Virtually-Interfaced Robotic Ankle & Balance Trainer

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Abstract
Due to the wide range of neurological impairments and orthopedic ankle injuries, there is a need for a device that can efficiently and accurately measure a patient’s ankle strength and balance abilities as well as monitor their progress throughout therapy. The device will be used in stable and dynamic operational modes and utilize a virtual reality user interface for the training exercises. Implementing a robotic system allows the device to be controlled in real-time, vary assistive and resistive forces, and analyze and provide feedback on patient performance. A thorough background and literature investigation was done in order to understand the market need for this type of device. The Virtually-Interfaced Robotic Ankle and Balance Trainer (vi-RABT) is the proposed robotic device that will improve overall ankle balance, strength, and mobility. A detailed list of design specifications has been generated from clinical needs that drove the preliminary concepts for this device. The overall system has been divided into four subsystems due to the complexity of the design. Starting with two initial design concepts, the design team progressed through a series of detailed designs until the design was finalized. The final design uses a DC motor to power a pulley and timing belt system on each axis of rotation to provide movement to the robotic platform. Moving forward, the team will be performing tests on the device with healthy subjects and then unhealthy patients.

Figure 1: vi-RABT classified into four subsystems
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The Need for Project

There is a large number of patients that require ankle rehabilitation each year. Currently the physical therapy field lacks a balance and strength training device that reflects today’s technological capabilities. The ankle joint bears all of the weight of the human body. Due to constant stresses on the ankle, it is one of the most commonly injured joints. More than one million people visit emergency rooms each year because of ankle related injuries [Ref 1]. Patients have higher risk for these injuries when they suffer from neurological impairments, such as stroke, Parkinson's disease, dementia, Lou Gehrig's disease, Muscular Dystrophy, Multiple Sclerosis, and traumatic head injuries. Disruption or reduction to one’s mobility severely degrades the perceived quality of life [Ref 2]. For these patients who suffer from neurological impairments, regaining ankle control and mobility is an ongoing challenge. The proposed vi-RABT device will aid these patients in regaining strength and balance in their ankles, therefore improving mobility which will ultimately lead to a better quality of life.

In addition to the patients who suffer from neurological disorders, this device will also benefit those who suffer from a variety of orthopedic ailments, such as chronic ankle sprains, shin splints, knee instability, arthritis, slow reaction times, and poor static and dynamic balance capabilities. Balance is the first step of all lower extremity treatment plans, the proposed device will have the ability to aid any person who has the need or desire to improve ankle strength and balance.

The Design Project Objectives and Requirements

The team’s objective is to design and build a robotic two degree of freedom rehabilitative device that is integrated with a virtual reality environment.

Design Objectives

The team’s goal is to design and build a robotic ankle and balance training device. This device will act on two degrees of freedom (DOF), be actuated by motors for active therapy, and fully sensored to provide diagnostic capabilities to the therapist. This device will interface with a virtual reality environment to provide the patient with a more exciting and immersive therapy experience. This will be the first device to offer a physical therapist a seamless approach to physical rehabilitation. The team interviewed 4 orthopedic and neurological therapy specialists and created a list of customer needs for the device. From this list a design specifications matrix was defined.
Design Specifications

The device will be designed for a maximum allowable patient weight of 300 lbs. Each robotic platform will have two degrees of freedom in the plantarflexion/dorsiflexion and inversion/eversion motions, these axes will be aligned with the human ankle. The allowable range of motion for plantarflexion/dorsiflexion will be 60° and 25° respectively, and for inversion/eversion will be 40° and 30° respectively. The torque rating for plantarflexion/dorsiflexion will be 230 N-m (2036 in-lb), and will be 64 N-m (567 in-lb) for inversion/eversion. The device will have a chair with adjustable height and seat angle features. For patient safety the device will have adjustable railings, a harness, foot release, and hard stops for the range of motion. For complete list of design specifications please see Rep. 3.2.

Design Concepts Considered

The team developed a series of concepts based on a design that incorporated the use of two motors. A final design was chosen that met all of the design criteria.

For this phase of the project the team was required to design and build a functional robotic platform and detail the design for the other subsystems in a CAD model, shown in Figure 1. The focus of this project term was the detailed design of the robotic platform in which four concepts were created. For the subsystem designs please see Rep. 5.

To control the platform the team considered a variety of motor configurations:

- Linear actuators
- Rotational motors with 4-bar linkage
- Rotational motors with U-joint
- Gears
- Right angle direct-drive
- Timing belts

To accommodate for the high torques, desired precision, space limitations, and cost of the motors and gearboxes the team has chosen a timing belt configuration for both axes. For a complete list and description of platform concepts please see Rep. 5.2.
Recommended Design Concept

The final design was broken into four subsystems, each of which were detailed in a CAD model. The final design for the robotic platform utilized a system of motors and timing belts.

Design Description

This device was broken down into 4 subsystems plus the control system, as shown in Figure 1. A detailed CAD model of the entire system can be seen in Figure 3.

Subsystem 1 - Stationary platform: This piece is the backbone of the device. The stationary platform provides the housing for the two robotic platforms, the attachment for the safety railings, the base for the safety harness frame, and will provide extra room for patient movement. The frame will be constructed out of 8020 and will have acrylic inserts to enclose the platform.

Subsystem 2 – Safety Features: This will include the railings, safety harness, mechanical stops, and the foot release mechanism. The railings will be constructed out of aluminum tubing to keep them study and light weight. The safety harness will be purchased and will attach to a suspension system over the center of the robotic platforms. Mechanical stops are designed into the robotic platform to prevent over rotation. A foot release mechanism will be used to ensure patient safety in the event that they become unstable.

Subsystem 3 – Chair: The chair will be used to transition patients training from the seated to standing position, and various angles in between. The device will be height adjustable and the seat will remotely change angles.

Subsystem 4 – Robotic Platforms: The chosen design uses 2 rotational motors and timing belt set up to transit the required torque, shown in Figures 4 and 5. The use of timing belts greatly reduces backlash and misalignment concerns. This configuration allows the motors to be mounted within the frame, reducing the overall size of the robotic platform. The outer frame is constructed of 8020, and the foot plate is fabricated with custom aluminum pieces and an acrylic platform. The axes of rotation are aligned with the ankle, and the platform configurations provide the full desired range of motion in each direction. The platform was sized to accommodate a wide range of foot sizes and medical braces a patient may need to wear during therapy.

Control Design: The robotic platform will be equipped with encoders for position measurement on each motor and a pressure map.
The feedback from these sensors will be input into a LabView program which will control the angular position and speed of the foot plate.

**Analytical Investigations**

An FEA analysis was done on the robotic platform. The overall deflection was found to be less than 2mm. The stress allowable was 210 MPa, which is well within the allowable stress for the aluminum components.

**Key Advantages of Recommended Concept**

The aluminum frame keeps the robotic platform relatively lightweight while still being robust enough to support the maximum patient weight. The use of rotational motors and timing belts reduced backlash and misalignment issues. This design allows the motors to be housed within the frame reducing the overall size of the platforms. The hard stops allow for the device to be used during static balance training.

**Financial Issues**

Each subsystem has been designed in detail in the CAD model, and the team has assembled one robotic platform. The prototype in current form was purchased for $4,650.97. The projected cost for the full prototype is approximately $10,000. The material cost for the commercial product is estimated to be about half the prototype cost and should be around $5,000.

Extensive research was done to show that there is no other device like this one on the market the combines ankle and balance training that can be used in either the seated or standing position. The projected cost of this device is also significant because other research prototypes are in the $50,000 range for their current material cost. This device will target the small hospital and physical therapy clinic market.

**Recommended Improvements**

The current prototype focused on the robotic platform, the next phase of the project will be adding the safety features and building the stationary platform. The team will be continuing the project next semester and will continue to build and test the entire design. Once all of the components are built, safety features are added, and the programming has been written and tested the team will conduct healthy human subjects testing on the device. Clinical patients will test following healthy human subjects testing the device.