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DISEÑO Y CONSTRUCCIÓN DE UNA ESCALERA DE SEGURIDAD INDUSTRIAL MANUAL DE PELDAÑOS PLANOS PARA REDUCIR LA FATIGA FÍSICA EN LA FUNDACIÓN ECOSUR - ECUADOR

DESIGN AND CONSTRUCTION OF A MANUAL INDUSTRIAL SAFETY LADDER WITH FLAT STEPS TO REDUCE PHYSICAL FATIGUE AT FUNDACIÓN ECOSUR - ECUADOR

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RESUMEN: El presente trabajo describe el diseño y construcción de una escalera de seguridad industrial manual de peldaños planos, desarrollada para el Departamento de Reconstrucción de Vivienda de la Fundación EcoSur - Ecuador, con sede en Riobamba, en el marco del "Proyecto de Mejoramiento de la Calidad de Vida de los Sectores más Vulnerables". El diseño tomó como referencia el modelo KENDO TOOLS, bajo los requisitos de la norma europea EN 131, integrando principios ergonómicos orientados a minimizar el estrés físico en piernas y espalda. Se priorizó el uso de materiales de larga vida útil y bajo peso, optimizando la movilidad, transporte y versatilidad en entornos de construcción, respetando los más altos estándares de calidad conforme al Control Estadístico 6 Sigma. La investigación se orientó a determinar cómo afecta el diseño y construcción de esta escalera en la reducción de la fatiga física y la mejora de la seguridad laboral dentro del sector de la construcción. Se establecieron tres objetivos específicos: diseñar la escalera mediante software CAD para determinar los parámetros geométricos más adecuados; construir el prototipo con base en el diseño CAD y una simulación tensodeformacional; y validar el producto mediante un análisis estadístico multivariado y un control de calidad 6 Sigma, con la elaboración de un manual técnico de uso y mantenimiento. La implementación de la escalera en los sitios de intervención de la Fundación EcoSur arrojó resultados altamente favorables, evidenciando mejoras en el bienestar general del trabajador, reducción del ausentismo por fatiga, incremento de la productividad y disminución de accidentes e incidentes laborales, tanto en Riobamba como en las demás localidades donde se desarrollan los proyectos en ejecución.

Palabras clave: ergonomía, seguridad industrial, peldaños planos, construcción, bienestar.

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ABSTRACT: This paper describes the design and construction of a manual flat-rung industrial safety ladder, developed for the Housing Reconstruction Department of the EcoSur - Ecuador Foundation, headquartered in Riobamba, within the framework of the "Project for Improving the Quality of Life of the Most Vulnerable Sectors." The design was based on the KENDO TOOLS model, following the requirements of European standard EN 131, and incorporated ergonomic principles aimed at minimizing physical stress on the legs and back. Priority was given to the use of long-lasting, lightweight materials, optimizing mobility, transportation, and versatility in construction environments, while meeting the highest quality standards in accordance with 6 Sigma Statistical Process Control. The research sought to determine how the design and construction of this ladder affects the reduction of physical fatigue and the improvement of occupational safety within the construction sector. The alternative hypothesis proposed that the use of the ladder significantly reduces physical fatigue among workers compared to a conventional ladder. To verify this, three specific objectives were established: to design the ladder using CAD software in order to determine the most suitable geometric parameters; to build the prototype based on the CAD design and a stress-strain simulation; and to validate the product through a multivariate statistical analysis and 6 Sigma quality control, along with the development of a technical manual for use and maintenance. The implementation of the ladder at EcoSur Foundation intervention sites yielded highly favorable results, evidencing improvements in workers' overall well-being, reduced absenteeism due to fatigue, increased productivity, and a decrease in occupational accidents and incidents, both in Riobamba and in the other localities where ongoing projects are being carried out.

Keywords: ergonomics, industrial safety, flat rungs, construction, well-being

INTRODUCTION

Industrial safety constitutes a technical discipline aimed at identifying, evaluating and controlling occupational risks with the purpose of preventing accidents and occupational diseases. Its historical evolution has moved from corrective approaches to systematic prevention models, supported by international reference organizations such as the International Labor Organization (ILO), the Occupational Safety and Health Administration (OSHA) and the International Organization for Standardization (ISO). Despite these advances, hundreds of thousands of deaths from workplace accidents are documented each year worldwide, a figure that highlights the persistent need for solid occupational health and safety management systems, particularly in high-risk sectors such as construction and housing reconstruction.

In the Ecuadorian context, safety and health at work is regulated by Executive Decree No. 255 of May 2, 2024, which strengthens the current regulatory framework together with the Labor Code, Decision 584 of the Andean Instrument for Safety and Health at Work, and the resolutions of the Ecuadorian Social Security Institute (IESS). This regulatory framework classifies occupational risks into six categories: physical, chemical, biological, safety, ergonomic and psychosocial. For its management, the ISO 45001 standard proposes a five-level hierarchy of controls that includes

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elimination, substitution, engineering controls, administrative controls and the use of personal protective equipment. However, the effective application of these principles in small-scale entities dedicated to social reconstruction remains limited.

Since 2007, the EcoSur - Ecuador Foundation, based in the city of Riobamba, has been developing projects aimed at improving the quality of housing in vulnerable sectors. The institution has a department specialized in housing reconstruction, made up of ten workers, whose work focuses on the structural and functional rehabilitation of homes to improve habitability conditions and social well-being. However, there is evidence of limited implementation of occupational risk prevention standards in said department, as well as the use of rudimentary and improvised work equipment. One of the main problems identified is the technical lack of knowledge regarding industrial safety and the construction and use of equipment such as ladders and scaffolding, which generates the urgency of implementing innovative solutions that prioritize the safety and well-being of the worker.

In the reconstruction industry, a recurring problem is the physical fatigue of workers, caused by intensive physical demands and prolonged use of inadequate equipment. The use of ladders with traditional circular tube steps generates a negative impact on the productivity, safety and well-being of operators, since these steps do not offer a stable or ergonomic surface. This fact increases the effort necessary to maintain balance and, consequently, increases the pressure on specific points of the body, increasing the risk of workplace accidents. In the long term, the use of this equipment can lead to occupational diseases such as musculoskeletal disorders in the lower extremities.

Faced with this problem, the fundamental principle of ergonomics establishes that the work must be adapted to the worker and not the worker to the work. In this sense, the technical intervention of this project is oriented towards the redesign of the work equipment - the ladder - and not towards actions that directly involve the reconstruction workers. The specialized literature on ergonomics applied to vertical access equipment indicates that the design of flat steps, non-slip surfaces and geometric dimensions adjusted to anthropometric parameters allows the pressure to be evenly distributed on the worker's foot, significantly reducing physical fatigue and the risk of falls. Studies such as those by Chaffin et al. and Karwowski have documented that the geometry of the step is one of the variables with the greatest impact on the biomechanical load of the lower limb during ascent and descent in height. In this framework, the European standard EN 131 establishes the technical reference criteria for the design of safe manual ladders, being applicable to this study as a regulatory basis for design.

In methodological terms, previous studies in the field of industrial safety and work equipment design have demonstrated the usefulness of combining computer-aided modeling (CAD), finite element analysis (FEA) and quality control methodologies such as Six Sigma to validate the performance of prototypes before their implementation. Likewise, the REBA (Rapid Entire Body Assessment) method has been widely used to evaluate postural load in tasks that involve the use of access equipment at height, constituting a valid instrument to compare ergonomic performance between conventional and proposed equipment. Depending on the frequency of

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use in reconstruction projects, the staircase has been selected as a priority object of technical intervention over other access equipment such as scaffolding, the installation of which implies greater logistical and structural complexity.

In this context, the present investigation raises the following research question: how does the design and construction of a manual industrial safety ladder with flat steps affect the reduction of physical fatigue and the improvement of occupational safety in the construction sector within the EcoSur Foundation - Ecuador? As a tentative response, the alternative hypothesis is formulated that the use of the proposed ladder significantly reduces the physical fatigue of Housing Reconstruction Department workers compared to a conventional ladder. To verify this hypothesis, the following specific objectives are defined: (i) design the staircase using CAD software to determine the most appropriate geometric parameters; (ii) build the prototype based on the CAD design and a stress-deformational simulation; and (iii) validate the ladder through multivariate statistical analysis and 6 Sigma quality control, with the subsequent preparation of a technical manual for use and maintenance.

MATERIALS AND METHODS

The present study adopted a quantitative experimental approach, with a controlled and randomized design, aimed at evaluating the effect of a manual industrial safety ladder with flat steps on the reduction of physical fatigue (1). It was a prospective trial with a control group (conventional staircase with circular steps) and experimental group (proposed staircase), following a scheme of repeated measures in the same subject (2). The level of research was explanatory, with a deductive modality (3).

The population was made up of 10 workers from the Housing Reconstruction Department of the EcoSur Foundation - Ecuador, Riobamba headquarters (average age 40.6 years, average mass 66.6 kg) (4). Census sampling was used (N=10), with random assignment of the order of use of the stairs. The study was developed in the real context of work in the El Altar parish and surrounding areas, province of Chimborazo, Ecuador, in socioeconomic conditions of vulnerable sectors and approximate altitudes of 2488 meters above sea level (5).

The interventions consisted of the standardized use of both stairs for 15 minutes per session, replicating real reconstruction activities (4). The proposed staircase was designed in AutoCAD 2026 demo version with flat steps 0.150 m wide × 0.400 m long (6063-T5 aluminum), spacing of 0.280 m and inclination angle of 75.5°. Its construction followed the EN 131 and ANSI A14.2 (6.7) standard. Finite element analysis was performed in Autodesk Inventor demo version 2026 to validate Von Mises stresses, displacement and safety factor.

Anthropometric variables (Figure 1) (8) and physiological tests were measured: vertical jump, heart rate, systolic pressure and static squat.

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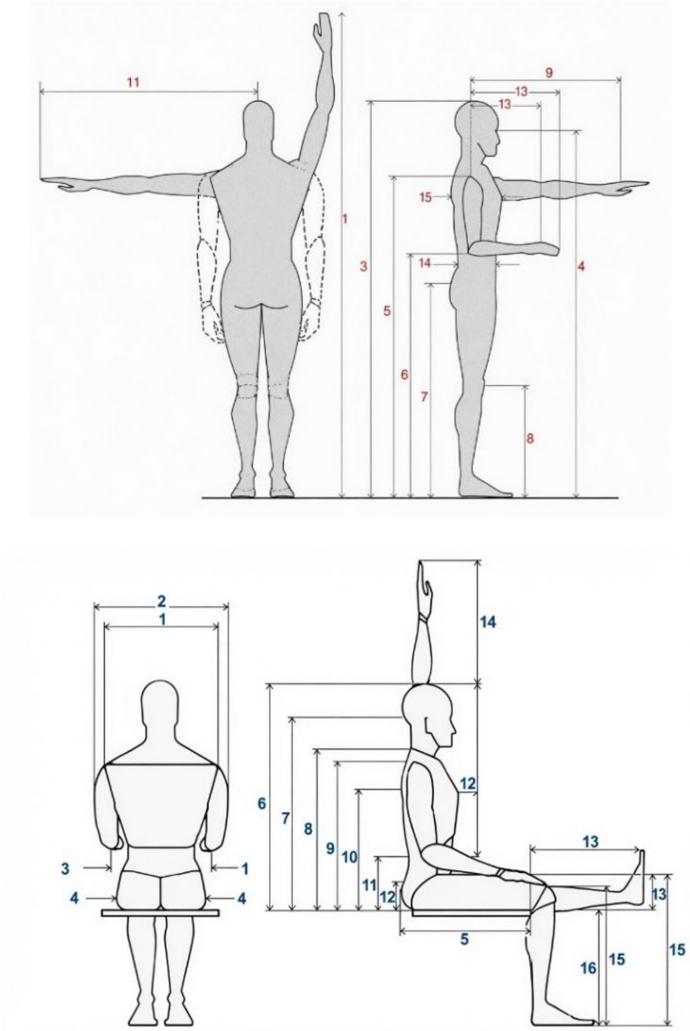

Figure 1. Anthropometric measurements.

Source: (8).

Each test was performed for 60 days over a period of 6 months. REBA methodology was applied for ergonomic evaluation (8) and 6 Sigma Statistical Quality Control (9) whose starting point is shown in Table 1.

Table 1. Quality criteria of the proposed staircase.

Item	Quality Criterion	Qualification
1	Construction Material	9.3
2	Distance between Steps	9.1

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3	Shape and surface of the step	9.2
4	Load capacity	9.2
5	Tilt angle	9.3
6	Stringers	9.3
7	Ergonomic comfort	9.4
8	Anchorage	9.5
9	Condition	9.5
10	Certification	9.6

Statistical analysis was performed in Wolfram Mathematica version 14.3 (10). Normality was verified using the Kolmogorov-Smirnov test. For normal data, Student's T test was used; for non-normals, Wilcoxon. 6 Sigma analysis included Cp, Cpk, DPMO and sigma level according to Equations 1-7 (11, 12). All procedures followed regulatory principles established in Executive Decree 255 and ISO 45001 (13,14).

$$Cp = \frac{ES - EI}{6\sigma} \tag{1}$$

$$Cpi = \frac{\mu - EI}{3\sigma} \tag{2}$$

$$Cps = \frac{ES - \mu}{3\sigma} \tag{3}$$

$$Cpk = Mínimo[\frac{\mu - EI}{3\sigma}, \frac{ES - \mu}{3\sigma}] \tag{4}$$

$$PPM = exp[\frac{29.37 - (Z - 0.8406)^2}{2.221}] \tag{5}$$

$$sigmalevel = 3(Cpk) + 1.5 \tag{6}$$

$$Z = 0.8406 + \sqrt{29.37 - 2.221\ x\ \ ln(PPM)} \tag{7}$$

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Where is the process capacity, the lower capacity, the upper capacity, the actual capacity, the upper specification, the lower specification, the process mean, the standard deviation, the parts per million out of specification and , are the sigma level.$C_p C_{pi} C_{ps} C_{pk} ES EI \mu \sigma PPM Z sigmalevel$

RESULTS

In the population studied, made up of 10 workers, with an average age of 40.6 years and average body mass of 66.6 kg, the proposed ladder showed consistent and statistically significant improvements in all indicators of physical fatigue compared to the conventional ladder with circular steps.

In the vertical jump test (Table 2, 3, Figure 2), the median reach increased from 2.575 m with the conventional ladder to 2.595 m with the proposed ladder, representing a difference of 0.020 m. This improvement indicates greater preservation of muscle power in the lower extremities. The Student's T test rejected the null hypothesis (p=0.0338), confirming that the observed difference is not due to chance.

Table 2. Count vertical jump values on conventional stairs.

Range	Count
2.40-2.45	12
2.45-2.50	8
2.50-2.55	22
2.55-2.60	18
2.60-2.65	30
2.65-2.70	10

Table 3. Count vertical jump values for proposed staircase.

Range	Count
2.40-2.45	6
2.45-2.50	12
2.50-2.55	12
2.55-2.60	20
2.60-2.65	30
2.65-2.70	16
2.70-2.75	4

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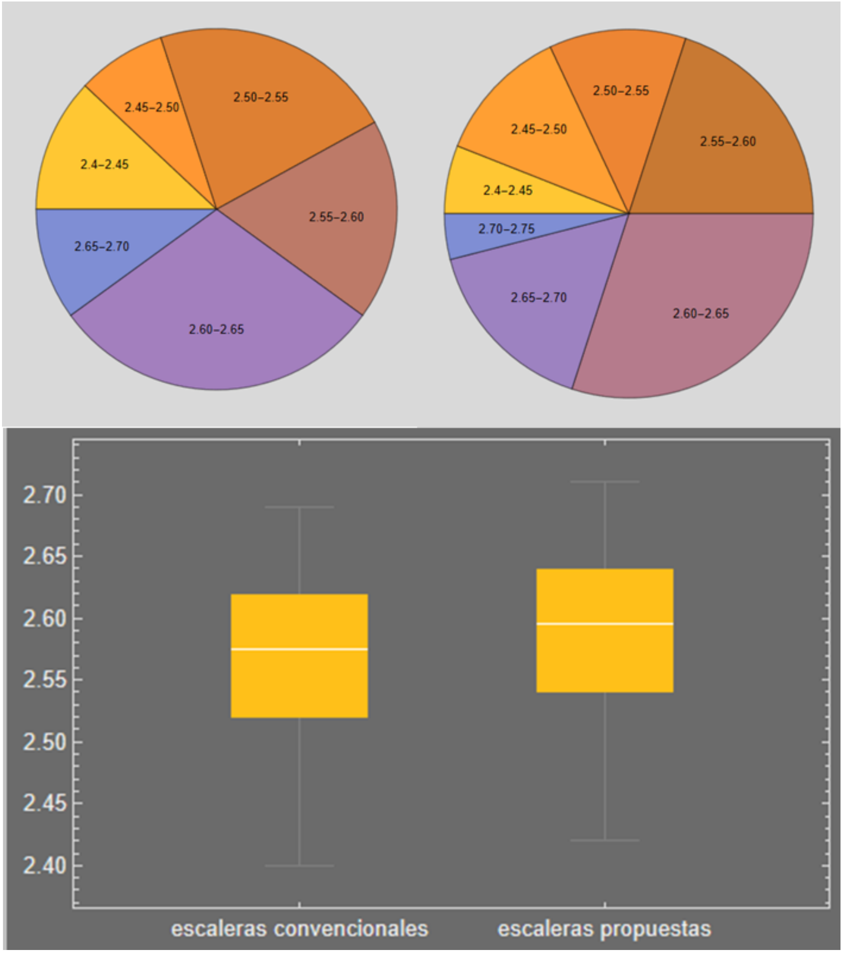

Figure 2. Diagrams of the vertical jump test.

Note: The top panels present pie charts for the conventional staircase (left) and the proposed one (right). The lower panel shows the comparison using box plots for both conditions.

Regarding heart rate (Table 4, 5, Figure 3), the median decreased from 83 to 80 bpm (difference of 3.4 bpm). This result reflects a lower cardiovascular demand during the use of the flat-step ladder. The Wilcoxon test yielded a p-value of 4.31×10^{-20}, highly significant.

Table 4. Conventional staircase heart rate count values.

Range	Count
74-76	1
76-78	7
78-80	10
80-82	19
82-84	17
84-86	15
86-88	19

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88-90	11
90-92	1

Table 5. Count heart rate values proposed staircase.

Range	Count
72-74	4
74-76	9
76-78	16
78-80	19
80-82	20
82-84	17
84-86	12
86-88	3

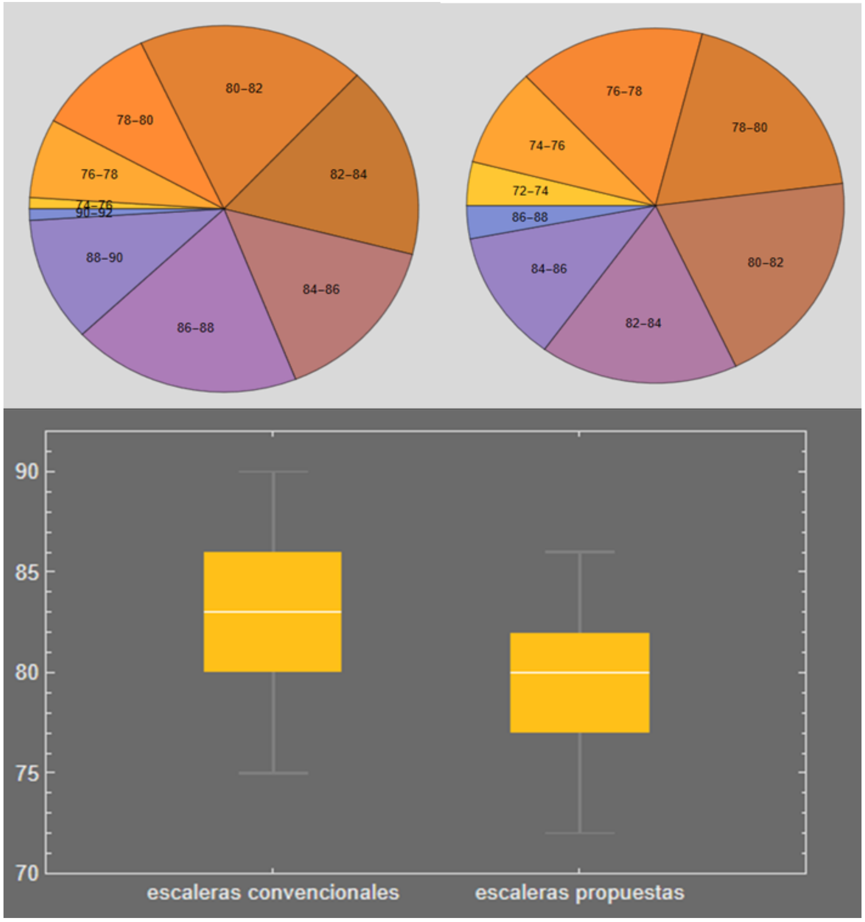

Figure 3. Diagrams of the heart rate test.

Note: The top panels present pie charts for the conventional staircase (left) and the proposed one (right). The lower panel shows the comparison using box plots for both conditions.

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In the systolic pressure test (Table 6, 7, Figure 4), the median decreased from 122 to 116 mmHg (difference of 6.02 mmHg). This reduction suggests less hemodynamic overload associated with physical effort. The Student's T test showed a p-value of 6.45×10^{-13}, confirming the statistically significant difference.

Table 6. Count conventional staircase pressure values.

Range	Count
110-115	11
115-120	26
120-125	30
125-130	23
130-135	10

Table 7. Count of proposed staircase pressure values.

Range	Count
100-105	1
105-110	14
110-115	28
115-120	29
120-125	21
125-130	7

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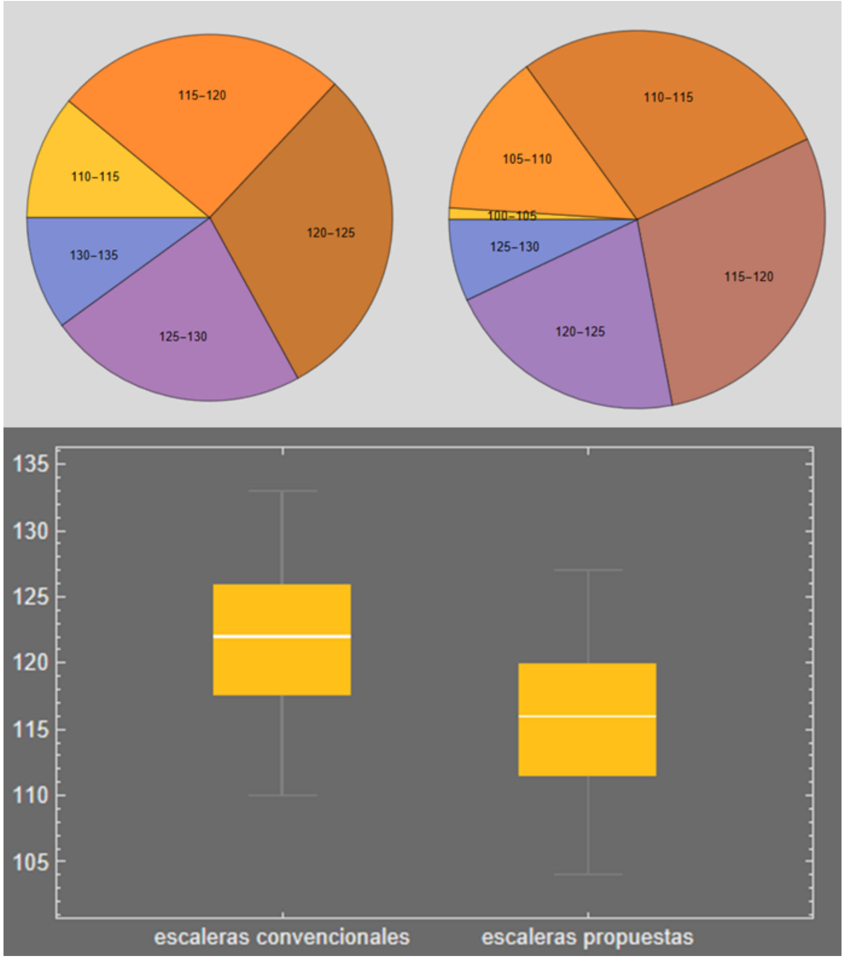

Figure 4. Systolic pressure test diagrams.

Note: The top panels present pie charts for the conventional staircase (left) and the proposed one (right). The lower panel shows the comparison using box plots for both conditions.

In the static squat test (Table 8, 9, Figure 5), the median endurance time increased from 46 to 51 seconds (difference of 4.01 s). This finding shows a better preservation of the muscular strength and resistance of the lower body after the use of the proposed staircase. The Wilcoxon test presented a p-value of 0.0, clearly rejecting the null hypothesis.

Table 8. Count values for conventional stair squat.

Range	Count
35-40	4
40-45	34
45-50	28
50-55	25
55-60	9

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Table 9. Count of proposed stair squat values.

Range	Count
40-45	9
45-50	32
50-55	31
55-60	21
60-65	7

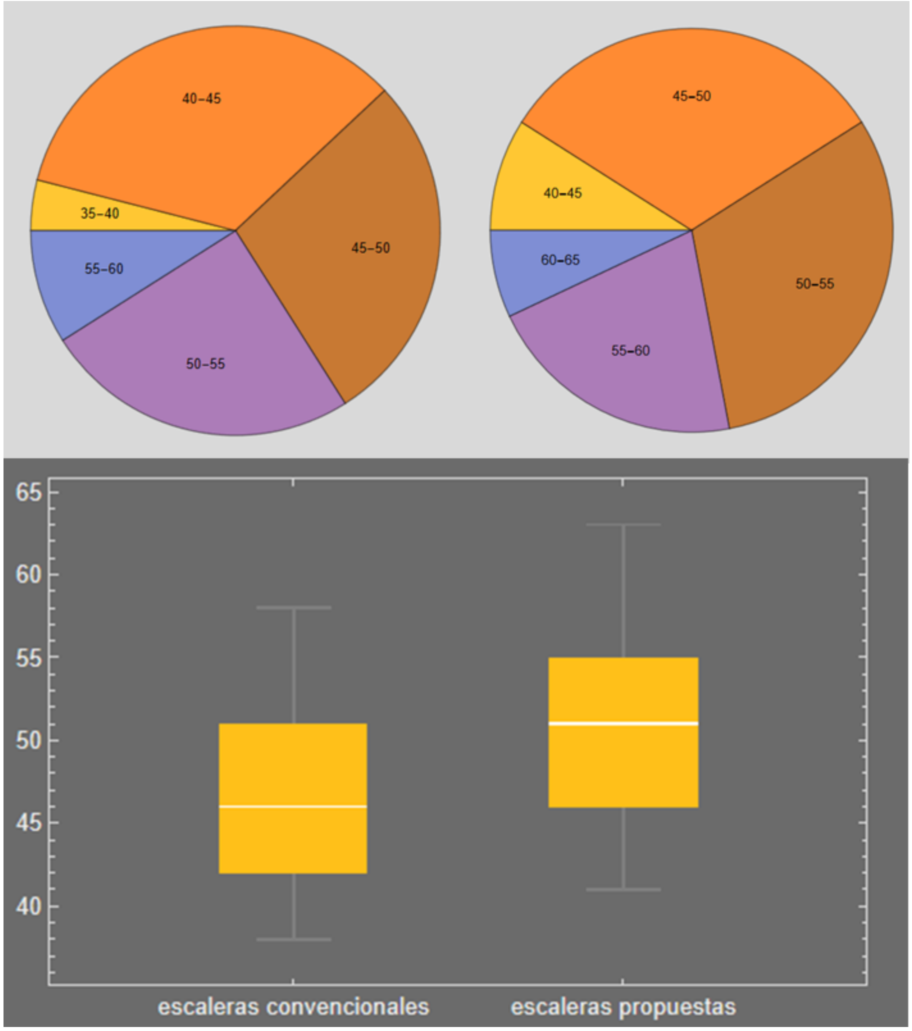

Figure 5. Diagrams of the static squat test.

Note: The top panels present pie charts for the conventional staircase (left) and the proposed one (right). The lower panel shows the comparison using box plots for both conditions.

The 6 Sigma analysis carried out on ten quality criteria of the proposed ladder (Table 1) gave an average of 9.34, with a real capacity index (Cpk) of 1.39, defects per million opportunities (DPMO)

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of 14.3 and a sigma level of 5.68 (Table 10). These values indicate an excellent level of design quality and reproducibility. The analysis showed a variation of 5.27% with respect to 6 sigma quality.

Table 10. Base statistics of 6 sigma analysis.

Statistical	Meaning	Value
n	data number	10.0
LSL	lower limit	7.00
USL	upper limit	10.0
T (nominal)	value ideal	8.50
x	mean	9.34
s^2	variance	0.0249
s	standard deviation	0.15
cv	coefficient of variation	1.69%
Cp	potential capacity	3.17
Cpu	higher capacity	1.39
Cpl	lower capacity	4.94
Cpk	actual capacity	1.39
Cpm	Taguchi index	0.585
DPMO	defects per million	14.3
Z	Sigma level	5.68

Source: (10).

Finite element analysis validated the structural safety of the prototype. For the individual step, a maximum Von Mises stress of 135.3 MPa, a maximum displacement of 0.98 mm and a safety factor of 2.03 were obtained (Figures 6, 7, 8) (15). In the complete ladder assembly, the values were: maximum Von Mises stress of 35.98 MPa, maximum displacement of 0.621 mm and minimum safety factor of 7.64 (Figures 9, 10, 11) (15). Both far exceed regulatory requirements.

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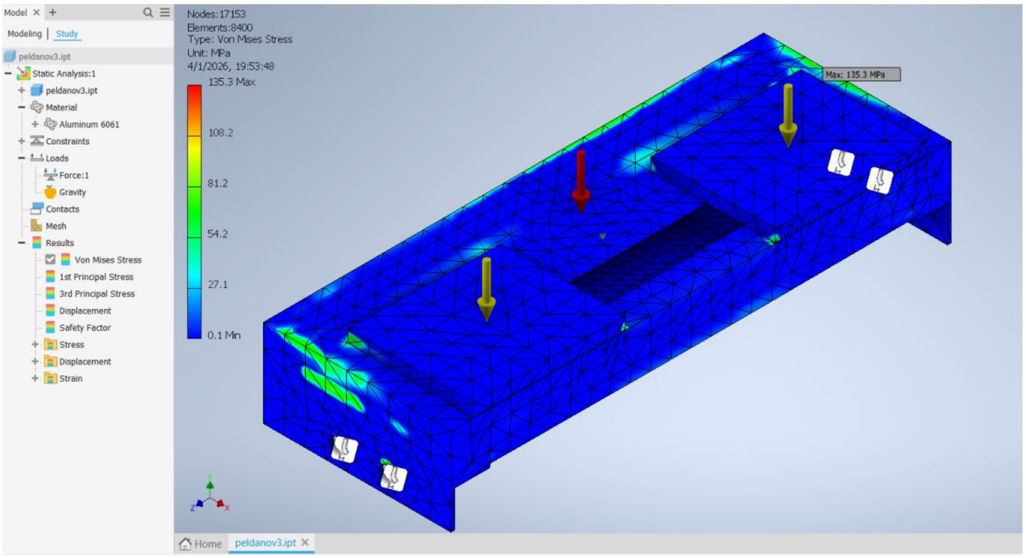

Figure 6. Von Mises stress result in step (maximum: 135.3 MPa).

Source: (15).

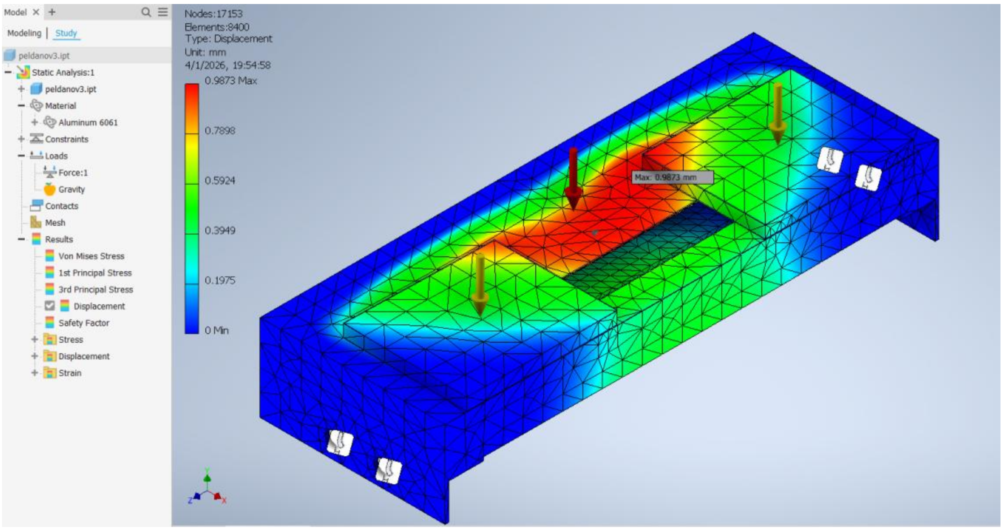

Figure 7. Step displacement result (maximum: 0.98 mm).

Source: (15).

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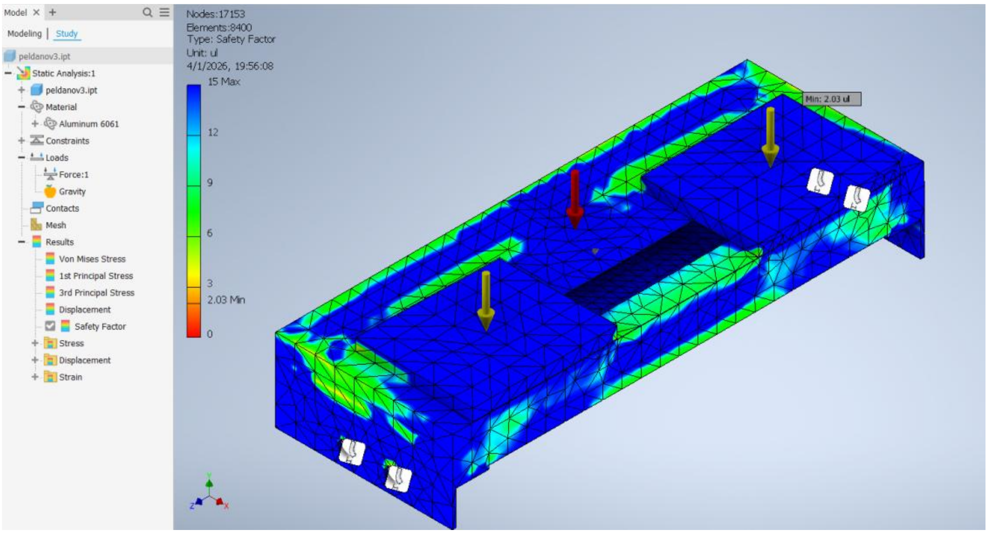

Figure 8. Safety factor result in step (2.03).

Source: (15).

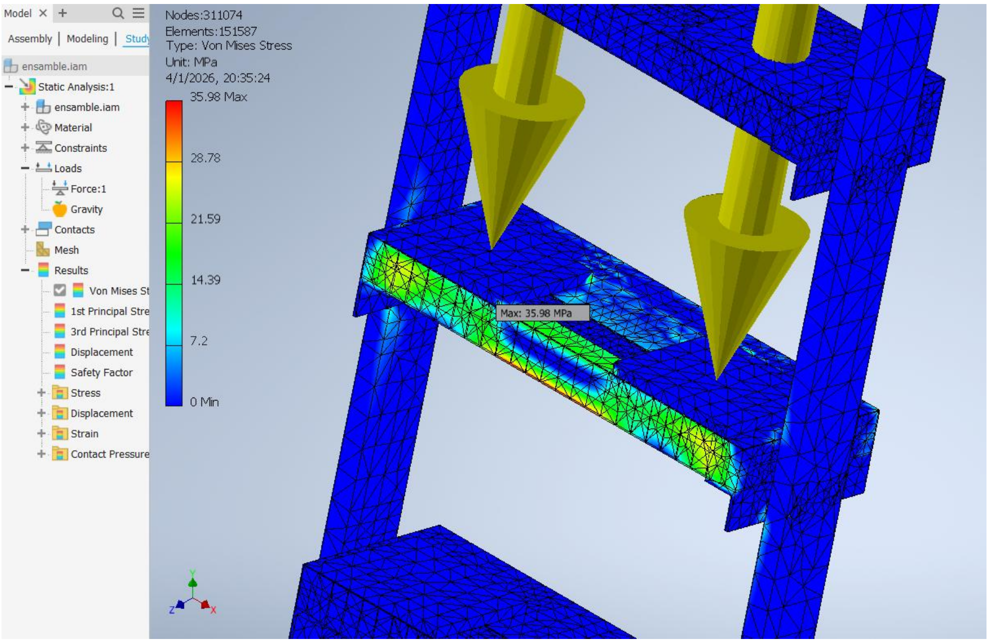

Figure 9. Von Mises stress result on stairs – approach to the step (maximum: 35.98 MPa).
Source: (15).

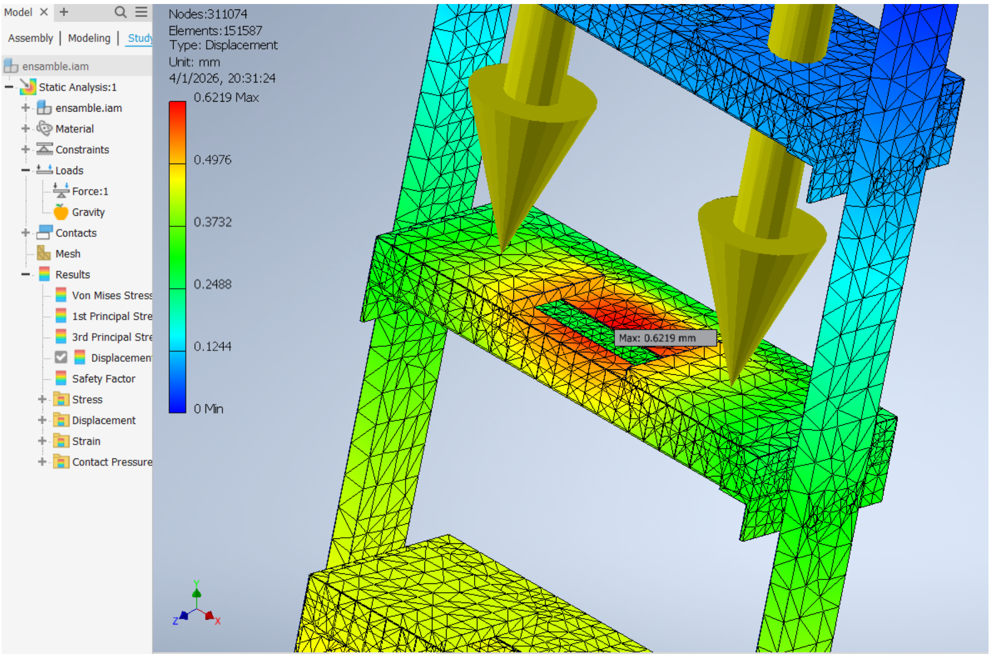

Figure 10. Stair displacement result (maximum: 0.621 mm).

Source: (15).

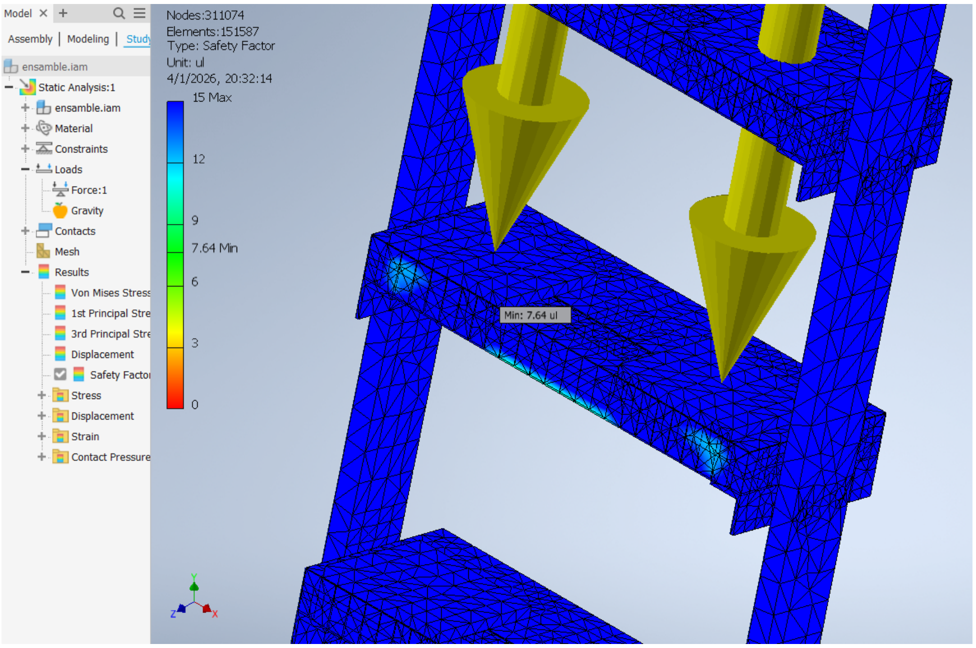

Figure 11. Stair safety factor result (minimum: 7.64)

Source: (15).

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The detailed geometry of the proposed staircase is presented in Tables 11 and 12, with steps 0.150 m wide and 0.400 m long.

Table 11. Geometry of the proposed staircase based on a maximum structure height (y) of 2.93 m.

Geometric Element	Value
Distance to the upper support (x)	3.02 m
Separation space with respect to the structure (x/4)	0.76 m
Angle of inclination of the staircase with respect to the horizontal (α)	75.50°
Total length of staircase (considering an excess of 3 feet or 0.91 m)	3.94 m

Table 12. Geometry of the proposed staircase.

Geometric Element	Normal Rung	Small Rung
	Value	Value
Step width	0.150 m	0.0750 m
Step length (distance between stringers)	0.400 m	
Flap width	0.0380 m	
Step spacing	0.2800 m	
Stringer width	0.0600 m	

Specialized literature supports the design parameters adopted in the proposed staircase. The adoption of separation between steps, with respect to the ANSI standards of 35 cm and EN 131 of 28 cm, significantly reduces the average heart rate during the climb and improves the worker's stay, with the spacing of 28 cm adopted in the proposed staircase being consistent with these recommendations (16). 6063-T5 aluminum presents predictable mechanical properties and adequate rigidity for moderately loaded structures, which validates its selection for the construction of steps and stringers of industrial stairs (17). The safety factors obtained through finite element analysis are representative of the real behavior of hollow sections of 6063-T5 aluminum under static loading, an aspect directly applicable to the structural validation of the proposed step (18). The REBA method was designed to evaluate musculoskeletal risk in tasks with unpredictable postures such as activities at height on stairs, establishing that scores less than 4 indicate low risk without the need for immediate intervention (19). A Cpk value greater than 1.33 guarantees an acceptable level of processes, a threshold that the proposed ladder exceeds with a Cpk of 1.39, confirming the safety of its use (20). The calculation of DPMO and the sigma level constitutes an internationally recognized standard methodology for the evaluation of quality in

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the design of engineering prototypes, with the 5.68 sigma level obtained being indicative of a performance superior to that of most conventional industrial processes (21).

Finally, the prototype of the staircase was delivered to the EcoSur Foundation - Ecuador, the technical manual for use and the plan of the staircase step (Figure 12,13).

Figure 12. Delivery of the proposed ladder and dissemination of the user manual.

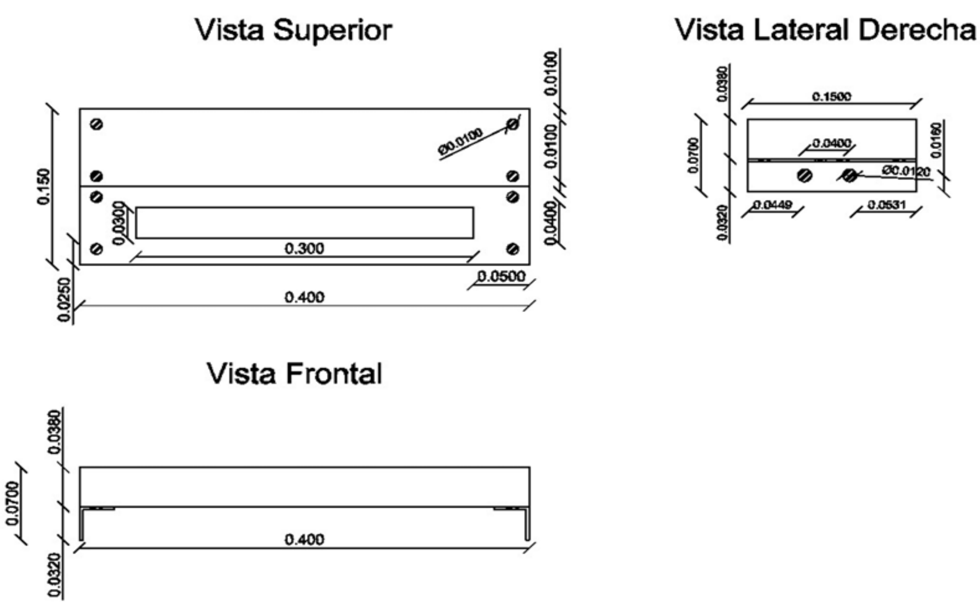

Figure 13. Step plan of the proposed staircase.

Source: (22).

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DISCUSSION

The results of the vertical jump indicate less muscle fatigue in the lower extremities with the flat rung ladder. The difference of 0.020 m is clinically relevant for repetitive tasks in construction.

The reduction in heart rate (3.4 bpm) suggests less cardiovascular demand during safety checks on stairs. This finding strengthens the ergonomic hypothesis of flat design.

The decrease of 6.02 mmHg in systolic pressure in the proposed stairs reduces hemodynamic risk in elderly workers.

The increase of 4.01 s in static squat confirms better preservation of muscle strength. The novelty lies in the implementation of flat steps, 6 Sigma analysis and finite elements. Through the study, the safety and protection of occupational risks of the workers of the EcoSur Foundation - Ecuador is increased.

The 5.68 sigma level is within industrial quality standards and validates the reproducibility of the design. The safety factors (2.03 and 7.64) exceed the requirements of the EN 131 standard.

In summary, all the results obtained support the rejection of the null hypothesis and the acceptance of the alternative hypothesis in the four physiological tests carried out, demonstrating the ergonomic and functional superiority of the flat-step ladder.

CONCLUSIONS

The designed and built manual industrial safety ladder with flat steps significantly reduced the physical fatigue of workers at the Housing Reconstruction Department of the EcoSur Foundation - Ecuador, evidenced by statistically significant improvements ($p<0.05$) in vertical jump (+0.020 m), heart rate (-3.4 bpm), systolic pressure (-6.02 mmHg) and static squat (+4.01 s), fulfilling the general objective.

The geometric design (AutoCAD 2026 demo version), structural validation (Inventor 2026 demo version) and 6 Sigma quality control (Wolfram Mathematica version 14.3) produced a safe (safety factor >2) and ergonomic prototype, superior to conventional stairs, complying with EN 131, ANSI and OSHA standards (4, 6, 7).

The implementation of the prototype and technical manual represents a practical contribution to the prevention of occupational risks in social construction in Ecuador, improving well-being, productivity and safety.

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