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DEVELOPMENT AND STRUCTURAL ANALYSIS OF A MOTORIZED ERGOMETER USING FINITE ELEMENT SIMULATION

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ABSTRACT

This paper presents the design and dynamic analysis of a motorized ergometer for upper extremity rehabilitation. The primary objective of the study is to develop a robust and efficient mechanical design that can accommodate varying user loads while ensuring smooth operation and structural stability. The system incorporates a worm gear mechanism to provide controlled motion of the pedals, driven by a DC motor. Key mechanical parameters such as torque, force transmission, and pedal geometry were carefully considered to optimize user comfort and performance. Finite Element Analysis (FEA) was conducted using ANSYS to evaluate the structural integrity of the design under real-world loading conditions. The simulation focused on stress distribution and deformation analysis of critical components, including the frame, pedals, and gear mechanism. The results demonstrated that the design is capable of withstanding the applied forces with minimal deformation and acceptable stress levels, ensuring long-term durability.

Key words: Mechanical Design, Dynamic Simulation, Gear Mechanism, Structural Analysis

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I. INTRODUCTION

Upper extremity injuries encompass a diverse array of conditions affecting the shoulder, elbow, wrist, and hand, and they can significantly impede daily activities and quality of life. These injuries are typically categorized as acute or overuse injuries [1]. Upper extremity rehabilitation is a critical area of research due to the high prevalence of injuries and neurological conditions affecting arm function [2]. Acute injuries result from sudden events, such as fractures and tendon ruptures, while overuse injuries develop gradually due to repetitive strain, commonly seen in individuals engaged in activities requiring repetitive motions [3]. Rehabilitation plays a crucial role in the treatment of musculoskeletal injuries, particularly in restoring function and preventing long-term disability [4]. Regenerative rehabilitation combines regenerative medicine with rehabilitation techniques to maximize tissue regeneration and patient function [5]. The rehabilitation process should begin immediately after injury and progress through stages including immobilization, range of motion, strength training, and return to activity [6]. For traumatic orthopedic injuries, rehabilitation approaches aim to promote musculoskeletal regeneration and plasticity, improving long-term functional outcomes [7]. Motorized ergometers have emerged as valuable tools in upper extremity rehabilitation, offering adjustable and low-impact workouts tailored to individual needs [8]. They enable repetitive exercises while minimizing therapist intervention, potentially increasing the number of patients treated per therapy [9]. Research has shown promising outcomes in improving upper extremity function, particularly for stroke patients [10]. This aims to improve muscle movements, functional abilities, and overall quality of life for individuals with upper extremity impairments across various populations and conditions.

II. DESIGN PHILOSOPHY

Motorized ergometers are a specialized category of exercise equipment intended to support rehabilitation and physical conditioning, particularly for upper limb injuries. These devices accommodate use in both seated and standing positions, making them accessible to individuals with diverse mobility and strength capacities. Research has shown that arm ergometry training can enhance cardiopulmonary fitness and improve lipid profiles in individuals with spinal cord injuries who rely on wheelchairs. [11]. Motorized ergometers offer notable benefits in rehabilitation environments by allowing patients to perform low-impact cardiovascular exercises that simultaneously strengthen upper body muscles. Research indicates that short-term aerobic exercise using arm ergometers can improve exercise capacity in patients with spinal cord injuries, though extended rehabilitation programs may be essential to achieve more comprehensive health outcomes. [12]. They are especially beneficial for individuals recovering from injuries or surgeries, as they can adjust the resistance to match the patient's current capabilities. By allowing controlled movements, these devices can help improve circulation, range of motion, and overall upper body strength [13] & [14].

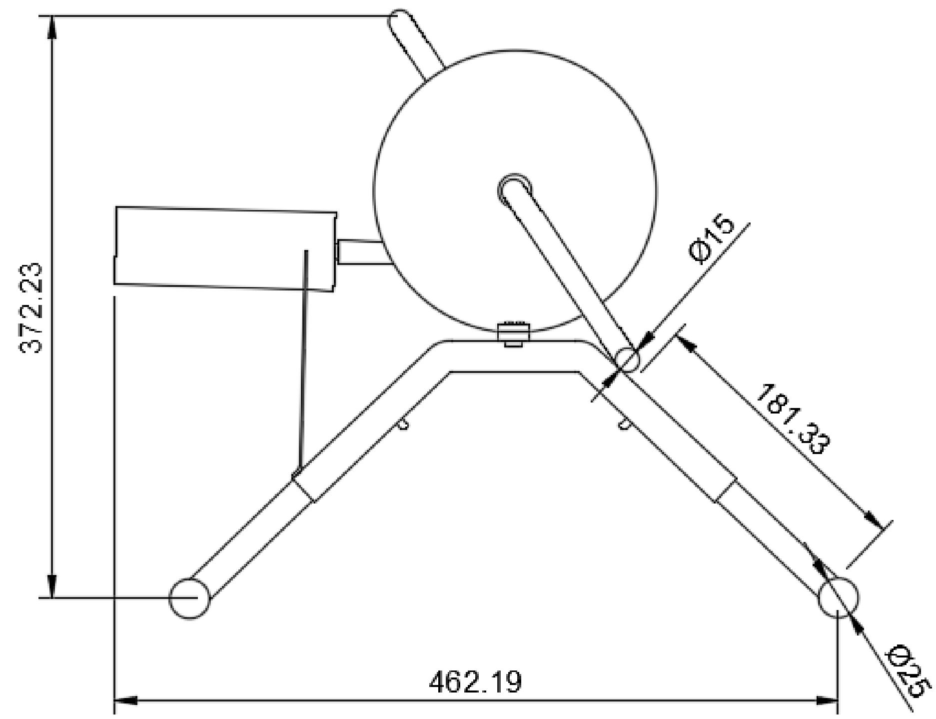


Fig. 1: Designed CAD Model of Ergometer.

The frame of arm ergometers is a critical component that supports the overall functionality and user experience. Many designs incorporate a modular structure, allowing for adaptability to various configurations based on user needs [15].The frame design, integrated with a rotating crank, enhances portability without compromising the device's compact form. Ergometer frames are constructed with average human dimensions in mind, ensuring comfortable use for individuals in both standing and seated positions. The device's overall dimensions strike a balance between user accessibility and spatial efficiency as shown in Fig.1. Portability remains a key advantage, as the lightweight construction—typically around 20 N—enables easy movement, making it suitable for home environments with limited space. Incorporating essential electronic components for data acquisition and power supply is paramount to optimizing the performance of the motorized ergometer. As the frame design progresses, provisions have been integrated to accommodate future additions, including sensors and servo motors within the structure. These components will enable precise movement tracking and real-time adjustments to exercise intensity, which are critical for enhancing user engagement and ensuring safety. Such considerations mark an important future scope of this project, enabling the development of a fully responsive and interactive rehabilitation system.

III. DESIGN SPECIFICATIONS AND MATERIAL SELECTION FOR MOTORIZED ERGOMETER

The materials chosen for the motorized ergometer structure are crucial in achieving an optimal balance of strength, weight, and durability. The following materials were selected based on their mechanical properties and suitability for specific components of the ergometer, each contributing to the overall performance and longevity of the design. An aluminum alloy 6061 is used for the main frame due to its high strength-to-weight ratio and corrosion resistance.

This provides the necessary structural integrity while maintaining a lightweight, portable design, ideal for easy transport and smooth operation in varied environments.

The two circular supports, made of cast iron, deliver high compressive strength and excellent vibration damping. With a compressive strength of up to 1,000 MPa, cast iron ensures frame stability and provides a solid, immovable base for the structure.

Carbon steel S45C, known for its high tensile strength (700 MPa) and wear resistance, is selected for the pedals. This choice allows the pedals to withstand cyclic loading and wear, ensuring long-term durability and user comfort through repeated, high-stress operation. SCM415 alloy steel is utilized for the worm gear due to its high surface hardness and fatigue resistance. Its ability to undergo surface hardening provides durability under repeated contact stresses, making it ideal for efficient and reliable torque transmission.

The material choices for the motorized ergometer system balance strength, weight, and durability to achieve a stable yet portable design. Each material was selected to optimize the performance of its respective component, ensuring the system can endure repeated mechanical loads, resist wear, and operate reliably over time. The aluminum frame provides lightweight structural integrity, while cast iron supports and carbon steel pedals enhance stability and wear resistance. SCM415 alloy steel in the worm gear maximizes durability under high-stress contact, contributing to the overall efficiency and longevity of the ergometer's mechanical system.

In designing the motorized ergometer, it is essential to establish the force and load requirements to ensure that all components meet structural integrity and performance standards under expected user conditions. Based on clinical and biomechanical studies, approximately 5.33% of a person's body weight is assumed to be supported by the upper extremity during such exercises [16]. With a standardized user weight of 80 kg, and applying a factor of safety (FOS) of 1.5 to account for variations, the equivalent design weight considered is 120 kg [17].

For each pedal, the force exerted is calculated as 10% of the adjusted body weight, equating to approximately 12 kg (or 117.72 N) per side. This force is assumed to act as a moment, rotating the pedals in clockwise and counterclockwise directions. Given that the lever arm length (distance from the pedal to the center of rotation) is 0.15 m, the torque exerted on each pedal can be calculated as follows:

$$\mathbf{Torque} = \mathbf{Force} \times \mathbf{Lever\ Arm\ Length} = \mathbf{117.72\,N} \times \mathbf{0.15\,m} = \mathbf{17.66\,Nm} \quad \text{-------(1)}$$

This calculated torque represents the critical loading requirements that the frame and all supporting components of the ergometer must endure without experiencing excessive deflection or compromising structural integrity. To account for the dynamic and cyclic loading conditions inherent to rehabilitation exercises, the design necessitates that material and structural choices ensure sufficient rigidity of the frame, thereby minimizing bending and maintaining precise alignment under load. Additionally, applying a factor of safety allows the structure to accommodate peak loads and unforeseen forces, thereby enhancing both durability and user safety. This torque analysis provides a foundational parameter for material selection and dimensioning of load-bearing elements within the ergometer, ensuring it meets the mechanical demands of sustained usage.

IV. DESIGN OF WORM GEARS FOR ASSISTED ERGOMETER APPLICATIONS

The application of worm gears addresses specific requirements for high torque, compact design, and self-locking functionality, which are essential for patient safety and controlled motor assistance. A worm gear mechanism, comprising a threaded worm and a helical worm wheel, enables efficient power transmission with the added benefit of preventing back-driving—an important feature in systems where resistance adjustments must be secure and precise. This self-locking property, combined with the worm's ability to deliver smooth motion control, makes worm gears especially suitable for applications in adaptive rehabilitation systems, where exercise resistance needs to be closely regulated according to real-time physiological feedback, such as a patient's heart rate.

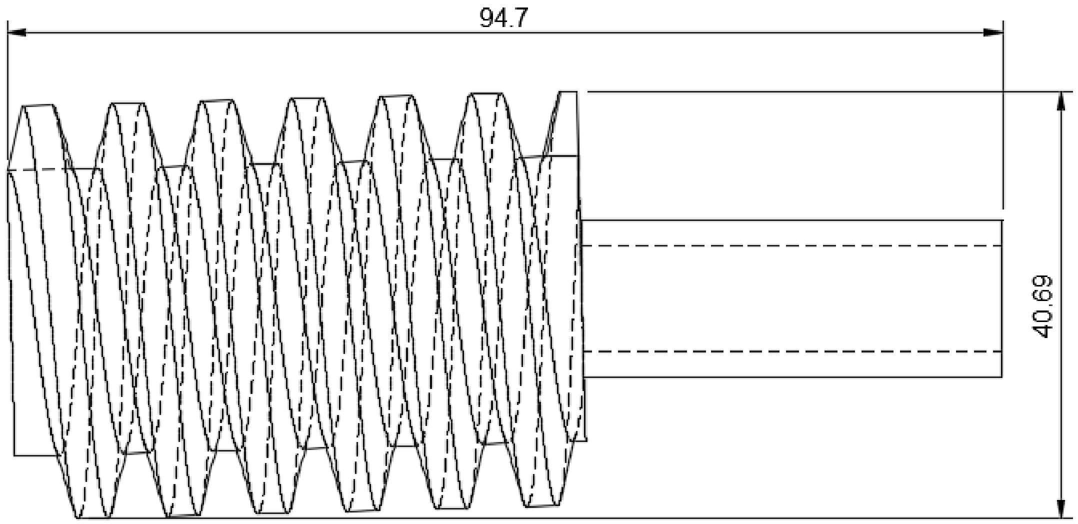


Fig. 2: Design and Dimensions of SCM415 alloy steel Worm Gear.

Critical design parameters, including the lead, pitch diameter, and helix angle, are carefully calculated to ensure compatibility with the motor's torque and speed output. These parameters directly impact the mechanical performance, durability, and smoothness of motion within the ergometer, thereby influencing both the user experience and the therapeutic effectiveness of the device as shown in Fig. 2.

Table 1: Parameters selected for Gear Design

Module	m	1 mm
Threads per inch	TPI	4
Lead angle	λ	75.5°
Gear ratio	GR	1:5

In the design and integration of a worm gear mechanism, achieving precise alignment is essential to reducing wear and ensuring consistent, reliable operation. To optimize power transmission efficiency, it is critical to carefully align the worm's lead angle with the gear's helix angle. Furthermore, appropriate lubrication plays a vital role in enhancing the system's durability and overall performance. Through the rigorous application of relevant design equations and calculations, a durable and efficient worm gear system can be developed and successfully implemented.

1. The output speed (ω_{out}) can be calculated as:

$$\omega_{\text{out}} = \omega_{\text{in}} \times \left(\frac{T_{\text{Driver}}}{T_{\text{Driven}}} \right)$$

$$\omega_{\text{out}} = 750 \times \left(\frac{4}{20} \right) = 150\,\text{RPM} \quad \text{———————————————————— (2)}$$

where ω_{in} is the motor's input speed, $T_{\text{Driven}}$is the number of teeth on the driven gear, and T_{Driver} is the number of teeth on the driving gear.

2. Force required at the lever arm to support the weight acting on the pedal:

$$\text{Force required} = \text{Weight acting on the pedal} \times \text{Acceleration due to gravity}$$

$$= 12\,\text{kg} \times 9.81\,\text{m/s}^2$$

$$= 117.72\,\text{N} \text{ ——————————————————————————————(3)}$$

3. Torque required at the lever arm to support the weight acting on the pedal:

$$\text{Torque required} = \text{Force} \times \text{Lever arm length}$$

$$= 117.72\,\text{N} \times 0.15\,\text{m} = 17.658\,\text{Nm} \text{——————————————————————(4)}$$

4. The output torque from the motor of Torque 5 Nm after considering the gear reduction and 10% transmission loss:

$$\text{Output torque} = \text{Input torque} \times \left(\frac{\text{Driven gear teeth}}{\text{Driver gear teeth}} \right) \times (1 - \text{Transmission loss})$$

$$= 5\,\text{Nm} \times \left(\frac{20}{4} \right) \times (1 - 0.1)$$

$$= 22.5\,\text{Nm} \text{———————————————————————————————(5)}$$

The output speed ω_{out} is 150 RPM. The force required at the lever arm is 117.72 N. The torque required at the lever arm is 17.65 Nm. The motor's output torque is 22.5 Nm. The designed system ensures reliability and stability during operation with a factor of safety of about 1.3.

V. FINITE ELEMENT ANALYSIS (FEA)

A comprehensive finite element analysis (FEA) was conducted on the gear assembly, a key component within the ergometer system, using the ANSYS 2023 R1 Student version on an assembly incorporating worm gears. The purpose of this analysis was to assess stress distribution, deformation, and the structural integrity of the gear components under specified loading conditions.

The model includes a worm gear fabricated from SCM415 alloy steel. This material was selected for its high tensile strength, toughness, and exceptional wear resistance, offering an ideal balance of durability and machinability for high-stress applications. SCM415's resistance to fatigue and impact allows the gear assembly to withstand the recurring mechanical loads encountered during operation. Additionally, SCM415 maintains structural integrity across varying temperatures, enhancing the reliability of the worm gear assembly in diverse environments. Consequently, the use of SCM415 alloy steel in the worm gear assembly design contributes significantly to the system’s durability, efficiency, and overall performance, ensuring prolonged functionality with minimal maintenance.

The gear geometry was imported as a STEP file, consisting of solid and surface bodies. To achieve accurate dynamic analysis, a structured mesh was applied to critical components, while a tetrahedral mesh was used for complex parts, such as the worm gear and pedal shaft. Coarse meshing was used for static components of the frame, while finer meshing was applied to rotational parts like the worm gear and pedal assembly to capture detailed interactions during motion. Three-dimensional solid elements were employed for structural parts, while rotating components were modeled as rigid bodies to represent their rotational degrees of freedom. Meshing around the contact interfaces between the worm and driven gear was refined to accurately represent contact mechanics and ensure effective force transmission throughout the gear assembly.

Boundary conditions for the ergometer simulation were established according to the physical constraints and expected motion of the device. Fixed support boundary conditions were applied to the base frame, fully constraining all degrees of freedom (DOFs) at points of contact with the ground to keep the structure stationary throughout the analysis. The worm gear, which is directly motor-driven, was set to an angular velocity of 750 RPM (equivalent to 78.54 rad/s) with a constant applied torque of 5 Nm to represent the motor's input.

The driven gear was linked to the worm gear through a gear pair constraint with a specified gear ratio of 5:1, ensuring that the driven gear rotates at one-fifth the worm's speed while proportionally increasing torque to the pedal shaft. Rotational DOFs were assigned to the pedal shaft, which is coupled to the driven gear. An opposing user-applied torque of 17.658 Nm, derived from a 12 kg force applied at a 15 cm lever arm, was applied to the pedal shaft to represent real-world user interaction.

In this configuration, the motor’s 5 Nm input torque was adjusted to account for a 22.5 Nm effective torque at the pedal shaft due to the gear ratio, while the counteracting user torque remained 17.658 Nm. The resulting net torque shows that motor torque exceeds user-applied torque, creating continuous pedal motion under simulated conditions.

Contact interactions between the worm and driven gears were defined using frictional contact pairs, with a no-penetration condition at contact regions to ensure accurate force transmission and realistic gear engagement.

This dynamic analysis successfully replicates the interaction between motor-driven motion and user-applied force, reflecting the counteracting torques and boundary constraints. The analysis provides a robust framework for optimizing the ergometer's design, with a focus on enhancing user experience and energy efficiency.

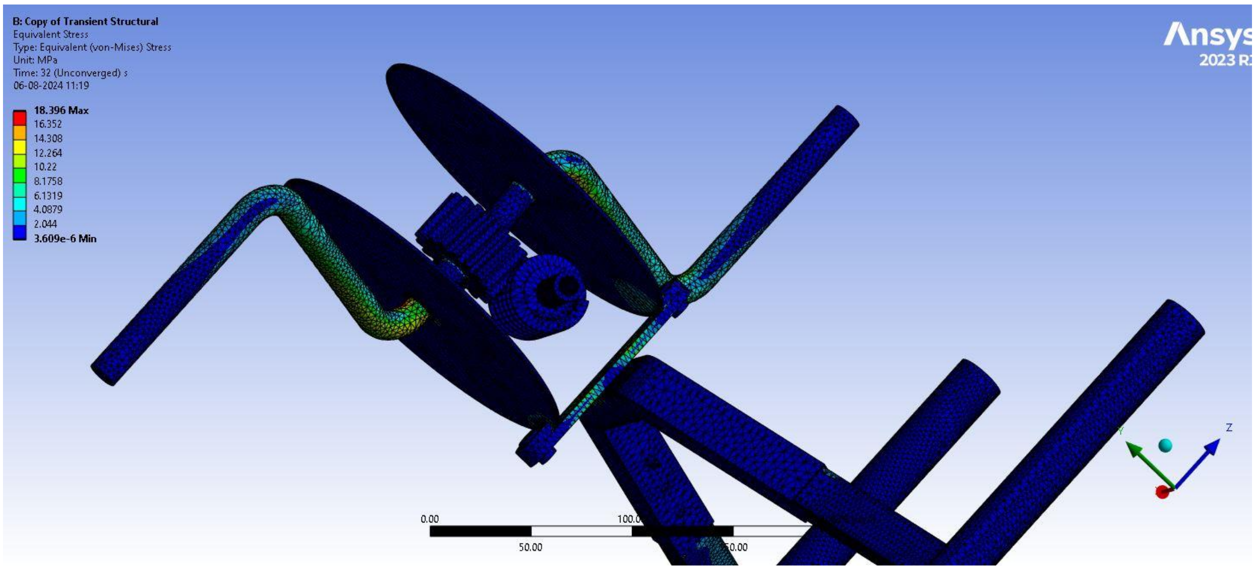
VI. RESULTS AND DISCUSSIONS

The following section presents the outcomes of the finite element analysis (FEA) conducted on the motorized ergometer's worm gear assembly, focusing on stress distribution and deformation under simulated loading conditions. The dynamic analysis aims to evaluate the structural integrity and performance of key components, specifically assessing how well the design accommodates the expected mechanical loads and user-applied forces.

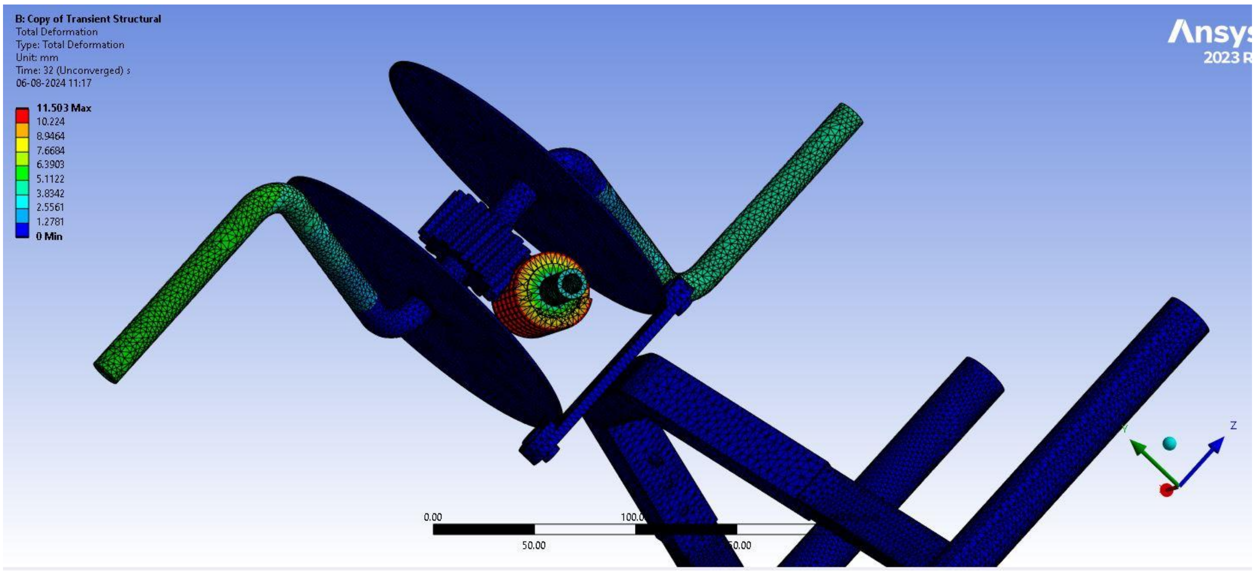
The results are analyzed to determine the adequacy of material selection, gear design, and applied boundary conditions in achieving the desired structural stability and operational efficiency. The discussions offer insights into the behavior of the worm and driven gear under the applied motor torque and counteracting user forces, highlighting areas where stress concentrations, deformation, or efficiency losses may impact overall performance.

The finite element analysis revealed that maximum deformation occurs at the gear teeth, pinpointing these areas as regions of highest stress concentration within the worm gear assembly. This finding aligns with the expected behavior of gears under load, as the teeth endure the most direct contact forces and torque transmission between the worm and driven gears. Detailed von-Mises stress analysis indicated that stress levels across the gear assembly remain well within the material's yield strength, confirming that the chosen alloy steel (SCM415) offers sufficient robustness to handle the applied loading conditions without risk of yielding or permanent deformation.

A. Results of Equivalent (Von-Mises) Stress Distribution



B. Results of Total Deformation



The ANSYS dynamic analysis provides comprehensive insight into the gear assembly's structural performance, demonstrating that the worm gear mechanism can withstand the applied forces and moments imposed by both motor input and user counter-torque. The alloy steel material offers an optimal balance of strength and stiffness, supporting the durability of the system under loading. The gear assembly's capacity to resist significant deformation, even under dynamic loading conditions, underscores the suitability of the material and design for high-stress applications within the ergometer.

In conclusion, the FEA results validate the design and material selection of the worm gear assembly for use in motorized ergometer systems. The analysis confirms that the assembly is capable of maintaining structural integrity and operational reliability under simulated real-world conditions. These findings suggest that the current design is well-suited for practical implementation in rehabilitation equipment, where durability, precision, and user safety are paramount. Future work could explore optimizing gear tooth geometry or introducing additional treatments to further enhance wear resistance and longevity, thereby ensuring consistent performance over extended use in rehabilitation settings.

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