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Original article

Design and Development of a Robotic Prototype for Ankle Rehabilitation

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Abstract

The purpose of this study was to design and develop a robotic device for ankle rehabilitation that is capable of reproducing physiological foot movements in three anatomical planes and supporting both active and passive therapy modes. The device is intended for use in rehabilitation therapy after injuries and surgeries of the ankle joint, for patients with neurological impairments of the lower limb motor function, and for biomechanical studies of foot motion. A computer aided design approach was applied to construct a platform capable of dorsiflexion and plantarflexion, inversion and eversion, and internal and external rotation. The mechanical system included a perforated fixation platform adapted to the anatomy of the foot, arc guides with roller supports, three linear actuators for movement conversion, and a central bearing unit to provide vertical axis rotation. Structural elements were manufactured from anodized aluminum and tool steel to ensure strength, low weight, and resistance to corrosion. The control system was based on a microcontroller architecture with position encoders, drivers, and safety mechanisms. The software supported manual, semi-automatic, and automatic therapy modes, with the ability to calibrate and store patient parameters. Kinematic modeling confirmed the possibility of achieving the required range of motion: dorsiflexion and plantarflexion up to ±25 degrees, inversion and eversion up to ±15 degrees, and smooth internal and external rotations. Simulation demonstrated accurate trajectory control with high repeatability. Biomechanical analysis indicated that the required force range could be achieved with selected actuators, while structural verification in the design software showed maximum stresses and deformations within safe limits. The developed robotic prototype demonstrates feasibility for clinical rehabilitation of the ankle joint, enabling precise reproduction of natural foot movements, secure patient fixation, and adaptable therapy modes. This system provides a promising technological solution to improve recovery outcomes after trauma or surgery and to expand research opportunities in biomechanics.

Keywords: ankle joint, rehabilitation, robotics, exoskeleton device, orthopedic procedures.

1. Introduction

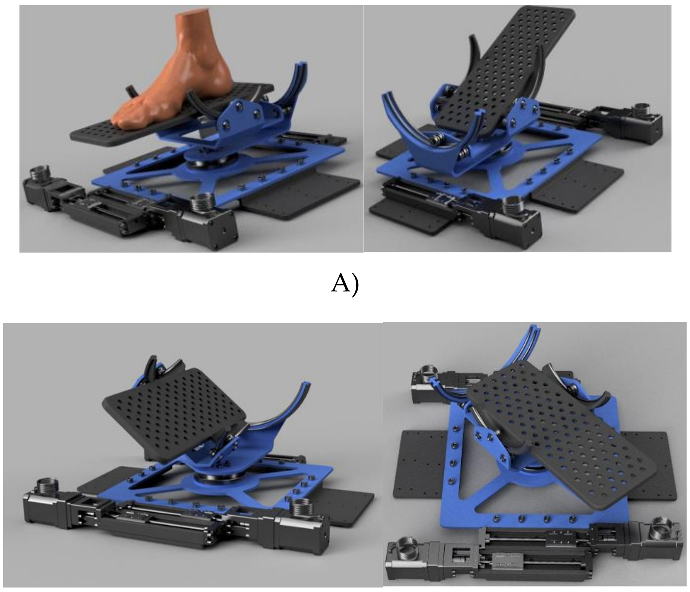
Ankle joint dysfunctions, whether due to trauma or neurological conditions, frequently impair gait and decrease independence, affecting quality of life across a broad patient population. Rehabilitation of the ankle is vital, as it plays a fundamental role in balance, ambulation, and functional mobility. However, conventional therapy methods are constrained by therapist availability, low training intensity, and patient-therapist variability. In contrast, robotic-assisted rehabilitation is emerging as an effective adjunct, enabling precise, reproducible, and high-intensity therapeutic sessions [1,2].

Despite increasing innovation, many ankle rehabilitation robots cover only one or two motion planes, usually limited to dorsiflexion and plantarflexion, failing to reproduce full physiological motion including inversion/eversion and rotation [3]. Wearable exoskeletons often lack Multi-Degree-Of-Freedom (MDOF) capability, whereas platform-based systems with 2-DOF cannot support comprehensive ankle biomechanics or research needs [4]. Although recent designs incorporate three-degree-of-freedom (3-DOF) mechanisms using spherical or parallel configurations , challenges remain in aligning mechanical axes with anatomical joints and in integrating both active/passive therapy and biomechanical assessment in a single system [5,6].

The aim of this study was to design and develop a robotic prototype for ankle rehabilitation providing three anatomical degrees of freedom: dorsiflexion/plantarflexion, inversion/eversion, and internal/external rotation with accurate alignment to the ankle joint. The device incorporates both active and passive therapeutic modalities, programmable trajectories, safety features, and biomechanical sensing capabilities. It targets applications including post-injury/surgery rehabilitation, neurological motor dysfunction therapy, and biomechanical research.

2. Materials and Methods

This study presents the design, development, and validation of a robotic platform for ankle joint rehabilitation. The system was conceived as a parallel kinematic mechanism with three active degrees of freedom aimed at replicating physiological ankle movements. The methodology included mechanical design, kinematic modeling, actuator selection, control system development, and trajectory simulation.



A)

B) C)

Figure 1 – Achievable ranges of motion of the prototype ankle rehabilitation robot. A: dorsiplantar flexion /extension, B: inversion/eversion, C: internal/external rotation

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No human participants were included in this stage of the work. The research was carried out using CAD models, engineering calculations, and biomechanical data used from published literature [7,8]. The mechanical components were modeled using SolidWorks CAD environment, with stress and deflection simulations performed for structural verification.

Device Construction

The mechanical system of the device consists of several key components designed to ensure stability, precision, and durability. The foot fixation platform, constructed as a perforated support, is anatomically adapted to the human foot to provide rigid fixation and uniform load distribution. Controlled movements in two angular degrees of freedom are achieved through guide arcs with precision roller supports, which enable smooth and repeatable trajectories. Three linear actuators, positioned around the base, convert translational motion into angular displacement, with each actuator equipped with feedback sensors to ensure accurate positioning. In addition, a central bearing unit provides vertical axis rotation, thereby enabling the third degree of freedom. To guarantee both mechanical strength and lightweight construction, all structural elements were fabricated from anodized aluminum and tool steel, offering corrosion resistance and long-term reliability.

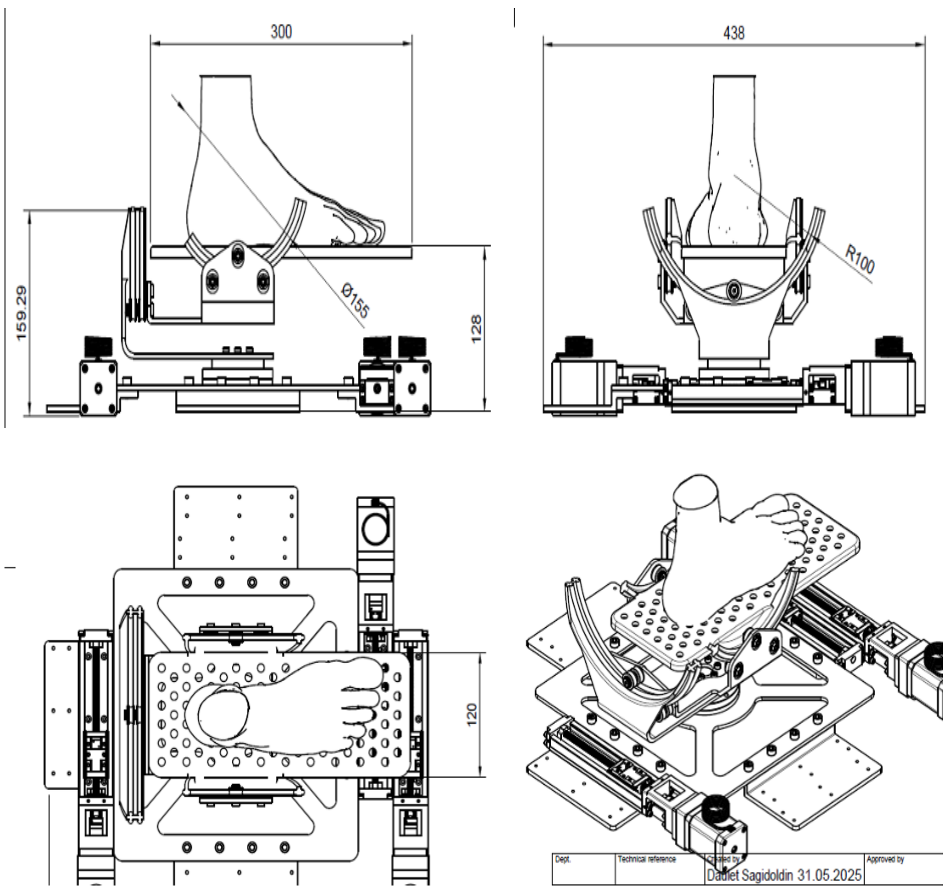

Figure 2 – Isometric views of the ankle rehabilitation robot prototype

Control System

The exoskeleton control system was based on a microcontroller/embedded computer architecture, coordinating all three DOFs. Each actuator incorporated an encoder, positioning driver, and safety stop mechanism. The software supported manual, semi-automatic, and automatic therapy modes, with adjustable amplitude limits and patient parameter calibration. Data exchange was enabled via USB/UART/CAN protocols.

Kinematic Modeling and Drivers Selection

The mechanism is a parallel structure with three active axes, each of which converts linear motion into angular rotation. Two of the three degrees of freedom are realized through movement along arc-shaped guides with rollers, and the third through the rotation of the platform on the central bearing.

Kinematic parameters of the arc:

Arc radius: R = 110 mm;

Maximum rotation angle:

Θ dorsi=±25 ∘ =±0.436 rad

Θ inversion =±15 ∘ =±0.262 rad

Translation into linear drive movement:

S = R Θ

- For dorsiflexion/plantarflexion (θ= ±25°), Smax = 47.96 mm.
- For inversion/eversion (θ = ±15°), Smax = 28.82 mm.

Selecting actuators

Requirements for linear actuators:

- Stroke: ≥50 mm;
- Force: ≥150 N with reserve;
- Speed: not less than 10–20 mm/s for passive therapy;
- Accuracy: ≤0.1 mm;
- Compactness and integration with the curved guide.

In the selected engine and propeller pair:

- NEMA 17 stepper motor with gearbox (if more torque is required);
- Screw with pitch p=2 mm/rev p=2 text{mm/rev} p=2 mm/rev;
- Gear ratio: 1:10 (if planetary gear is used);
- Encoder: optical or magnetic, 1024 imp/rev.

Calculation of the required torque on the engine shaft:

$$M_{eng} = \frac{F \cdot r_{shaft}}{\eta} = \frac{150 \cdot 0.318 \cdot 10^{-3}}{0.8} \approx 0.0596H$$

$$F_{load} = 150 \quad H, \qquad r_{shaft} = \frac{p}{2\pi} = \frac{2}{6.283} = 0.318 \quad mm$$

Taking into account the 1:10 gearbox:

M output = 0.596 N/m

Which is within the capabilities of compact stepper motors with gearboxes.

Structural verification

To confirm the strength of mechanical elements, stress and displacement assessments were carried out in the CAD environment.

To confirm the strength of mechanical elements, stress and displacement assessments were carried out in the CAD environment:

Materials:

- Main arms and arches - 6061-T6 aluminum;
- Bearing units - steel 45;

Analysis in SolidWorks Simulation:

- Maximum stress: 42 MPa (with permissible 250 MPa);
- Maximum deflection: ≤0.4 mm (within the permissible limits).

Biomechanical efforts

The required force was determined based on published biomechanical data on the resistance of the foot to movement in adults weighing 70–90 kg [7,8].

Translation into linear force (via lever radius R = 110 mm).

$$F = \frac{M}{R} \qquad F = \frac{15}{0.11} \approx 136.4\,\text{H}$$

Dorsiflexion:

- Inversion:
- Rotation (axis): if the radius of rotation of the center is Rrot=80 mm.

Table 1 – Typical moments of resistance

Degree of freedom	Range	Required moment, Nm
Dorsiflexion / Plantarflexion	±25°	10–15 Nm
Inversion/Eversion	±15°	5–8 Nm
Internal/External Rotation	±20°	3–5 Nm

3. Results

Structural Verification

- Maximum stress: 42 MPa (below material limit of 250 MPa);
- Maximum deflection: ≤ 0.4 mm, within permissible safety limits.

Trajectory Simulation

- Dorsiflexion/plantarflexion: fastest movement at 0.5 Hz, maximum amplitude;

●Inversion/eversion: moderate speed, smaller amplitude;

● Rotation: smoothest trajectory, representing natural but infrequent ankle movements.

The simulation confirmed the ability of the device to reproduce physiological ankle motions across three DOFs.

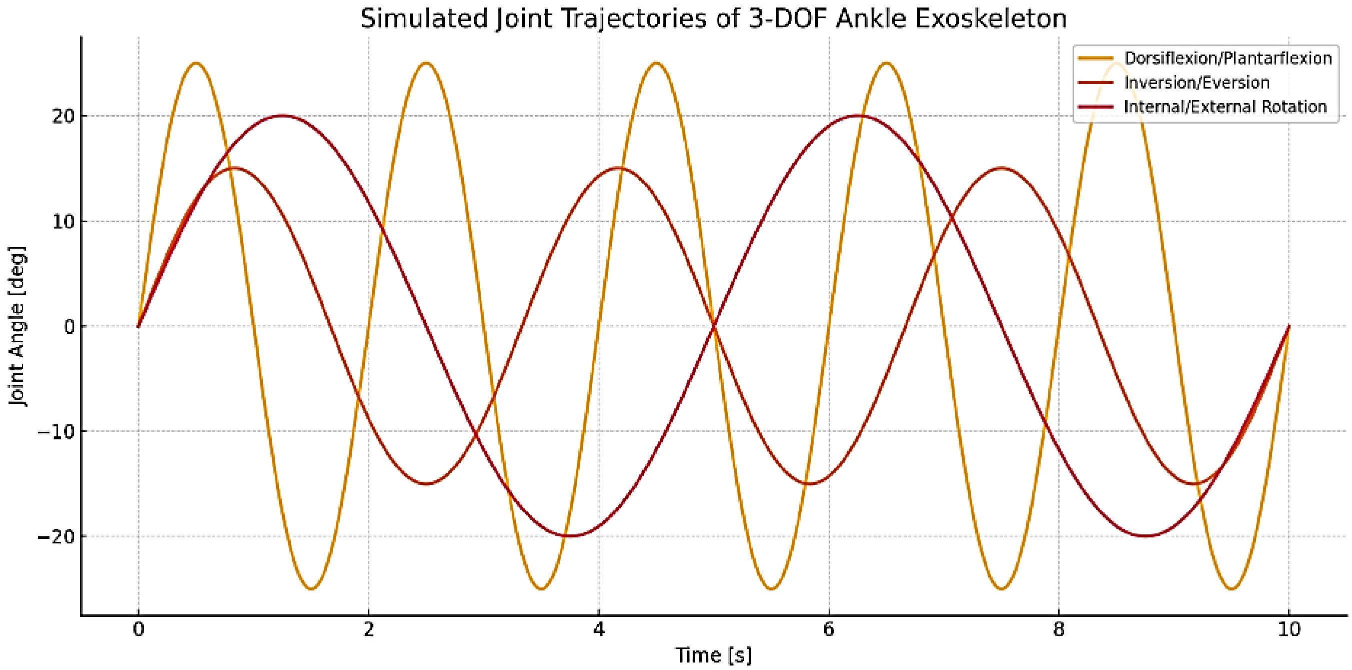

Figure 3 – Joint trajectories of 4-DOF Ankle Exoskeleton

The graph shows

Dorsiflexion is the fastest (0.5 Hz), with maximum amplitude;

Inversion - slightly slower, smaller amplitude;

Rotation - the smoothest, reflects rare rotational movements.

4. Discussion

The proposed exoskeleton platform addresses an important gap in ankle rehabilitation technologies by enabling three controlled degrees of freedom with high accuracy and repeatability. Unlike many existing ankle rehabilitation devices, which are often restricted to dorsiflexion and plantarflexion training [1,2], this platform provides a more comprehensive replication of ankle biomechanics by incorporating inversion/eversion and internal/external rotation. This versatility expands its potential applications, making it suitable not only for post-injury rehabilitation but also for patients with neurological impairments where multidirectional ankle control is crucial [3].

The kinematic analysis confirmed that actuators with a 50 mm stroke and force capacity of at least 150 N are sufficient to reproduce physiological ankle ranges of motion. These values are consistent with biomechanical standards established in prior foundational work and align with requirements reported in contemporary robotic rehabilitation studies [4-6]. Additionally, structural testing and CAD-based simulation demonstrated that the selected materials (aluminum 6061-T6 and steel 45) provided adequate strength, with maximum stress levels well below material yield limits, while maintaining a lightweight and portable design. Such properties are critical for ensuring both device safety and patient comfort during repeated rehabilitation sessions [7].

The integration of three DOFs also enables diverse therapy modes, including passive, active-assistive, and resistive exercises, which are considered essential for promoting motor recovery in both orthopedic and neurological rehabilitation [9]. Furthermore, the validation through CAD-based stress and trajectory simulations adds robustness to the preliminary design phase, ensuring that the mechanical and control systems are adequately prepared for future clinical implementation.

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Future work will therefore focus on clinical validation of the device in patients recovering from ankle injuries, stroke, and other neurological disorders, as well as long-term mechanical reliability testing. Moreover, the incorporation of advanced sensing technologies such as electromyography (EMG) and adaptive control algorithms could enhance the device's ability to deliver personalized therapy tailored to the specific needs of individual patients [10].

5. Conclusions

The aim of this study was to design and simulate a robotic exoskeleton capable of reproducing physiological ankle movements in three planes for rehabilitation purposes. The developed device demonstrated accurate kinematic performance, structural reliability, and the ability to provide versatile therapy modes, thereby addressing the limitations of existing rehabilitation technologies that are often restricted to single-plane movements. The findings confirm that the proposed system has significant potential for clinical application in the rehabilitation of patients with musculoskeletal injuries and neurological disorders, as well as for use in biomechanical research. While the current results are based on simulation and mechanical validation, future work will focus on experimental testing with patients to evaluate therapeutic effectiveness and long-term reliability.

Conflicts of Interest. The authors declare no conflicts of interest.

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Author Contributions. Conceptualization, O.K.A.; methodology, U.Sh.; examination, A.O.; design and analysis, A.O., B.A.; writing (original draft preparation), K.M.; writing (review and edition), K.M.; D.M.

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Тобық буынын оңалтуға арналған роботтандырылған прототипті жобалау және әзірлеу

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Түйіндеме

Бұл зерттеудің мақсаты табанның физиологиялық қозғалыстарын үш анатомиялық жазықтықта қайталауға және белсенді әрі пассивті терапия режимдерін қолдауға қабілетті тобық буынын оңалтуға роботтандырылған құрылғыны жобалау және жасау болды. Құрылғы жарақаттар мен операциялардан кейінгі оңалтуда, төменгі аяқтың қимылдық функциясының неврологиялық бұзылыстары бар науқастарда, сондай-ақ аяқ қозғалысының биомеханикалық зерттеулерінде қолдануға арналған. Платформаны әзірлеу үшін автоматтандырылған жобалау әдісі қолданылды. Құрылғы табанның бүгілуі мен жазылуын, инверсия мен эверсияны, сондай-ақ ішкі және сыртқы айналуын қамтамасыз етеді. Механикалық жүйе табанға бейімделген перфорацияланған бекіту платформасынан, доға тәрізді бағыттаушылардан роликті тіректермен, қозғалысты бұрыштыққа айналдыратын үш сызықтық жетектен және тік ось бойымен айналу үшін орталық тірек торабынан тұрады. Барлық элементтер анодталған алюминий мен аспаптық болаттан жасалған. Бұл берік, жеңіл әрі коррозияға төзімділікті қамтамасыз етеді. Басқару жүйесі энкодерлермен, драйверлермен және қауіпсіздік механизмдерімен жабдықталған микроконтроллерге негізделген. Бағдарламалық жасақтама қолмен, жартылай автоматты және автоматты терапия режимдерін қолдайды, сонымен қатар науқастың параметрлерін калибрлеуге және сақтауға мүмкіндік береді. Кинематикалық модельдеу қажетті қозғалыс ауқымына қол жеткізу мүмкіндігін растады: табанның бүгілуі мен жазылуы ±25° дейін, инверсия мен эверсия ±15° дейін, сондай-ақ ішкі және сыртқы айналуының бірқалыпты орындалуы. Модельдеу траекториялардың жоғары дәлдігін және қайталануын көрсетті. Биомеханикалық талдау күштердің жеткілікті ауқымын растады, ал беріктік есептеулері қауіпсіз мәндер шегіндегі кернеулер мен деформацияларды көрсетті. Тобық буынының оңалтуына әзірленген роботтық прототип клиникалық қолдану мүмкіндігін көрсетті. Ол табиғи қозғалыстарды дәл қайталауды, сенімді бекітуді және бейімделетін терапия режимдерін қамтамасыз етеді. Бұл жүйе жарақаттар мен операциялардан кейінгі қалпына келтірудің тиімділігін арттыруға және биомеханикалық зерттеулердің мүмкіндіктерін кеңейтуге арналған перспективалық технологиялық шешім болып табылады.

Түйін сөздер: тобық буыны, оңалту, робототехника, экзоскелет, буындағы қозғалыс көлемі, ортопедиялық процедуралар.

Проектирование и разработка роботизированного прототипа для реабилитации голеностопного сустава

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Резюме

Целью данного исследования являлась разработка и создание роботизированного устройства для реабилитации голеностопного сустава, способного воспроизводить физиологические движения стопы в трех анатомических плоскостях и поддерживать как активные, так и пассивные режимы терапии. Устройство предназначено для реабилитации после травм и хирургических операций на голеностопном суставе, для пациентов с неврологическими нарушениями двигательной функции нижней конечности, а также для проведения биомеханических исследований движений стопы. Для разработки платформы использован метод автоматизированного проектирования. Конструкция обеспечивает тыльное и подошвенное сгибание, инверсию и эверсию, а также внутреннюю и наружную ротацию. Механическая система включает перфорированную платформу для фиксации стопы, дуговые направляющие с роликовыми опорами, три линейных актуатора для преобразования поступательных движений в угловые и центральный опорный узел для вращения по вертикальной оси. Все конструктивные элементы изготовлены из анодированного алюминия и инструментальной стали, что обеспечивает прочность, легкость и устойчивость к коррозии. Система управления основана на микроконтроллере с энкодерами, драйверами и механизмами безопасности. Программное обеспечение поддерживает ручной, полуавтоматический и автоматический режимы терапии с возможностью калибровки и сохранения параметров пациента. Кинематическое моделирование подтвердило возможность достижения требуемого диапазона движений: тыльное и подошвенное сгибание до ±25°, инверсия и эверсия до ±15°, а также плавная внутренняя и наружная ротация. Моделирование показало высокую точность и повторяемость траекторий. Биомеханический анализ подтвердил достаточный диапазон усилий, а прочностные расчеты показали напряжения и деформации в пределах безопасных значений. Разработанный прототип робота для реабилитации голеностопного сустава демонстрирует возможность клинического применения, обеспечивая воспроизведение естественных движений стопы, надежную фиксацию и адаптивные режимы терапии. Система является перспективным технологическим решением для повышения эффективности восстановления после травм и операций, а также для расширения возможностей биомеханических исследований.

Ключевые слова: голеностопный сустав, реабилитация, робототехника, экзоскелет, объем движений в суставе, ортопедические процедуры.

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