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Article

Sustainable design of dynamic elbow orthoses for adult rehabilitation treatment

Diseño sustentable de órtesis dinámica de codo con fines de rehabilitación en adultos

Castillo-Aguirre, Alfredo Humberto*[a], Báez-Guzmán, Ricardo[b], Cruz-Gómez, Marco Antonio[c] and López-Aguilar, Genaro Roberto[d]

[a] Benemérita Universidad Autónoma de Puebla • KQF-3856-2024 • 0009-0007-1564-2611 • 2030591
[b] Benemérita Universidad Autónoma de Puebla • LSJ-2261-2024 • 0000-0002-7182-4870 • 627039
[c] Benemérita Universidad Autónoma de Puebla • S-3098-2018 • 0000-0003-1091-8133 • 349626
[d] Benemérita Universidad Autónoma de Puebla • AAN-6708-2021• 0000-0003-0140-7163 • 504343

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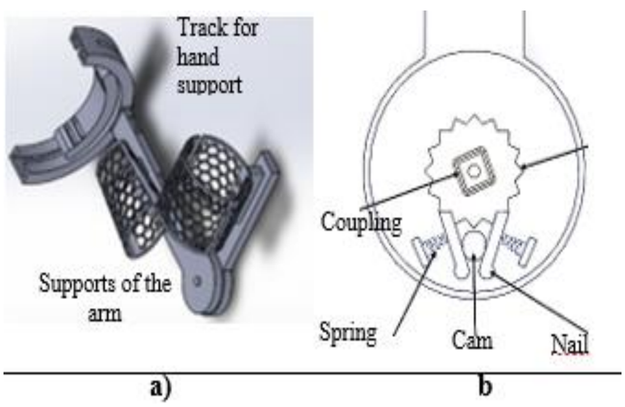
* ✉ [castilloaalfredoh@gmail.com]

Abstract

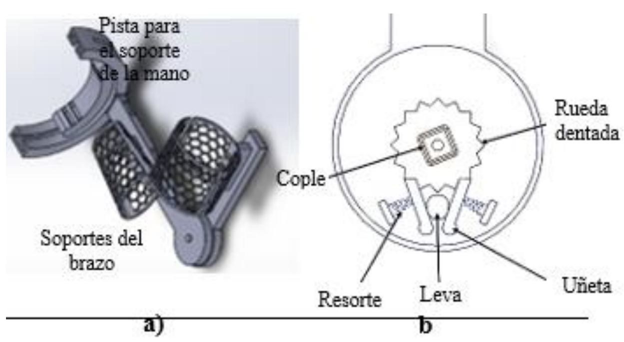
The elbow joint is prone to degenerative diseases, injuries from work, sports, or accidents. Rehabilitation often requires surgery and mechanical rehabilitation by health professionals. This research aimed to design a dynamic elbow orthosis using the finite element method for sustainable adult rehabilitation. Elbow orthoses can reduce treatment time effectively, but their high cost and importation limit accessibility. The study involved a mixed analysis of orthosis design and optimization, considering variables like anthropometric measurements, mobility ranges, biomechanical parameters, and mechanical design. Technical data from human anatomy were used to create biomechanical models, optimizing the orthosis design for sustainable systems. Future work will focus on further rehabilitation optimization by health professionals.



Elbow orthosis, Biomechanics, Finite element

Resumen

La articulación del codo está constantemente expuesta a enfermedades degenerativas y lesiones por actividades laborales, deportivas o accidentes. La rehabilitación suele requerir una intervención quirúrgica y rehabilitación mecánica por parte de personal de salud. Esta investigación buscó diseñar una órtesis dinámica de codo usando el método de elementos finitos para una rehabilitación sustentable en adultos. Las órtesis de codo reducen significativamente el tiempo de tratamiento, pero su alto costo y necesidad de importación limitan el acceso. Se realizó un análisis mixto en el diseño y optimización de la órtesis, considerando variables como medidas antropométricas, rangos de movilidad, parámetros biomecánicos, diseño mecánico y control de rehabilitación. Los datos técnicos de la anatomía humana se transformaron en modelos biomecánicos, optimizando el diseño de la órtesis para sistemas sustentables. La caracterización de la rehabilitación de la órtesis será objeto de futuros trabajos y optimización por parte del personal de salud.



Órtesis de codo, Biomecánica, Elemento finito

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Introduction

The human body has 360 joints in total. These are divided into 86 in the skull, 6 in the throat, 76 in the spine and pelvis, 66 in the thorax, 32 in each of the arms and finally 31 in each of the legs.

These are structures that connect two or more bone surfaces allowing; mechanical movements, provide elasticity, serve as a union between bones, bones-cartilage and finally bone tissue and teeth. The elbow is a joint that corresponds to the arm, it has two degrees of freedom, two movements, flexion-extension and pronation-supination.

The first movement has an arc of motion of 0°-160°, however, most activities are performed between 30° and 130°. The second has a range of mobility between 160°-170°. The elbow joint is constantly exposed to degenerative diseases, injuries generated by work activities, sports or accidents. To rehabilitate it, a surgical intervention is necessary in most cases, followed by constant mechanical rehabilitation by health personnel. Elbow rehabilitation consists of different therapies to strengthen it until the patient returns to their daily lives.

The therapies involve flexion-extension and pronation-supination exercises with the help of an elbow orthosis. (Gil-Henao et al., 2021). The elbow is one of the three main joints in the upper body kinetic chain, along with the shoulder and wrist.

This is essential for interaction and communication with the environment. A failure in health hinders nutrition, hygiene, recreation, work, and countless activities of daily living, decreasing the quality of human life. (Fuensalud, 2022).

Orthoses are a device applied externally to the body to improve joint mobility and can be classified as unloading, immobilization, stabilization-support, functional, postural, corrective and mixed. (Segnini et al., 2020) and (Sevik et al., 2024). The objective of this research was to design a dynamic elbow orthosis using the finite element method as an optimization tool, for sustainable rehabilitation purposes in adults.

The characterization of technical data obtained from human anatomy was transformed into biomechanical models, optimizing the design of the elbow orthosis in sustainable development systems.

The design and optimization of the dynamic orthosis for elbow rehabilitation aims to help patients by reconciling viability, sustainability and equity, complying with the three fundamental axes of sustainability; economic, ecological and social to improve the quality of life and human survival.

In such a way that the design of the elbow orthosis used CAD and CAE software tools for optimization, (CAD/CAM/CAE, 2022), the use of 3D printing.

The stress analyzes in the mechanisms were carried out by the finite element method; supported by SolidWorks software and finally based on the results, the materials for the manufacture of the orthosis were proposed, optimizing its mechanisms.

The rehabilitation characterization of the elbow orthosis will be the subject of future work and its optimization by health personnel.

Anatomy of the elbow joint

The elbow joint is made up of three joints; the humerus-radial, humerus-ulnar (flexion-extension movement) and intermediate proximal radio-ulnar (pronosupination movement), belonging to the human upper limb. However, they are considered as a single joint; because the joint cavity, the synovial membrane, the capsule and the ligaments are common in the three joints.

Including figures and tables-Editable

In the article content any table and figure should be editable formats that can change size, type and number of letter, for the purposes of edition, these must be high quality, not pixelated and should be noticeable even reducing image scale.

This complex joint allows the forearm to approach or separate from the arm, through the flexion-extension movement and the orientation of the palm of the hand, through the pronosupination movement.

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The flexion-extension movement is 0°-150° and pronation-supination is 160°-170°, with arcs of movement in daily activities of pronation 80° and supination 85°. (Hamill et al., 2022).

The bone structure of the elbow joint is made up of three bone structures (humerus, radius and ulna) that coincide in three joints. The distal end of the humerus is made up of the trochlea (known as the condyle) and the olecranon fossae (coronoid fossa and radial fossa).

The faces of the condyle articulate with the head of the radius and a trochlea that articulates with the proximal end of the ulna, known as the ulna. The coronoid fossa receives the coronoid process of the ulna during complete flexion of the elbow, while in full extension the olecranon fossa is responsible for accommodating the olecranon of the ulna. The shallow radial fossa accommodates the edge of the radial head when the forearm is fully flexed. (Dalley et al., 2022).

The condyle-trochlea assembly can be compared to the association of a diabolo and a ball, crossed by a flexion-extension axis of the elbow. The condyle and trochlea are internally rotated by 3-8° and have a 94-98° valgus angle with respect to the longitudinal axis of the humerus. The distal part of the humerus has an angle of 30° along the longitudinal axis of the humerus. (Nordin et al., 2020).

The ulna (or ulna) is the longest, medial bone of the forearm that stabilizes the human upper extremity. The proximal end of the ulna articulates with the humerus proximally and with the head of the radius laterally. To articulate with the humerus, it has the olecranon that acts as a lever for the extension of the elbow, and it has the coronoid process in contact with the radial notch.

The olecranon and coronoid process form the walls of the trochlear notch of the humerus. The joint between the ulna and the humerus allows flexion and extension movements of the elbow, however, in the pronation and supination of the forearm a certain degree of abduction-adduction takes place. Inferior to the coronoid process is the tuberosity of the ulna that inserts the tendon of the brachialis muscle. (Dalley et al., 2022 and Koizumi et. Al., 2023).

On the lateral aspect of the body of the ulna is the crest of the muscle and the supinator fossa. The articular surface of the ulna has an angle of 4-7° of valgus with respect to the longitudinal axis of its diaphysis. This articular surface is rotated 30° posteriorly with respect to its longitudinal axis. (Nordin et al., 2020).

The proximal end of the radius has a short head. The superior surface of the radial head is concave to articulate with the humerus during flexion and extension. The head of the radius also articulates peripherally with the radial notch of the ulna.

The neck of the radius is a limiter of the head of the radius and the tuberosity of the radius is distal to the medial part of the neck and marks the boundary between the proximal end (head and neck). The radial neck has an angle of 15° with respect to the longitudinal axis. (Dalley et al., 2022). The joint capsule with capsuloligamentous joints that contribute to the static stability of the elbow include the anterior, posterior, and medial and lateral joint capsules. (Part et al., 2021). The ligaments form the complex thickening system of the medial and lateral region of the capsule, being responsible for 70% of the containment of distraction of the joint, in addition to 30% of the stability in varus and 40% in valgus.

The medial ligamentous complex originates in the lower middle area of the medial epicondyle and adopts a fan shape. This is made up of three fascicles, anterior medial collateral ligament, posterior or Bardinet and transverse or Cooper's ligament. (Chanlalit et al., 2023).

The lateral ligamentous complex is composed of 4 ligaments, lateral ulnar collateral, radial collateral, annular collateral and accessory collateral. The ligaments, lateral ulnar collateral and radial collateral originate at an isometric point in the anterior region of the lateral epicondyle, maintaining a constant tension throughout the flexion-extension arc of the elbow. The accessory collateral ligament extends from the annular ligament to the supinator crest. Finally, the annular ligament surrounds the radial head, with insertions on the anterior and posterior borders of the minor sigmoid fossa. Its anterior portion is tense in supination and the posterior portion in pronation. (Tortora et al., 2021).

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Flexion-extension and pronosupination movements are carried out by the action of the muscles that surround the elbow joint. Flexion is carried out by three muscles, the brachialis anterior; being the primary flexor of the forearm, the biceps brachii muscle; its contraction produces a flexor action when the forearm is in a neutral position (supination) and the brachioradialis muscle; it acts as a stabilizer when the forearm is mobile, and as a forearm flexor when it is fixed.

The primary extensor of the elbow is the triceps brachii muscle and is made up of three heads: long, lateral and medial. The muscular effectiveness of the triceps brachii depends on the position of the elbow. Between 20° and 30° of flexion, the action of the triceps brachii muscle is maximum, decreasing in favor of joint stabilization. In full extension of the elbow, the force exerted by the triceps brachii muscle tends to posteriorly dislocate the ulna. When acting on the flexed elbow, the dislocation component is nullified. Another extensor muscle is the anconeus, which is involved in regulating the extension and stabilization movement of the elbow.

The pronosupinator muscles are four, short and flat muscle; whose action is to uncoil, long muscle; which inserts into the apex of a curve and the supinator muscles. The supinator muscle, coiled around the neck of the radius and inserted into the supinator fossa of the ulna; biceps brachii muscle, is inserted at the apex of the supinator curve at the level of the radial tuberosity, the maximum effectiveness of this muscle occurs when the elbow is at an angle of 90°. The biceps brachii muscle has the most power of all the muscles that act in pronosupination.

The pronator quadratus muscle is coiled around the lower end of the ulna and acts to "unwind" the ulna in relation to the radius. Pronator teres muscle, inserted at the apex of the pronator curve, its moment of action is weak. (Netter, 2023). The flexion-extension movement is carried out through an axis, it is carried out by the humero-ulnar and humero-radial joints. The normal range of motion ranges between 0° and 140-146° of flexion and increases up to 160°, which is the maximum flexion. However, between 30° and 130° of arc of motion is performed in daily activities and is known as the functional arc of the elbow.

Bending movements are limited by factors such as; contact between the brachial and antebrachial muscle masses as a result of contraction during active flexion, bony collision between the radial head and the coronoid with the bottoms of their respective housing fossae, tension of the posterior capsule and the posterior fascicles of collateral ligaments, passive tension of the triceps brachii muscle, limited extension movements, contact of the peak of the olecranon with the bottom of the olecranon fossa, tension of the capsule and anterior fascicles of the collateral ligaments and passive tension of the flexor muscles.

To perform the pronosupination movement, the elbow is placed at 90° of flexion. Pronation movement is defined as medial rotation that places the thumb inward and the palm of the hand downward.

Supination is the movement that brings the thumb outward and the palm of the hand upward. The range of motion for pronosupination is around 160-170°, divided between pronation (80°) and supination (85°).

The pronosupination movement requires two joints, the proximal radio-ulnar and the distal.

Elbow pathology and rehabilitation

The human body is exposed to dislocations, sprains, sprains of joints, ligaments and other diseases, accompanied by road, work or sports accidents. These may or may not culminate in surgical intervention. In most cases, passive rehabilitation will be required, where a person or device mobilizes or immobilizes the patient's affected area.

Elbow pathologies are; fractures, dislocation and chronic instability, trauma, soft tissue injuries, infections and burns. Their rehabilitations are usually long-term, 6-12 months. (McMahon et al., 2021) and (Verstuyft et al., 2021). In the case of the elbow joint, it is subjected to a pre-established range of angular motion for a certain period of time. (Segnini et al., 2020). Rehabilitation of injuries is achieved by controlling the mobility of the elbow, to simultaneously recover joint range and muscle strength, in flexion-extension and in pronosupination. (Leal, 2021).

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The treatment methods provided by the therapist are usually manual with the use of various mechanical tools, that is, they are rehabilitation exercises for long days of therapeutic work, of great resistance and arduous rehabilitation work. (Ibarra, 2020) and (Graves, 2024).

In the international market, there are patents for elbow rehabilitators with different configurations that can use linear springs, torsion, pneumatics, electronics, hydraulics and mechatronics to control the movements of the elbow joint, which have evolved from mechanical to advanced mechatronic systems with autonomy that are programmed to be friendly in control by the patient, who possess a certain degree of mobility. (Segnini, et al., 2020).

An orthosis is a device applied externally to the body to improve its musculoskeletal function; it can be classified as static and dynamic. (Alvarado Huaranga et al., 2023).

There are three types of elbow rehabilitator orthoses; continuous passive motion rehabilitator (continuous motion reduces stiffness and pain), range of motion rehabilitator (designed for people with elbow stiffness), and dynamic flexion and extension rehabilitator (devices that allow movement of weakened muscles).

The dynamic orthoses that exist on the market focus on a single movement, flexion-extension, leaving aside the pronation-supination movement.

The only devices that cover these two movements are exoskeletons, which are usually imported and have high acquisition and maintenance costs and require levels of specialization in their handling. (Segnini, et al., 2020), therefore, it is of utmost importance to develop orthoses that are capable of meeting this need in an accessible way.

Investigation methodology

This research had a mixed approach, applying both quantitative and qualitative technologies, using systematic processes, as well as records and estimated data.

The objective of this research was to design a dynamic elbow orthosis using the finite element method as an optimization tool, for sustainable rehabilitation purposes in adults.

For this, the application of the quantitative method was relevant in the identification of control variables involved in previous studies such as; anthropometric measurements, ranges of mobility, biomechanical parameters, mechanical design and rehabilitation control.

The characterization of technical data obtained from human anatomy was transformed into biomechanical models, optimizing the design of the elbow orthosis in a sustainable development system. The records of results obtained by different Companies and medical suggestions from health personnel were considered as the application of the qualitative method that allowed the possibility of obtaining results from the estimation of variables, which played an important role in decision-making for control of rehabilitation.

The operational data resulting from this research determined special adjacent requirements such as an uncertainty in the way the orthosis adapts to the needs of each patient, among others. Finally, using the mixed method, an analysis of the control variables was carried out to allow the optimization of the model based on mechanical stresses in each component by the finite element method.

From the results obtained, a discussion of the results generated was carried out on the technological proposal that meets the parameters of sustainable development and the optimization of materials per element of the orthosis system.

Elbow biomechanics

Detailed knowledge of the biomechanics of elbow function is essential for the clinician to effectively treat pathological conditions affecting the elbow joint. (Nordin et al., 2020).

The cortical bone can support greater stress in compression, approximately 190 MPa and in tension it supports around 130 MPa, shear force 70 MPa, Young's Modulus of 17 GPa when the load is longitudinal or axial and when it was transversely its Young's modulus is 11 GPa.

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Cancellous or trabecular bone resists less load, 50 MPa in compression and 8 MPa in tension, Young's Modulus of 0.0-0.4 GPa.

Cancellous bone is up to 5 times more ductile than cortical bone, approximately 25% denser, and 5-10% more rigid. (Nordin et al., 2020).

The maximum force that a muscle can develop is 0.25 to 0.6 MPa. (Rueda, 2021).

Elbow kinematics in daily life are in the range for the case of flexion-extension of 30°-130° and for the case of pronation-supination around 50° for pronation and 50° for supination. Contractures are greater than 30° causing discomfort that causes loss of movement

A static analysis was carried out considering the positioning of the elbow at an angle of 90° and in supination, at the ends of the arm (wrist and hand), shown in figure 3. For this analysis, a mass of 12.5 kg was placed, which was determined based on NOM-036-1-STPS-2018 as the maximum established mass that a person can permissibly carry, that is, the maximum load allowed within the biological parameters is 25 kg, in both arms. (Leal, 2020) and (Secretaría de Trabajo y Previsión Social 2024).

Box 1

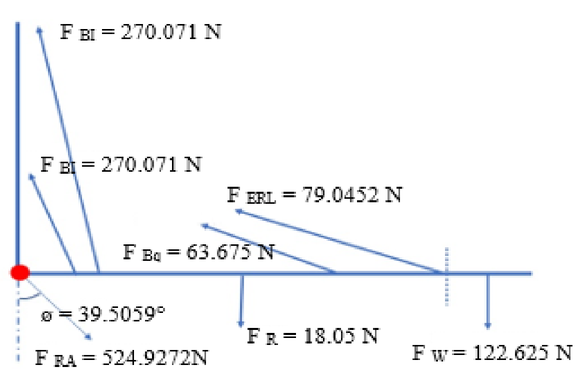

Figure 1

Free body diagram with muscle forces and resultant force at the elbow

The proposed elbow prosthesis consists of two mechanisms, the first consists of a support in which the palm of the hand is fixed and performs a semicircular movement, this range of movement was 160°, divided into 80° in pronation and 80° in supination, the second mechanism was considered fixed to the elbow flexion-extension mechanism.

The muscles for isometric exercises were considered as if it were a ratchet mechanism; This mechanism works to prevent the rotation of an axle in one direction and allow rotation in one direction only. It consists of an external or internal toothed wheel with oblique teeth and a claw that acts against the teeth.

It can be operated by means of a spring. or by the own weight of the nail, this mechanism allows us to regulate the movement ensuring a single direction of rotation.

Results

A finite element simulation of the 90° band fastener gives us a Von-Mises stress shown in Figure 2.

Box 2

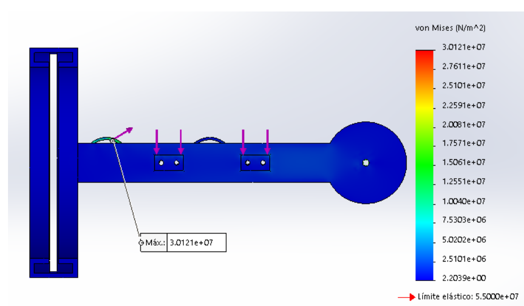

Figure 2

Maximum Von-Mises stress at 90°

An analysis of the piece of the upper part of the arm, when the forces acting on the piece that is fixed at the height of the biceps were studied to determine the forces of the elastic band that is fixed on the support, see figure 5.

Box 3

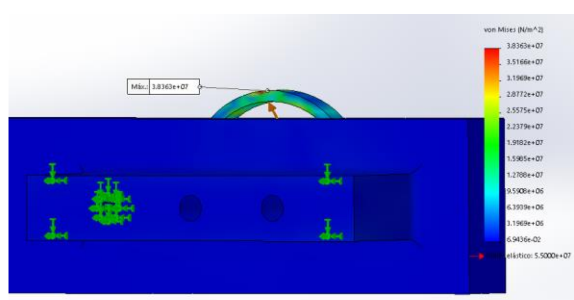

Figure 5

Stress when the elbow was at 90°

The main forces on the mechanism are formed on the support of the elastic band, considering a critical part of the mechanism, the forces generated by the ratchet shown in Figure 4.

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Box 4

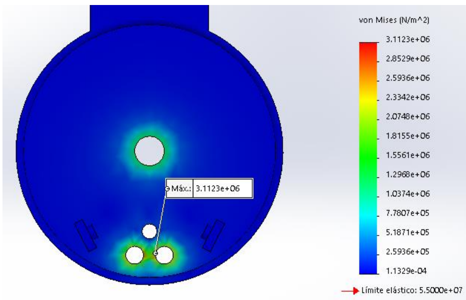

Figure 4
Stress in the mechanism generated by the ratchet

The analyzes carried out on the sprocket helped to determine the maximum stress, when the 90° elbow mechanism is fully extended, see figure 5.

Box 5

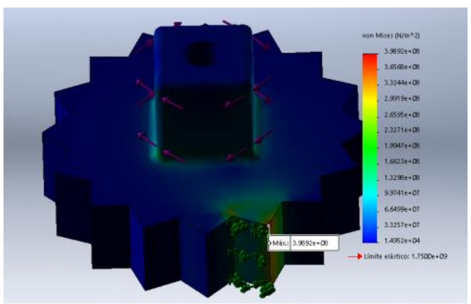

Figure 5
Stress on the sprocket when the mechanism is in the extended position and the elbow at 90°

The maximum force to which the fingernail is subjected in an extended position and the elbow at 90° generates a maximum stress of 14,465 MPa; however, as rehabilitation progresses, the patient must regain strength and mobility, increasing the load until reaching a maximum of 12.5 kg per upper extremity.

The elbow orthosis is composed of the following critical parts that make up the driving mechanism with their maximum forces shown in table 1.

Box 6
Table 1
Maximum stress in each piece.

Part name	Maximum generated stress
Forearm piece	30.121 MPa
Upper arm piece	38.363 MPa
Cogwheel	800.93 MPa
Second position nail	110.58 MPa
Third position nail	14.465 MPa

The mechanical characteristics of the materials for 3D printing are shown in table 2.

Box 7
Table 2
Characteristics of materials for 3D printing

Material	Young's modulus	Elastic limit	Flexural strength
ABS	2300 MPa	45 MPa	65 MPa
PLA	2346.5 MPa	49.5 MPa	103 MPa
TPU	26 MPa	8.6 MPa	4.3 MPa
PETG	2200 MPa	53 MPa	79 MPa

With the results obtained from the maximum efforts, it was determined that PLA and PETG were the appropriate materials for the manufacture of the body of the mechanism.

The ratchet mechanism must withstand the maximum forces generated in the gear wheel, which is why several materials were proposed for its manufacture such as; AISI 1045 steel, 1.6582 steel, 1.6587 steel, 1.6657 steel and 1.8519 steel.

The elastic limit of each material would not be able to withstand the stress generated in the ratchet mechanism, however, each one is characterized by the type of heat treatment to which it can be subjected to obtain better resistance, meeting the specifications. see table 3.

Box 8
Table 3
Characteristics of the steels for manufacturing the ratchet

Steel name	Tensile strength (MPa)	Elastic limit (MPa)	Heat treatment Tensile strength (MPa)
1045 AISI	630	530	1583
1.6582 Steel	900	600	1200
1.6587 Steel	980	685	1270
1.6657 Steel	1176	931	1180
1.8519 Steel	1100	900	1300

According to a proposed safety factor of 1.5 for the manufacturing of the parts, the nails could be manufactured by 3D printing, with materials such as PLA or PETG which provide a safety factor of 3.42 or 3.66 respectively. In the case of the nail, an AISI 4140 steel or a 1018 steel can be used.

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These two steels are widely used in the industry with an elastic limit of 390 MPa and the second of 370 MPa, with safety factors of 3.52 and 3.35 respectively, exceeding at all times the design feasibility and optimizing the technical specifications of each material (Hernández Soriano, 2023).

Conclusions

The results of the prototype of a dynamic orthosis for elbow rehabilitation managed to reproduce the flexion-extension and pronosupination movements, with a purely mechanical mechanism, which reduces the complexity of the prototype with a positive impact to cover the sustainable development parameters pursued in the objectives of mechanical design.

The proposal to carry out a design that covered the functionality and mechanical stresses per finite element that allow the selection of appropriate materials for the manufacture of each element ensures that theoretically the mechanism would not present failures during the rehabilitation activities.

Declarations

Conflict of interest

All the authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Castillo-Aguirre, Alfredo Humberto: Contributed to the project idea, research method and technique, about to develop all the project.

Baez-Guzman, Ricardo: Apported the studies, and bases of the finite element of the orthoses.

Cruz-Gomez, Marco Antonio: Supported the simulation of the Project by the software ANSYS

López-Aguilar, Genaro Roberto: Resarched mutiple papers and information about the topic and verify the empleability

Hernández-Soriano José Luis: Contributed with the bases of the funtion and empleatibility of the orthoses of elbow with his tesis.

Availability of data and materials

The obtained data, about the efforts, and multiple forces, that can be repercute in the orthoses, in the case of the steels, that was mention in the project, can be upgrade with a thermal treatment, specifications: Steel 1045 AISI, Tensile strength (MPa): 630, Elastic limit (MPa): 530, Heat treatment Tensile strength (MPa): 1583; 1.6582 Steel (900, 600, 1200); 1.6587 Steel (980, 685, 1270); 1.6657 Steel (1176, 931, 1180); 1.8519 Steel (1100, 900, 1300).

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Abbreviations

CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing

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Antecedents.

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