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Original Article

Design and Development of an Ankle Rehabilitation Device

Jillian A. Bejoc[1], Randy K. Salazar[2,8,*], Lovelyn G. Tipon[3], Lance Aldwin S. Adlaon[4], Ulysses M. Cutamora[5], Alex E. Aparicio[6], Nera Mae P. Lagahid[7], Joselito C. Kuizon Jr.[8], Janclyde C. Espinosa[9], Rhonieljoyd G. Navales[6], Francisco Emmanuel Jr. III Munsayac[10], and Nilo T. Bugtai[10]

[1] College of Nursing & Allied Health Sciences, Cebu Normal University, Cebu City, Philippines

[2] Recoletos Biomedical Devices Innovation Laboratory, University of San Jose-Recoletos, Cebu City, Philippines

[3] Research Institute for Ageing & Health, Cebu Normal University, Cebu City, Philippines

[4] College of Medicine, Cebu Normal University - Vicente Sotto Memorial Medical Center, Cebu City, Philippines

[5] Physical Therapy Department, Velez College, Cebu City, Philippines

[6] Electronics and Communications Engineering, University of San Jose-Recoletos, Cebu City, Philippines

[7] Industrial Engineering Department, University of San Jose-Recoletos, Cebu City, Philippines

[8] Mechanical Engineering Department, University of San Jose-Recoletos, Cebu City, Philippines

[9] Civil Engineering Department, University of San Jose-Recoletos, Cebu City, Philippines

[10] Evelyn D. Ang Institute of Biomedical Engineering and Health Technologies, De La Salle University, Manila, Philippines

*Correspondence:
r_ksalazar@usjr.edu.ph

Abstract

Background: *Ankle injuries significantly impair function and mobility. Timely physical therapy is crucial for minimizing complications, accelerating healing, and facilitating a quicker return to everyday life. Lapses in therapy adherence can have detrimental consequences, prolonging recovery and potentially leading to long-term limitations. This project intends to design and develop an assistive device prototype for foot ankle rehabilitation, improving access to and adherence to necessary therapy.*

Methods: *A patient's narrative on her experience with ankle injury and rehabilitation offered crucial information for designing and developing the ankle rehabilitation assistive device. A series of discussions led to establishing design requirements and device specifications ready for prototyping. Experts in engineering, nursing and medical care, physical therapy, and ergonomics contributed to innovating physical rehabilitation therapy. A prototype was constructed and subjected to functionality testing and initial evaluations.*

Results: *Results of the prototype functionality tests show a need to make several adjustments, including changes in the driving mechanisms—improvements in the load capacity, programming, and control fine-tuning.*

Conclusion: *Future work on the prototype includes the implementation of the functional test results. Subjecting the prototype to clinical testing and validation, developing and integrating the mobile app, IP registration, and commercialization.*

Keywords

foot-ankle rehabilitation, collaborative research, design thinking, kinematics of walking, biomedical device, assistive device, user-centered, human-centered design

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INTRODUCTION

Walking is fundamental to quality of life, symbolizing independence and enabling individuals to perform daily tasks, engage in recreation, and interact with their environment (Bayón et al., 2023). As the most accessible form of mobility, walking depends on the complex coordination of the musculoskeletal, nervous, and cardiovascular systems (Vaughan et al. 1999). Among the various body components involved, the ankle joint plays a pivotal role in all phases of the gait cycle, contributing significantly to stability, propulsion, and control (Conner et al., 2022; Moltedo et al., 2018; Shorter et al., 2013).

Injuries to the ankle—whether bony, soft tissue, or both—can severely impact mobility and daily function. Beyond physical limitations, they may lead to sensory deficits, psychological distress, and reduced quality of life. Anxiety, depression, and social isolation are common consequences, further complicated by pre-existing conditions and socio-economic constraints (National Institute for Health and Care Excellence [NICE], 2022). The burden extends to caregivers, and the financial strain is often substantial, especially with prolonged recovery.

Effective management of ankle injuries aims to minimize complications and restore function early. Depending on severity, fractures may be treated conservatively through immobilization or surgically via internal fixation. Rehabilitation must begin once callus formation, or fracture stability is confirmed to prevent complications such as malunion, contractures, and soft tissue atrophy. Early range-of-motion exercises promote bone healing, preserve soft tissue function, and accelerate recovery.

However, patient adherence to rehabilitation protocols remains a challenge. Factors such as low self-efficacy, pain, psychological barriers, financial constraints, and logistical difficulties—especially in rural or underserved areas—often hinder participation (Jack et al., 2010).

In the Philippines, while public rehabilitation services like the "Malasakit" program offer free therapy, strict attendance rules and limited slots reduce accessibility for many patients. Missed appointments or late arrivals can lead to forfeited slots and longer waiting times, discouraging compliance despite the cost-free model. Private rehabilitation, on the other hand, often entails prohibitive expenses, delaying treatment, and compromising outcomes.

Non-adherence increases the risk of complications, including prolonged disability, reduced range of motion, and further medical costs. These systemic challenges highlight the urgent need for a cost-effective, user-friendly assistive solution that allows independent or minimally supervised ankle rehabilitation, especially in home settings. The majority of the market-available assistive devices are foreign-developed and costly. These are not accessible to the majority of the local patients. As per collated reviews, these devices have great potential for rehabilitation therapy; however, these potentials and advantages have yet to materialize fully. According to reviews, designers must validate some requirements in the existing devices. These include patient adaptability, a lack of range of motion that tackles the full kinematics of the ankle joint, and a lack of validity and clinical testing to claim that it can treat ankle injuries effectively.

This project intends to design and develop a homegrown prototype for an assistive ankle rehabilitation device that can be used independently with little supervision, like in a home environment, improving accessibility to therapy. The device strongly emphasizes age-appropriateness, affordability, safety, and adherence to ethical and therapeutic standards. By offering a reliable and replicable rehabilitation protocol, the project seeks to improve patient access to prescribed physical therapy, increase compliance, reduce therapy-related complications, and help broaden the reach and efficiency of rehabilitation services. Grounded in user-centered design principles, the prototype was conceptualized through collaboration with multidisciplinary experts and guided by secondary data relevant to local user needs.

The technology development process follows an iterative approach, with the initial phase focused on prototyping, ergonomic alignments, and safety testing. A second phase involves a working prototype that is subjected to clinical validation, user customization, ergonomic refinements, and ethics protocol compliance to ensure the device meets both therapeutic objectives and real-world demands.

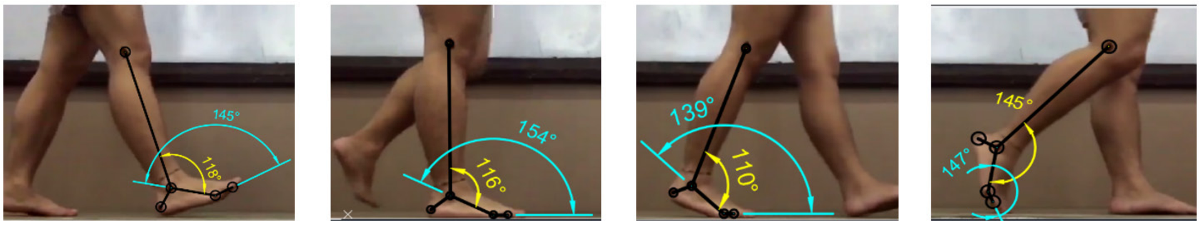
Review of Literature and Prior Arts

Ankle injuries can significantly impair function and mobility, hindering participation in everyday activities. Ankle immobilization after surgery is a necessary procedure that can further compromise the range of motion, strength, and overall function of the legs. The Global Burden of Disease (GBD) in 2019 reported a widespread impact on musculoskeletal conditions. These include ankle injuries, which are estimated at 1.71 billion people worldwide (Cieza et al., 2020).

These conditions affect individuals of all ages globally, with the Southeast Asia Region accounting for 369 million cases (World Health Organization, 2022). Lower leg fractures (patella, tibia, fibula, and ankle) represent a particularly prevalent and burdensome category, exhibiting the highest age-standardized incidence rate of 419.9 cases per 100,000 population and age-standardized rate of years lived with disability (YLDs) of 190.4 per 100,000 population in 2019. Globally, these fractures resulted in 15.5 million YLDs (Asia Pacific Fragility Fracture Alliance, 2021). Based on these global figures and the Philippine population of approximately 110.4 million, a rough estimate suggests approximately 463,570 cases and 210,202 YLDs attributable to lower leg fractures in the Philippines.

Ankle Joint Kinematics and Its Role in Walking

The ankle joint is a critical part of the human walking cycle. Each leg alternates between a stance phase when the foot is on the ground supporting the load (Figure 1b), and a swing phase, when the foot is in the air (Figure 1d). The leg switches from swing to stance at heel-strike (0% gait cycle), and it switches back to the swing phase at toe-off (around 60% of the gait cycle), Figure 1d (Zoss et al., 2006). In this cycle, the ankle joint alternately balances the body upright, shifting the angular position of the leg to align the body weight to the axis of the center of gravity.

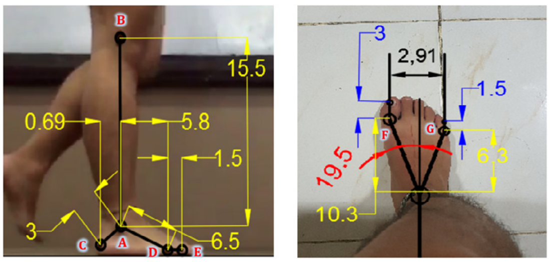


(a) *(b)* *(c)* *(d)*

Figure 1. *Mechanics of Walking: a) heel strike, b) opposite toe off, c) force shaft shear reversal, d) opposite foot strike (Crescencio et al., 2018)*

The stance phase imposes a significant demand on the ankle joint (Shorter et al., 2013). Carrying the load of the whole-body weight, Figure 1d.

Figure 2 shows sample dimensions of the lower limbs. Figure 2a shows the joint nodes and their distance from the other critical joints in the foot.

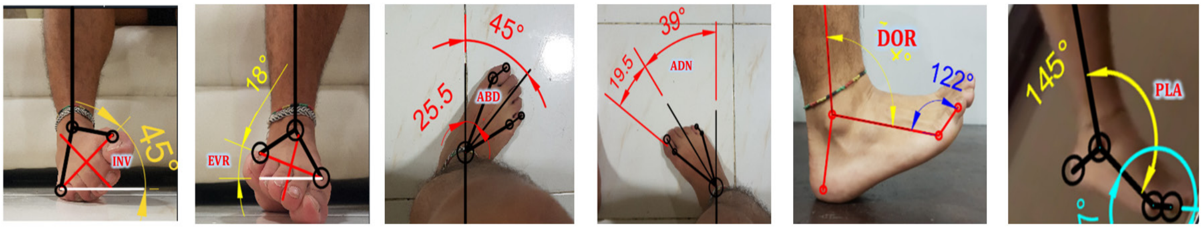


(a) *(b)*

Figure 2. *Lower Limb Kinematics: a) Side Elevation, b) Foot Width (Crescencio et al., 2018)*

Figure 3 shows the sample angular displacement measures. Each angular deflection has a flexibility limit depending on the point of reference and the person. These dimensions in Figure 3 may not be typical of all other people but are within the mobility range.

Figure 3a, inversion when the sole of the feet tends to twist inside the leg, 3b eversion when the sole tries to twist outside the leg. The pictures are included to show the different directions of the movement, and the dimensions are added to show how the measures are taken. This kinematics of the ankle is critical to physical therapy when an ankle is injured and undergoes rehabilitation.



(a) (b) (c) (d) (e) (f)

Figure 3. *Ankle Kinematics:*
a) inversion, b) eversion, c) abduction, d) adduction, e) dorsiflexion, f) plantar flexion (Crescencio et al., 2018)

Impact Management and Rehabilitation of Ankle Injuries

The ankle is a complex weight-bearing synovial hinge joint that plays a central role in supporting body weight and facilitating critical movements and motions of a person. It is composed of the tibia, fibula, and talus and supported by ligaments, muscles, nerves, and blood vessels (Arthritis Foundation, n.d.; Foot and Ankle Structure and Function, 2023; Sabalbal et al., 2013). Proper biomechanical function is essential for daily activities, and any trauma involving bones or soft tissues can significantly impair mobility and physical independence (Horak, 1987; Ramadi et al., 2022; Runge et al., 1999).

Ankle injuries may involve fractures, dislocations, sprains, or contusions, affecting individuals across all age groups, particularly the young and elderly (NICE, 2022). These injuries can result in pain, reduced mobility, sensory disturbances, and psychological effects such as depression and anxiety, with far-reaching social and economic impacts on both patients and caregivers (Horak, 1987; NICE, 2022). Management depends on injury type: stable fractures may require immobilization, partial or non-weight bearing, or internal fixation; soft tissue injuries are treated with rest, elevation, and ice compression to reduce inflammation (Ramadi et al., 2022).

Rehabilitation is critical to restoring ankle function and preventing long-term disability. It should be individualized, considering injury severity, pre-existing conditions, and functional goals. Programs typically follow a phase-based progression:

- **Acute Phase (1–3 days):** Focuses on reducing inflammation and pain using rest, ice, compression, elevation (RICE), and protection through braces or crutches.
- **Subacute Phase (3–6 weeks):** Introduces gentle range-of-motion and isometric exercises, followed by proprioceptive and balance training to improve joint stability and prevent reinjury (Bleakley et al., 2010).
- **Rehabilitation Phase (6+ weeks):** Involves advanced strengthening, agility, and functional drills tailored to lifestyle or sport-specific goals (Vykoukal, 2021).

Exercises like calf raises, ankle circles, and wobble board drills help restore strength, flexibility, and neuromuscular control throughout rehabilitation. Modalities such as manual therapy, electrical stimulation, or ultrasound may also reduce pain and promote healing (Management of Ankle Sprains, 2025; Slimmon & Brukner, 2010).

Post-surgical rehabilitation, especially after procedures like open reduction and internal fixation (ORIF), requires close collaboration between physical therapists and orthopedic surgeons. Rehabilitation timelines should be guided by tissue healing rates, surgical outcomes, and complications (Kyriacou et al., 2021; Rehabilitation Protocol for Ankle Fracture with ORIF, n.d.).

Ultimately, timely and structured rehabilitation enhances recovery outcomes, reduces reinjury risk, and supports a safe return to daily activities or sports participation.

Review of Assistive Devices for Lower Limbs Rehabilitation

Generally, the process of restoring the functionality of the ankle joint is done manually by a licensed physical therapist (PT). However, the number of patients and limited access to a physical therapist necessitate having other options, like using an assistive device. Assistive devices for lower-limb rehabilitation, especially the robotic kind, represent a rapidly advancing field, incorporating a variety of technological approaches to restore mobility and improve gait function. These systems are typically classified based on their operational modality and targeted anatomical regions. The current clinical practice prescribes a broad spectrum of off-the-shelf and custom-made assistive devices to patients with gait and mobility problems. Exercising the ankle to the full range of motion will help boost joint and ankle mobility to the surrounding tissue, muscle, and ligaments and help promote flexibility (Vykoukal, 2021). Some assistive devices help patients involve in work, engage in family life, and enjoy social activities (Dinkel et al., 2023).

The lower limb assistive devices can be classified into the following categories shown in Figure 4; a) treadmill gait trainers, b) foot-plate-based systems, c) overground gait trainers, d) stationary gait trainers, e) ankle rehabilitation systems, and active foot orthoses (Díaz et al., 2011).

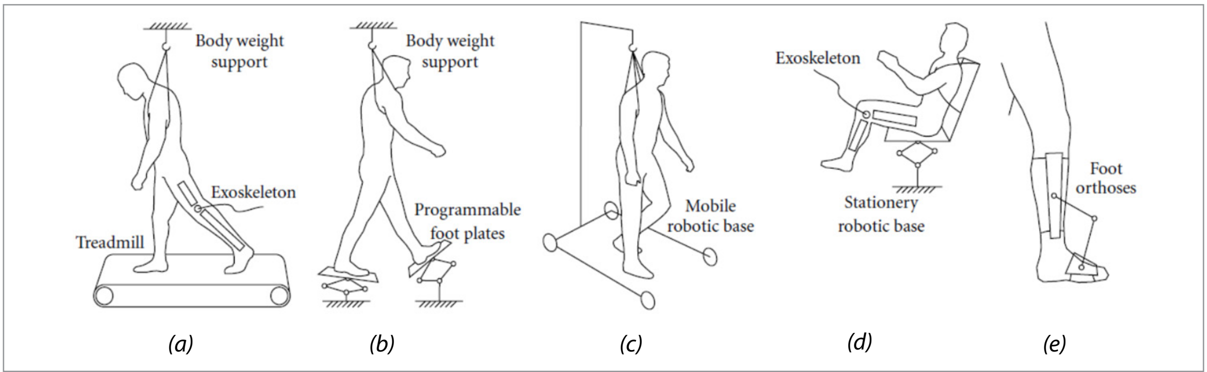
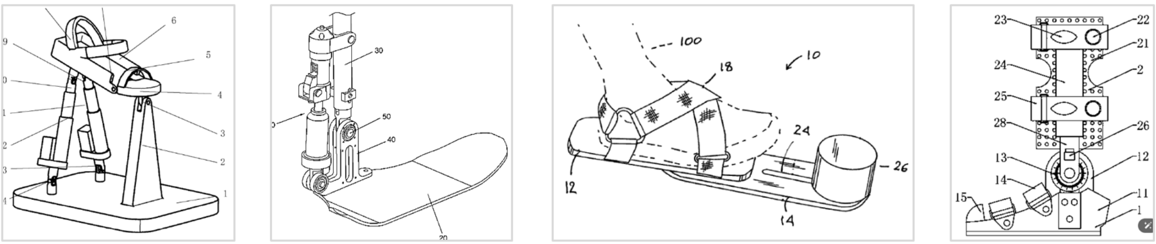


Figure 4. *Lower Limb Assistive Devices: a) treadmill gait trainers, b) foot-plate-based systems, c) overground gait trainers, d) stationary gait trainers, e) ankle rehabilitation systems, and active foot orthoses (Díaz et al., 2011)*



(a) *(b)* *(c)* *(d)*

Figure 5. *Patented Foot Ankle Rehabilitation Devices a) Foot-Ankle rehabilitation training device (Zhang et al., 2016) b) (Ji et al., 2018); c) Ankle rehabilitation device (Terrio, 2013); d) Medical Joint Rehabilitation (Xia, 2019)*

(a) (b) (c) (d)

Figure 6. *Foot and Ankle Exercise Apparatus:*
a) Total Ankle Trainer ROM (RehabMart, n.d.); b) Portable Robotic System Ankle Joint Rehabilitation (Nursultan et al., 2023); c) Ankle fracture rehabilitation training device (AliExpress, n.d.); d) Electric ankle trainer

Figures 5 and 6 show some of the latest searchable registered prior arts and commercially listed assistive devices. These are foot-ankle rehabilitation trainers or assistive devices that can be wearable or simply stationary. The focus of the design is the ankle joint mobility. Based on the reviews, even those devices with sophisticated robotics, systems are reported to have limited kinematics or mobility.

While robotic systems promise to transform lower-limb rehabilitation, continued innovation, clinical validation, and cost-effective use and development of the device are the probable keys to successful implementation in mainstream healthcare. Tables 1, 2, and 3 summarize a list of reviews from different articles. The list contains strengths, challenges, and further actions. Despite the strengths and advantages of several assistive devices, especially the robotic system, several significant challenges must be addressed.

Table 3 shows the suggested future research that the different articles have suggested.

Table 1. *Collated Reviews: Strengths of the Robotic System Rehabilitation Device*

1.	They reduce the physical workload of therapists by automating repetitive tasks,
2.	Provide consistent and intensive movement therapy,
3.	Programmability and repeatability of treatments
4.	Programmability for progressive training
5.	Allow for detailed and objective tracking of patient progress through integrated sensors and data collection.
6.	Robotic systems can provide objective, quantifiable data on patients' progress, facilitating precise monitoring and adjustment of therapy.
7.	The diversity of systems allows for tailored rehabilitation strategies based on individual patient needs.

Table 2. *Collated Reviews: Challenges of the Foot-Ankle Rehabilitation Devices*

1.	Many assistive devices do not provide a full range of motion, limiting their ability to emulate natural ankle joint movement and hindering rehabilitation.
2.	Most wearable robots do not allow adduction-abduction movement, leading to uneven muscle development or impairing gait and instinctive balancing actions (Dinkel et al., 2023).
3.	Joint angular displacements are often not adaptable to individual patient needs or a wide range of pathologies.
4.	AFOs have been reported to cause physical pain and discomfort during daily activities.
5.	In 12 studies by Dinkel et al. (2023), 6% to 80% of patients did not use a prescribed device due to medical issues, poor functionality, uncomfortable properties, or improper fit.
6.	The cost-effectiveness of treatments remains poorly defined (Mehrholz et al., 2018; Sale et al., 2012; Walsh et al., 2022).

Table 2. *continued*

7.	High development and purchase costs make many systems inaccessible to smaller clinics or home users.
8.	Many devices are bulky, have limited battery life, and are not user-friendly, making them difficult for patients to adapt to and use regularly.
9.	Most systems are not marketed or designed for home use, limiting their accessibility and applicability in day-to-day rehabilitation.
10.	Clinical validation is lacking; certified outcomes are needed to guide best practices and determine the appropriateness of interventions (Mehrholz et al., 2018; Sale et al., 2012; Walsh et al., 2022).
11.	Current clinical studies do not conclusively demonstrate that robotic rehabilitation outperforms traditional therapy methods.
12.	The ankle's complex multi-planar motion requires highly sophisticated systems, necessitating further research for effective rehabilitation solutions.

Table 3. *Collated Reviews: Suggested Further Research*

1.	Continue advancement and optimization of assistive technologies.
2.	Develop customizable and adaptive robotic rehabilitation systems.
3.	Integrate AI.
4.	Establish the standardized protocols and assessments for clinical integration.
5.	Develop an affordable, accessible, and user-friendly device for home-based rehabilitation.
6.	Subject the assistive device to a long-term clinical validation and sustainability of outcomes, which will establish the therapeutic benefits of the assistive device:

Design Requirements and Specifications

This project intends to design and develop a homegrown prototype of an ankle rehabilitation device. In general, this endeavor seeks to improve patients' accessibility to physical therapy, increase compliance, reduce therapy-related complications, and help broaden the reach and efficiency of rehabilitation services.

A multidisciplinary team met, discussed, and developed the general requirements and prototype specifications. The team is composed of two (2) nursing professionals, a medical professional, a physical therapist, three (3) mechanical engineers, an ergonomics specialist, two (2) electronics engineers, and a civil engineer (1).

Registered intellectual properties (IP) and commercially available foot-ankle rehabilitation devices were reviewed to evaluate design viability and protect against intellectual property infringements. The participant's experience as a former patient provides the most important information. Important details of the experience in ankle injury and the treatment and therapy process of the injury are vital information for understanding the importance of developing the assistive device. A licensed physical therapist served as a project consultant and verified the data.

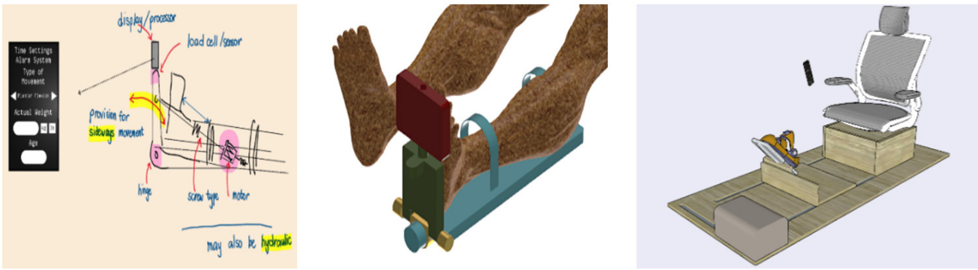
Table 4 shows the possible technical specifications or options for each key idea and general requirements based on the discussions and analysis of the project's requirements.

The team worked collaboratively to develop the prototype's design features and specifications. It then constructed the final prototype and tested it for functionality and performance to meet the required technical standards.

Figure 7 illustrates the series of design iterations that emerged from these discussions. Figure 7a shows the initial concept—a basic ankle boot design for therapy. Figure 7b presents a 3D model of a portable version, highlighting the mechanical components of the ankle therapy equipment. Figure 7c displays the final design. It is non-portable but offers a more comfortable, relaxed, seated therapy experience. The design incorporates a readily available ergonomic chair. The base of the chair was modified for stability. Figure 8 is the suggested Final Design details for prototyping. Seat dimensions were adapted from a chosen ergonomic chair. The therapist's stool is adjustable left or right, and the foot-ankle rehabilitation unit is adjustable left or right. It can be adjusted nearer or farther from the patient's seat. The foot-ankle unit is positioned for a comfortable seating position. The system is operated using a wired handheld control unit.

Table 4. *General Design Requirements Assessment*

Key concepts	General requirements	Possible technical solution
a. enhance accessibility	• a device that can run independently or with minimal supervision and • can be used in a home setting and can be run by the patient • a design that runs similarly to a vending machine	• a programmable and automated setup – Arduino-controlled system • Robust programming and instrumentation • Equipment that can be placed in health centers for anyone to go and have therapy sessions can be supervised by their PTs remotely.
b. the age-appropriate device	• user-centered, • customizable and person-fitted • safe	• Use of equipment with ergonomic features • customizable setup, personalized, programmable
c. follows ethical and therapeutic standards	• a device that is tested and validated • reliable, should safely run every time as designed • repeatable- settings and calibrations must always be true	• Validation can be done in the 2nd phase of the project • robust programming and reliable instrumentation
d. an affordable device	• can be owned	• Locally sourced or alternative materials, equipment, • cheaper parts alternatives



(a) (b) (c)

Figure 7. *Initial Sketches and Final Design*

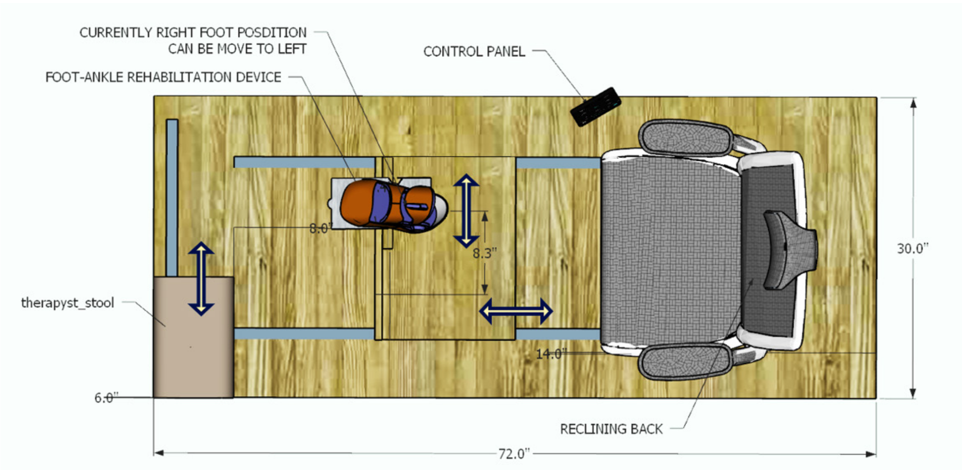


Figure 8(a). *Final Design with Dimension: Top View*

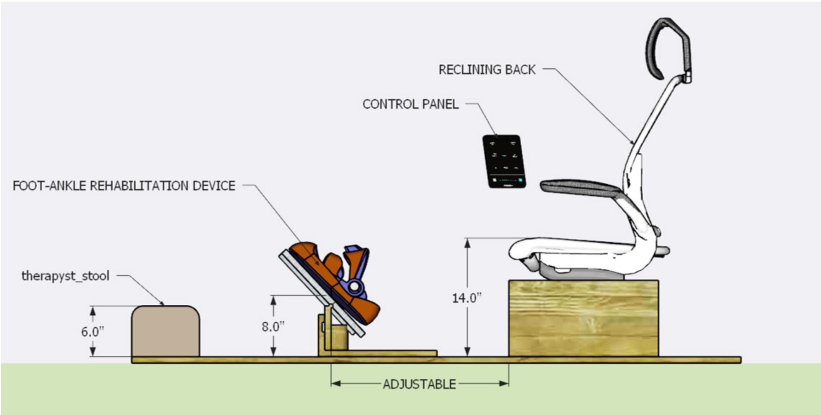


Figure 8(b). *Final Design with Dimension: Side View*

The final design has been officially registered under industrial design protection with the Philippine Patent Office, registration number PH32024051046.

As approved by the group, the foot-ankle unit mechanism design is shown in Figure 9. Figure 9b shows the three-axis foot pedal mechanism with three degrees of freedom, in three axial rotations, each having its own driving motor. Axial rotation (b2) for eversion and inversion, for adduction and abduction, axial rotation (b3), and for dorsiflexion and plantarflexion axial rotation (b1). The motors may be used singly or in combination to achieve a more fitting angular movement for a patient during therapy.

Table 5 shows specifications for the ankle angular displacement limits (Ankle and Foot, 2018; Clinical Gate, 2015; Foot and Ankle Structure and Function, 2023). These values present the maximum limits of angular movements the foot-ankle rehabilitation device must achieve.

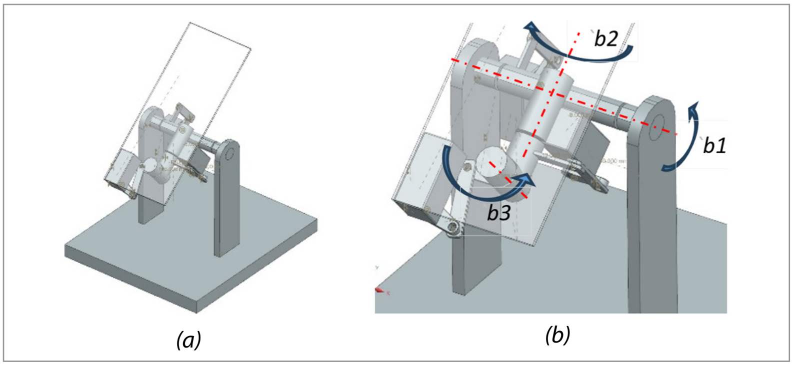
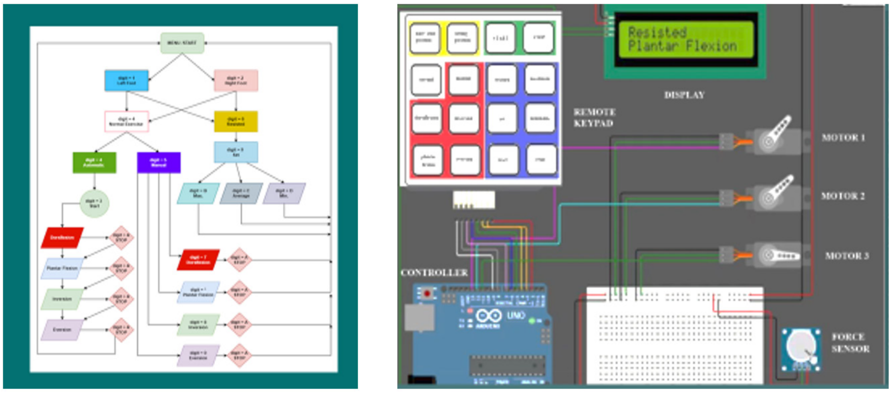


Figure 9. *Foot-Ankle Unit 3-Axis Mechanism: a) overall view;*
b) mechanism details - b1) Plantar flexion/dorsiflexion, b2) inversion/eversion, b3) adduction/abduction

Table 5. *Foot-Ankle Angular Displacement Limits*
(Ankle and Foot, 2018; Clinical Gate, 2015; Foot and Ankle Structure and Function, 2023)

Measure	*INVERSION*	*EVERSION*	*ABDUCTION*	*ADDUCTION*	*DORSIFLEXION*	*PLANTAR FLEXION*
Angle max	*30 deg*	*18 deg*	*45 deg*	*39 deg*	*25 deg*	*50 deg*

Figure 10 shows the motor control system for the foot-ankle mechanism. The programming design parameters include the therapy process and the acceptable limits of therapy movements and forces of the foot-ankle device. These protocols are embedded in the control system. Figure 10a shows the control algorithm, and Figure 10b shows the block diagram of the Arduino-controlled system.



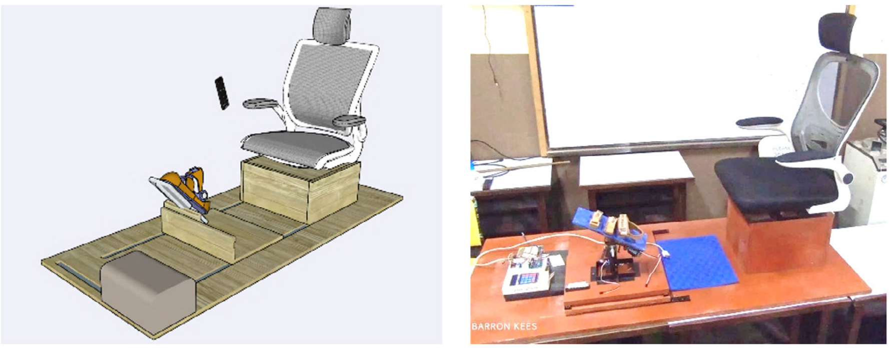
(a) (b)

Figure 10. *Suggested Design for Control System*
a) Control Algorithm and b) Arduino-Motor Control Diagram

Project Implementation

The prototype was constructed from locally sourced materials. The ergonomic chair, the Arduino units, and the motors were bought online. The cost of the setup, including construction, was kept very minimal.

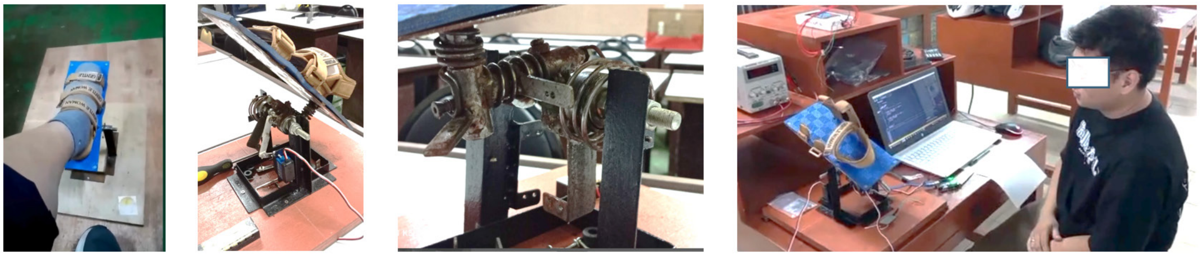
Figure 11a shows the team-approved final design, and Figure 11b shows the prototype. The prototype was fabricated according to the design measurements and specifications of the final design drawing. The seat is a commercially available ergonomic chair selected for comfort with proper back and neck support. The chair can be reclined for a relaxed and resting position during rehabilitation therapy. The foot-ankle unit can be nearer or farther from the seat. This position allows adjustability on the knee positioning. A patent has been applied for the three-axis foot pedal mechanism.



(a) (b)

Figure 11. *a) Final Design and b) Actual Prototype*

Figures 12a, 12b, and 12c present the foot-ankle mechanism. Figure 12d shows the Arduino control unit programmed to control the 3-axis mechanism of the foot-ankle unit. Figures 12b and 12c show the 3-axis revolute joint that allows the foot ankle unit 3 degrees of rotational freedom. This 3-axis joint can rotate singly through its actuating servo motor or any combination of the two or three axes servo motors. These allow a wide range of rotational movements. Figure 12c shows the 3-axis joint with the coil springs on each axis. The coil springs are installed to counter the weight of the mechanism enough to hold the footplate upright in its home position.



(a) (b) (c) (d)

Figure 12. *a) Foot Ankle Device Flexing Mechanism; b & c) 3-axis mechanism; d) with the Arduino control unit installed*

The Arduino unit, Figure 12d, drives the three servo motors for each axis. It also accepts feedback from the force sensor resistors installed on the footplate. The force sensor senses the force experienced in the footplate and sends feedback to the control unit. The addition of a force sensor allows for force adjustments on the mechanism. The servo motors facilitate three key foot-ankle flexing exercises: (a) plantar flexion and dorsiflexion, (b) inversion and eversion, and (c) abduction and adduction. Figure 13 shows the assembled foot-ankle mechanism. Motors are not visible.

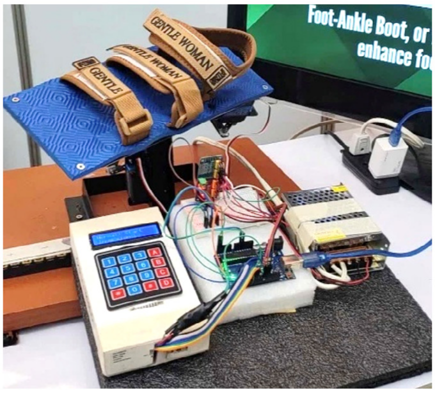


Figure 13. *Foot-Ankle Assemble*

Testing, Evaluations, and Discussions

Seat Ergonomics

The seat is a ready-made, commercially available ergonomics chair that was selected and tested for comfort and relaxation (Figures 14a and 14b). The chair's base was removed and replaced with a more stable wood base to ensure the user's safety. The height was retained and kept at the height of 14" (355.6 mm), which allows a smaller person to sit comfortably. The foot-ankle unit can be adjusted nearer or farther, depending on the patient's height, and allows for comfortable therapy, Figure 14c, including tall persons.

Overall, those who took a seat in the unit unanimously gave good feedback on the seating and reach of the foot-ankle mechanism.

(a) (b) (c)

Figure 14. *Seating Ergonomics*

Foot-Ankle Mechanism

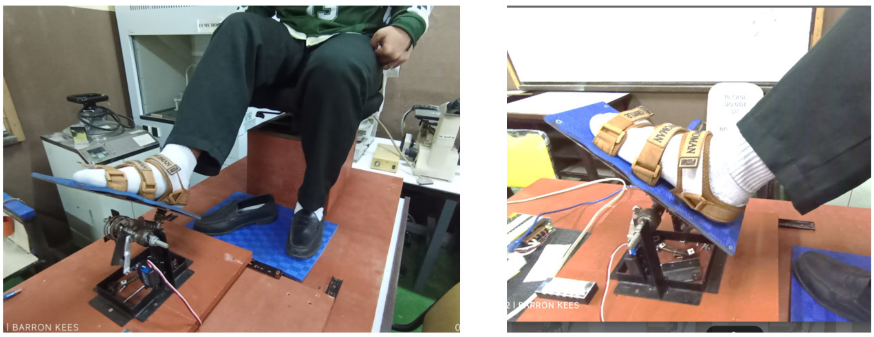
Initial tests were conducted on the foot-ankle mechanism, Figure 14, with the following results in Table 6. To stretch a healthy adult's ankle could require applying a rotational moment of roughly 5 to 20 Nm (which, depending on your method, might correspond to a force of tens to a couple hundred newtons), the exact numbers will vary widely from person to person and depend on the specifics of how you are applying the force (Wilken et al., 2011; Yamada et al., 2020).

A healthy body of 50kg may experience an ankle moment of 29 Nm to support the weight upright (Martínez-Jiménez et al., 2020). However, stretching to flex the ankle often targets specific muscles or tendons, not the general muscle group needed to stand upright. Thus, the moment may be further reduced, especially for those with injuries. Table 6 is the angular tests and force delivery results.

The data results, Table 6, show a need for recalibration and centering of the angular displacement. Given the device's intended use for both left and right feet, this displacement must be symmetrical about the neutral position. The angular displacements were generally satisfactory except for the abduction and adduction. The servo motor's force delivery requires improvement. A healthy individual typically requires a rotational moment of approximately 5 to 20 Nm (4 to 15 kg) for ankle flexion.

The current actuating mechanism, shown in Figure 16, utilizes a parallel bar linkage to connect the servomotor to the device platform. Initial testing has shown several shortcomings. First, slippage causes the platform to retract under the weight of the user's foot when the device is inactive.

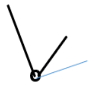
The parallel linkage and servomotor design have a low self-locking force that cannot support the foot's weight. A self-locking mechanism, such as a screw and nut assembly, would provide a more robust solution. Second, the parallel bar mechanism exhibits a poor speed-to-torque conversion ratio. Replacing it with a screw and nut mechanism would significantly improve this ratio. This design would significantly increase the effective force delivered by the servomotor to the device.

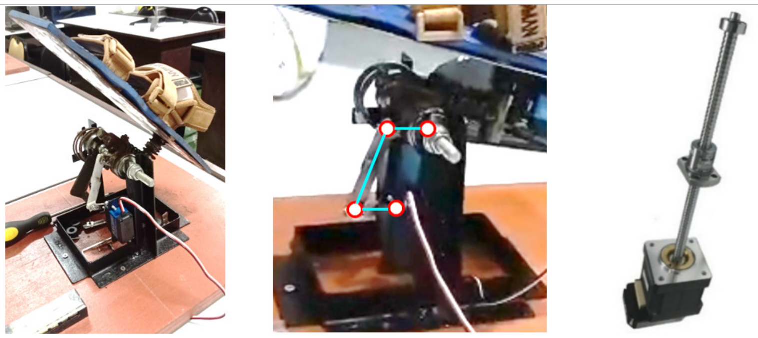


(a) (b)

Figure 15. *Foot Ankle Unit*

Table 6. *Foot-Ankle Device Angular Test and Force Results*

Measure	INVERSION	EVERSION	ABDUCTION	ADDUCTION	DORSIFLEXION	PLANTAR FLEXION
						
Angle max	20 deg	17 deg	25 deg	25 deg	25 deg	35 deg
Force kg	*5 kg*	*5 kg*	*2.5 kg*	*2.5 kg*	*2.7 kg*	*2.7 kg*



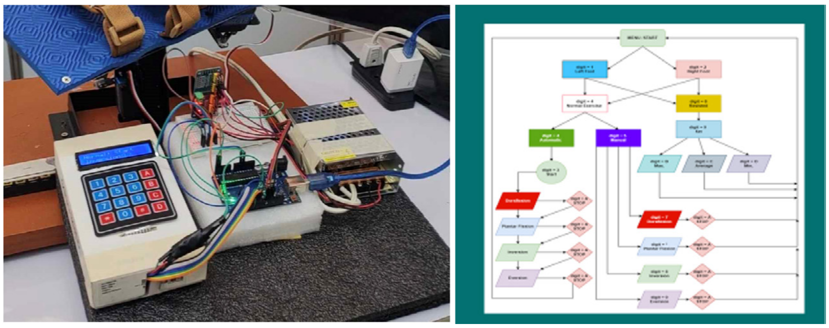
(a) *(b)* *(c)*

Figure 16. *Driving Mechanism; a) foot-ankle unit b) parallel Linkage, c) Servomotor + screw and nut linkage*

Control System performance and evaluation

Figure 17 shows the actual implementation of the Control System. The system utilizes an Arduino as the control unit and a motor driver to support a large-capacity servo motor. A power supply, a 12v DC unit, is used to run the system. A digital display and keypad are used as the user interface. The algorithm is shown in Figure 17b.

According to several runs and tests, the codes were adjusted several times to calibrate the proper angular displacements needed for the different axes. The strength of the servo motor is highly dependent on the driver circuit. The prototype shows enough allowance for stronger capacity delivery for the servo motors. More current means the motor can deliver a much stronger torque output. Code calibration will be finalized once the mechanism is final and appropriately calibrated. The programming code will be separately published or copyrighted.



(a) *(b)*

Figure 17. *Arduino Uno Control System*

CONCLUSION

This project was designed to develop a homegrown prototype for an assistive ankle rehabilitation device that can be used independently with little supervision, like in a home environment, improving accessibility to therapy. The design intent emphasized age-appropriateness, affordability, safety, and adherence to ethical and therapeutic standards.

By incorporating ergonomics in the design, the therapy process became a comfortable experience. The adjustability of the foot ankle therapy unit allowed customization of the setup to cater to different people's sizes and ages. Based on the reaction of those who took a seat on the prototype, the feel was similar to having a foot massage session.

The Arduino control unit allowed the programming of the rehabilitation process and the customization of the degree and intensity of the therapy. These features and the future additions of a mobile application, permitted a monitored progressive rehabilitation therapy. However, the current issue of the mechanical aspect of the prototype must be addressed.

The functionality testing results, Table 6, highlighted the need for calibration and design improvements, specifically increased power and a self-locking mechanism to prevent unintended retraction. Further testing will follow these modifications.

The control system power output can be improved; adding motor controllers for each servomotor increases the servomotor's power output. The finalization of the control system programming will depend on completing the mechanical revisions.

Overall, the study made significant progress toward developing an ankle rehabilitation device to increase access to physical therapy. The prototype is a step towards the next phase: patient customizations and clinical testing to validate its efficacy in treating and rehabilitating ankle injuries. The collaboration of experts from significant fields is key to creating the prototype. Maintaining the ergonomic design will provide the patient comfort and ease of use. The control system performance indicates a possible consistent and repeatable therapy delivery. The functionality tests have identified critical areas that require further development before the device can be deemed safe and effective for independent use.

The following activities are the suggested plan of work to improve the prototype:

1. Prioritizing the Mechanical Revisions;
2. Enhancing and finalizing the Control System, adding motor drivers, and adjusting the programming based on the new mechanism
3. Ergonomic Safety Validation, Initial assessments are positive, but further testing with diverse users is needed to ensure comfort and safety for all patient sizes and ages.
4. Establish Safety Protocols for device use and therapy process. These include clear instructions and visual aids on how the device must be used for self-administered and independent use with no injury risks.
5. Conduct clinical trials under medical professionals' supervision and evaluate the therapeutic effectiveness of the device.
6. Integrate mobile app features for monitoring and programming of therapy. These include data logging and remote monitoring to help therapists track progress and adjust therapy programs for greater effectiveness.
7. Perform Cost Analysis.

Author Contributions

Bejoc: Conceptualization (literature and clinical insights), Writing – original draft; **Salazar:** Conceptualization (mechanical design and technology integration), Data curation, Methodology, Funding acquisition, Project administration, Writing – review & editing, Resources; **Tipon:** Conceptualization (literature and clinical insights); **Adlaon:** Conceptualization (literature and clinical insights); **Cutamora:** Validation (Physical Therapy); **Aparicio:**

Conceptualization (control system electronics); **Navales:** Conceptualization (control system electronics), Software; **Lagahid:** Validation (ergonomics); **Kuizon Jr.**: Conceptualization (mechanical design); **Espinosa:** Conceptualization (mechanical design); **Munsayac Jr. III**: Project Consultant; **Bugtai:** Project Consultant

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Ethical Approval
This project adhered to the highest ethical standards in research and dissemination of findings. The data used in this study are secondary and derived from expert discussions, ensuring that no personal or patient-specific information was collected, processed, or analyzed. The project did not involve direct interviews with individuals outside the collaborating professionals; all discussions were conducted within the professional circle and in an academic setting.

Competing Interest
The authors declare no conflicts of interest.

Data Availability
Data will be made available by the corresponding author on request.

Declaration of Artifical Intelligence Use
In this work, artificial intelligence (AI) was utilized strictly for language editing and grammatical refinement. AI tools were not employed for data generation, idea formation, or content creation. All information, concepts, and analyses presented in this work are original contributions from the authors. AI-assisted modifications were limited to improving clarity, coherence, and readability without altering the substantive content of the research.

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REFERENCES

AliExpress. (n.d.). Adjustable ankle rehabilitation foot pedal trainer. Retrieved May 13, 2025, from https://www.aliexpress.com/item/1005006232835995.html?gatewayAdapt=glo2ita

Ankle and foot. (2018, February 5). Musculoskeletal Key. https://musculoskeletalkey.com/ankle-and-foot-2/

Arthritis Foundation. (n.d.). Ankle anatomy. https://www.arthritis.org/health-wellness/about-arthritis/where-it-hurts/ankle-anatomy

Asia Pacific Fragility Fracture Alliance. (2021, November 26). Bone fractures: A systematic analysis from the Global Burden of Disease Study 2019. https://apfracturealliance.org/bone-fractures-a-systematic-analysis-from-the-global-burden-of-disease-study-2019/

Bayón, C., Hoorn, M. van, Barrientos, A., Rocón, E., Trost, J. P., & Asseldonk, E. van. (2023). Perspectives on ankle-foot technology for improving gait performance of children with cerebral palsy in daily-life: Requirements, needs and wishes. Journal of Neuroengineering and Rehabilitation, 20(1). https://doi.org/10.1186/s12984-023-01162-3

Bleakley, C. M., O'Connor, S. R., Tully, M. A., Rocke, L. G., MacAuley, D. C., Bradbury, I., Keegan, S., & McDonough, S. M. (2010). Effect of accelerated rehabilitation on function after ankle sprain: Randomised controlled trial. BMJ, 340, c1964. https://doi.org/10.1136/bmj.c1964

Cieza, A., Causey, K., Kamenov, K., Hanson, S. W., Chatterji, S., & Vos, T. (2020). Global estimates of the need for rehabilitation based on the global burden of disease study 2019: A systematic analysis for the global burden of disease study 2019. The Lancet, 396(10267). https://doi.org/10.1016/s0140-6736(20)32340-0

Clinical Gate. (2015, March 11). The leg, ankle, and foot. https://clinicalgate.com/the-leg-ankle-and-foot/

Conner, B. C., Remec, N. M., Michaels, C. M., Wallace, C. W., Andrisevic, E., & Lerner, Z. F. (2022). Relationship between ankle function and walking ability for children and young adults with cerebral palsy: A systematic review of deficits and targeted interventions. Gait & Posture, 91, 165–178. https://doi.org/10.1016/j.gaitpost.2021.10.024
Crescencio, V., Wyndyll, S., Alajas, J., Torralba, K., Jude, R. , & Salazar, R. (2018). Lower limb kinematic analysis and design [Unpublished undergraduate thesis]. University of San Jose-Recoletos.
Díaz, I., Gil, J. J., & Sánchez, E. (2011). Lower-Limb robotic rehabilitation: Literature review and challenges. Journal of Robotics, 2011, 1–11. https://doi.org/10.1155/2011/759764
Dinkel, D., Rech, J. P., Hassan, M., DeSpiegelaere, H., Johanning, J., Pipinos, I., & Myers, S. (2023). A comparison of the perceptions of wearing an ankle foot orthosis by individuals with peripheral artery disease according to their baseline-level of physical activity. Journal of Bodywork and Movement Therapies, 35, 268–272. https://doi.org/10.1016/j.jbmt.2023.04.050
Foot and ankle structure and function. (2023, March 30). Physiopedia. https://www.physio-pedia.com/index.php?title=Foot_and_Ankle_Structure_and_Function&oldid=329337
Horak, F. B. (1987). Clinical measurement of postural control in adults. Physical Therapy, 67(12), 1881–1885. https://doi.org/10.1093/ptj/67.12.1881
Jack, K., McLean, S. M., Moffett, J. K., & Gardiner, E. (2010). Barriers to treatment adherence in physiotherapy outpatient clinics: A systematic review. Manual Therapy, 15(3), 220–228. https://doi.org/10.1016/j.math.2009.12.004
Ji, Y. H., Shin, D. B., Hwang, S. H., Han, Y. H., Lee, S. C., Jang, H. Y., & Han, C. S. (2018). Ankle module for wearable gait rehabilitation robot (Korean Patent No. 1019129200000) World Intellectual Property Organization (WIPO). https://patentscope.wipo.int/search/en/detail.jsf?docId=KR219380216&_cid=P11-M6U6WW-12161-1
Kyriacou, H., Mostafa, A. M., Davies, B. M., & Khan, W. S. (2021). Principles and guidelines in the management of ankle fractures in adults. Journal of Perioperative Practice, 31(11), 175045892096902. https://doi.org/10.1177/1750458920969029
Management of ankle sprains. (2025). Physiopedia. https://www.physio-pedia.com/index.php?title=Management_of_Ankle_Sprains&oldid=366925
Martínez-Jiménez, E. M., Losa-Iglesias, M. E., Becerro-de-Bengoa-Vallejo, R., Díaz-Velázquez, J. I., López-López, D., Calvo-Lobo, C., & Rodríguez-Sanz, D. (2020). Immediate effects of intermittent bilateral ankle plantar flexors static stretching on balance and plantar pressures. Journal of Manipulative and Physiological Therapeutics, 43(1), 24–31. https://doi.org/10.1016/j.jmpt.2019.02.012
Mehrholz, J., Pohl, M., Platz, T., Kugler, J., & Elsner, B. (2018). Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database of Systematic Reviews, 9(9). Cochrane Library. https://doi.org/10.1002/14651858.cd006876.pub5
Moltedo, M., Baček, T., Verstraten, T., Rodriguez-Guerrero, C., Vanderborght, B., & Lefeber, D. (2018). Powered ankle-foot orthoses: The effects of the assistance on healthy and impaired users while walking. Journal of NeuroEngineering and Rehabilitation, 15(1), 1–25. https://doi.org/10.1186/s12984-018-0424-5
National Institute for Health and Care Excellence. (2022, January 18). Rehabilitation after traumatic injury. https://www.nice.org.uk/guidance/ng211
Nursultan, Z., Marco, C., & Balbayev, G. (2023). A portable robotic system for ankle joint rehabilitation. Electronics, 12(20), 4271. https://doi.org/10.3390/electronics12204271
Ramadi, A., Beaupre, L. A., Heinrichs, L., & Pedersen, M. E. (2022). Recovery and return to activity 1 year after ankle fracture managed with open reduction and internal fixation: A prospective longitudinal cohort study. Foot & Ankle Orthopaedics, 7(2). https://doi.org/10.1177/24730114221091806
Rehabilitation protocol for ankle fracture with ORIF. (n.d.). Massachusetts General Hospital. https://www.massgeneral.org/assets/mgh/pdf/orthopaedics/sports-medicine/physical-therapy/rehabilitation-protocol-for-ankle-fracture-with-orif.pdf
RehabMart. (n.d.). Total Ankle Trainer ROM machine with two pedals. Retrieved May 13, 2025, from https://www.rehabmart.com/product/total-ankle-trainer-rom-machine-two-pedals-51473.html
Runge, C. F., Shupert, C. L., Horak, F. B., & Zajac, F. E. (1999). Ankle and hip postural strategies defined by joint torques. Gait & Posture, 10(2), 161–170. https://doi.org/10.1016/s0966-6362(99)00032-6
Sabalbal, M., Johnson, M., & McAlister, V. C. (2013). Absence of the genicular arterial anastomosis as generally depicted in textbooks. Annals of the Royal College of Surgeons of England, 95(6), 405–409. https://doi.org/10.1308/003588413x13629960046831
Sale, P., Lombardi, V., & Franceschini, M. (2012). Hand robotics rehabilitation: Feasibility and preliminary results of a robotic treatment in patients with hemiparesis. Stroke Research and Treatment, 2012. https://doi.org/10.1155/2012/820931
Shorter, K. A., Xia, J., Hsiao-Wecksler, E. T., Durfee, W. K., & Kogler, G. F. (2013). Technologies for powered ankle-foot orthotic systems: Possibilities and challenges. IEEE/ASME Transactions on Mechatronics, 18(1), 337–347. IEEE Xplore. https://doi.org/10.1109/TMECH.2011.2174799
Slimmon, D., & Brukner, P. (2010). Sports ankle injuries: Assessment and management. Australian Family Physician, 39(1/2), 18–22. Informit. https://search.informit.org/doi/10.3316/informit.711096749930841
Terrio, T. (2013). Ankle rehabilitation device (U.S. Patent No. 8,439,854 B2). World Intellectual Property Organization (WIPO). https://patentscope.wipo.int/search/en/detail.jsf?docId=US43449081&_cid=P11-M6U6WW-12161-34
Vaughan, C. L., Davis, B. L., & O'Connor, J. C. (1999). Dynamics of human gait (2nd ed.). Kiboho Publishers.
Vykoukal, J. (2021, December 22). The best exercises for broken ankles. Vive Health. https://www.vivehealth.com/blogs/resources/exercises-for-broken-ankle
Walsh, T. P., Merlo, G., Rutter, C., Abell, B., Platt, S., & Arnold, J. B. (2022). Cost-Effectiveness of interventions for musculoskeletal foot and ankle conditions: A systematic review. Arthritis Care & Research, 74(4), 626–637. https://doi.org/10.1002/acr.24514
Wilken, J., Rao, S., Estin, M., Saltzman, C., & Yack, H. J. (2011). A new device for assessing ankle dorsiflexion motion: Reliability and validity. Journal of Orthopaedic & Sports Physical Therapy, 41(4), 274–280. https://doi.org/10.2519/jospt.2011.3397

World Health Organization. (2022, July 14). Musculoskeletal health. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/musculoskeletal-conditions

Xia, B. (2019). Medical joint rehabilitation physical therapy device based on ergonomics (Chinese Patent No. CN109806128A). World Intellectual Property Organization (WIPO). https://patentscope.wipo.int/search/en/detail.jsf?docId=CN243497943&_cid=P11-M6U6WW-12161-3

Yamada, N., Okamoto, S., Akiyama, Y., & Yamada, Y. (2020). Principal motion analysis of manual stretching techniques for the ankle joints. Journal of Physical Therapy Science, 32(9), 584–590. https://doi.org/10.1589/jpts.32.584

Zhang, L., Qin, T., Wen, C., Wang, X., Wang, P., Chen, Z., Zhu, H., Pei, Y., Wang, Y., & Li, L. (2016). Ankle foot rehabilitation training device and balance training system (Chinese Patent No. CN103961240B).World Intellectual Property Organization (WIPO). https://patentscope.wipo.int/search/en/detail.jsf?docId=KR219380216&_cid=P11-M6U6WW-12161-1

Zoss, A. B., Kazerooni, H., & Chu, A. (2006). Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). IEEE/ASME Transactions on Mechatronics, 11(2), 128–138. IEEE Xplore. https://doi.org/10.1109/tmech.2006.871087

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