions between components were defined using rigid connections, assuming that the surfaces remain connected without separation or slippage; therefore, the base was designated as a fixed constraint to restrict displacement and rotation. Likewise, a vertical force of $2452.5N$ was applied to the load-transfer zone, directed downward to represent the mechanism's operating condition.

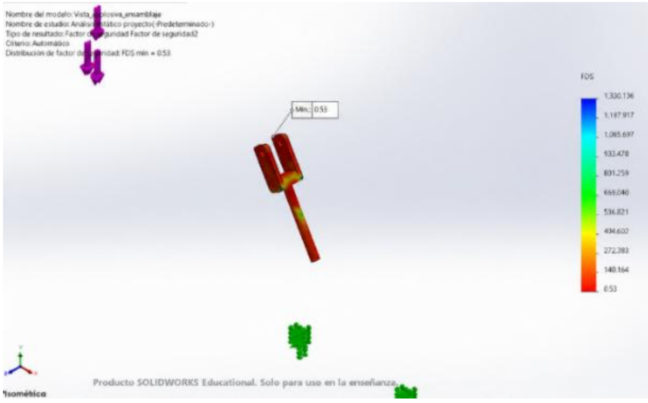

Figure 7) Simulation with analysis (FEA)

(Source: compiled by the author)

After establishing the boundary conditions, the model was divided into elements by generating a mesh, which made it possible to calculate the structural response in different regions of the model. The main variables evaluated were the equivalent von Mises stress—which is used to determine the loss of stiffness—the unit strain, and the safety factor, which is obtained from the ratio of the material's elastic limit to the calculated critical stress.

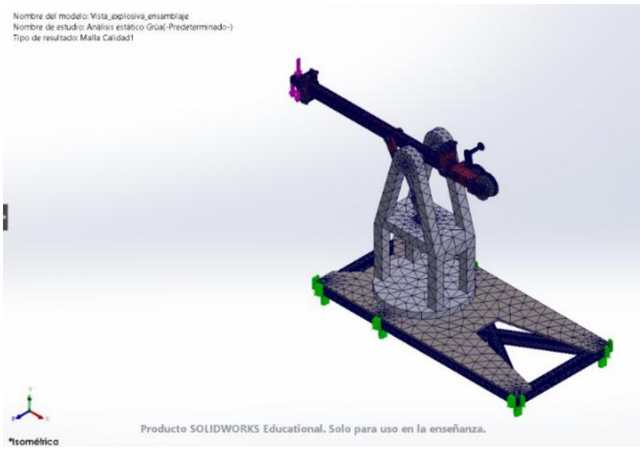

Figure 8) Generating a mesh

(Source: compiled by the author)

Finally, the simulation made it possible to establish the analysis conditions necessary to evaluate the structural behavior of the vertical load-lifting system. Defining the material, analysis constraints, loads, contacts, and mesh provides a technical basis for identifying the areas of highest stress, highest strain, and lowest safety factor.

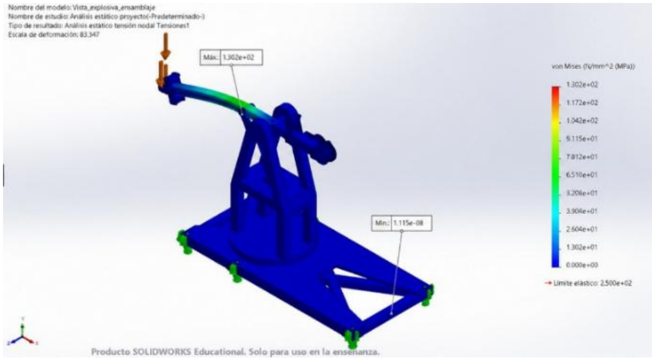

Figure 9) Full system simulation

(Source: compiled by the author)

Prototype manufacturing

Furthermore, for the production of the scale prototype of the model, the 3D printing method using PETG (polyethylene terephthalate glycol-modified) filament was chosen due to its mechanical properties; it has a flexural modulus of 2040 MPa according to the ISO 178 test method, a tensile strength of 53 MPa (test method: ISO 527-2), a tensile modulus of 3,000 MPa (test method: ISO 527-2), and a deflection under load of 8.6 mm (test method: ISO 178). Official Technical Data Sheet (TDS) for the PETG filament by IEMAI 3D. Characteristics that make it suitable for prototyping mechanisms subjected to impact, deflection, tensile loads, etc.

For the prototype construction process, we chose to print the components separately using this type of printer Bambulad A1.

Experimental validation

For experimental validation, it was decided to conduct a controlled load test on a full-scale prototype of the vertical load-lifting system; this type of test involves applying a known load gradually, uniformly, and without impact, in order to observe the mechanism's functional response under predetermined conditions.

During the test, the mass of the load, its equivalent weight calculated using the conventional formula F = mg, the vertical displacement achieved, and the presence of deformations, tilts, or abnormal movements were recorded. The test was conducted on a horizontal, rigid, and level surface at room temperature, ensuring that the load remained centered and controlled at all times.

The evaluation confirmed the prototype's ability to lift, support, and lower different loads vertically without visible deformations, tilts, or abnormalities. Due to the scale and the materials used, the results only demonstrate the functional validation of the mechanism; they do not provide a direct estimate of the structural capacity of the full-scale system.

Level	Load percentage	Applied mass	Applied weight
1	20%	0.070 kg	0.0071 N
2	40%	0.140 kg	0.0142 N
3	60%	0.210 kg	0.0214 N
4	80%	0.280 kg	0.0285 N
5	100%	0.350 kg	0.0356 N

Table 4) Controlled load test

(Source: compiled by the author)

Proposed innovation

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This research focuses on the design of a winch-type vertical cargo lifting system that is easily transportable and operates entirely mechanically, designed for small- and medium-scale construction sites where the use of heavy machinery is not feasible. This system replaces manual handling, thereby preventing physical overexertion and the development of lower back injuries. Its main competitive advantage lies in its ease of operation, which ensures worker safety at an affordable cost. This solution has been technically validated through engineering calculations and FEA simulations.

RESULTS AND CONCLUSIONS

Prototype Description

The vertical load-lifting system is a prototype designed to prevent lower back injuries in civil construction. Engineered for use in confined spaces, it features a mechanically driven, portable unit made from ASTM A36 steel for high strength and weldability. Key components include a machined spur gear train, transmission pulleys, and a safety ratchet mechanism for quick-action safety. The system can lift up to 250 kg to a height of 20 meters, utilizing mechanical advantage for controlled lifting. A modular design enables easy assembly and relocation, eliminating the need for welding and facilitating rapid on-site setup.

Figure 9) Full system

(Source: compiled by the author)

Parameter	Specification
Máximum load capacity	250 kg
Maximum lifting height	20 m
Structural material	ASTM A36 Steel
Drive system	Mechanical / Manual
Retention mechanism	Passive automatic-locking ratchet
Design innovation	Modular architecture for rapid on-site assembly without welding

Table 5) Parameter table

(Source: compiled by the author)

Experimental Results

To assess performance, static analysis was conducted using Finite Element Analysis (FEA) in SolidWorks. An external force of 2452.5 N was applied to the pulley, simulating a maximum load of 250 kg. The tests evaluated the ASTM A36 steel's mechanical behavior, revealing a maximum Von Mises stress of 130.2 MPa, located primarily at the joints between the boom and the transmission system, where the highest bending and shear loads are concentrated due to the transfer of the suspended load. This value represents the system's critical operating condition and constitutes the primary criterion for evaluating the material's mechanical behavior. When compared to the elastic limit of ASTM A36 steel (250 MPa), it can be seen that the maximum stress corresponds to approximately 52% of its strength capacity, indicating that the structure operates within the elastic range and that no permanent deformations are expected under the maximum design load of 250 kg. The assembly's deflection measured 3.18958 mm at the boom's end, indicating significant structural rigidity. The Factor of Safety (FoS) analysis showed the boom joint pin with a FoS of 27.607 and the drum with 8.457, while the retaining ratchet had a concerning FoS of 0.6371, signaling a need for redesign or treatment due to high stress concentration.

Evaluated variable	Maximum value obtained	Reference limit	Unit (SI)
Internal stress (Von Mises)	130.2	250 (Yield strength)	MPa
Static displacement (URES)	3.18958	-	mm

Table 6) Structural stress and deformation results

(Source: compiled by the author)

Analyzed component	Minimum recorded FoS	Integrity diagnosis
Main joint pin (FoS 3)	27.607	Optimal
Winding drum (FoS 1)	8.457	Optimal
Safety ratchet (FoS 2)	0.671	Critical / Requires redesign

Table 7) Factors of safety (FoS) analyzed by component

(Source: compiled by the author)

Graphical Analysis

To justify our engineering decisions, we developed graphs that illustrate stress trends and critical points. Our initial field research indicates that 77% of challenges in small-scale civil construction are linked to lower back injuries and physical exertion. This finding reinforces the necessity of designing the winch to minimize manual effort, supporting the implementation of our mechanical system.

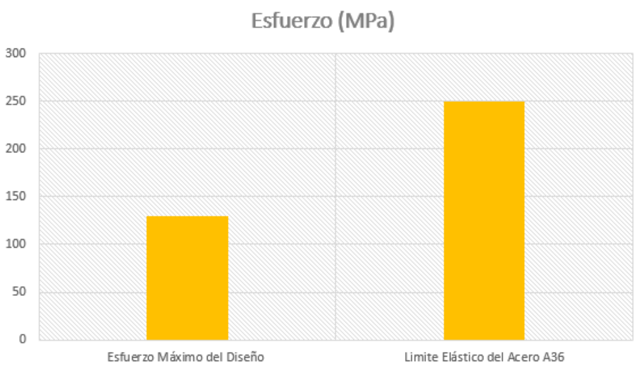

Figure 9) Comparison of maximum stress (Von Mises)

(Source: compiled by the author)

The bar chart illustrates the maximum stress of key assembly elements against a 250 MPa reference line. All components are well below the risk zone, with the highest stress at 130.2 MPa, indicating structural stability and no risk of plastic deformation.

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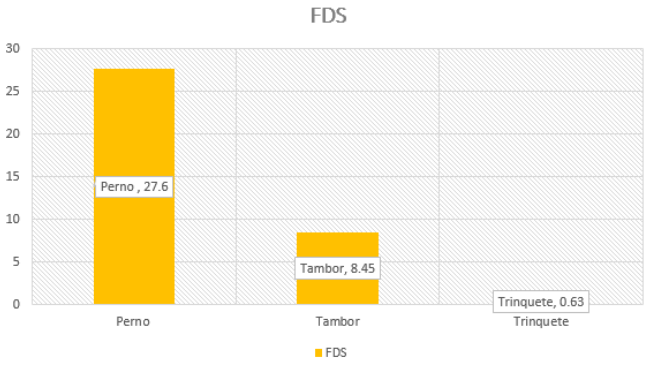

Figure 10) Factor of Safety (FoS) distribution

(Source: compiled by the author)

Discussion

The vertical lifting system is designed to reduce physical exertion on-site by lifting 250 kg with just 205 N of manual force using a gear train. This mechanical advantage, achieved without motors or hydraulic systems, makes it ideal for small- and medium-scale projects with limited energy resources.

Structurally, the critical von Mises stress (130.2 MPa) represents only 52% of the yield strength of ASTM A36 steel ($S_y = 250\,MPa$), confirming fully elastic behavior with no risk of permanent deformation. This validates the selection of A36 for its balance of strength, ductility, and weldability.

These findings are consistent with those of Jiménez and Ayala (2023) in their design of a 300-kg portable hoist, where prior simulation validated the mechanical behavior of the equipment. They also align with Barahona et al. (2019), who state that calculation reports and FEA modeling are essential for optimizing geometry and preventing operational failures in lifting equipment.

Compared to commercial alternatives identified through benchmarking, the design stands out for its portability, lower cost, and electrical autonomy. However, the analysis identified a limitation in the ratchet mechanism, which had a safety factor of 0.637—insufficient for dynamic loads. Future work will focus on its geometric redesign, the use of higher-strength materials, or surface heat treatments to ensure the reliability of the full-scale prototype.

CONCLUSION

The mechanism for the vertical load lifting system significantly aids construction workers, reducing health and safety risks by lessening the physical strain of transporting heavy materials, thus preventing potential accidents and injuries. This design merges mechanical engineering with ergonomics and safety principles for small to medium construction projects, emphasizing portability and reduced physical effort. Future work includes creating a functional prototype for testing and biomechanical assessments to validate the ergonomic effectiveness and lower musculoskeletal disorder risks.

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