MECHANICAL DESIGN AND CONTROL SYSTEM
DEVELOPMENT OF NOVEL 2 DEGREE-OF-FREEDOM ANKLE AND BALANCE REHABILITATION ROBOTIC SYSTEM

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Abstract

Stroke is a leading cause of serious long-term disability in the United States. Ankle and balance disabilities are caused by neurological impairments such as traumatic brain injury, cerebral palsy and stroke. Due to increased survival rates after stroke, significant growth in stroke population is projected by 2030, which will make rehabilitation procedures even more important. Common rehabilitation techniques require intensive cooperation and effort of therapists and patients over prolonged sessions. Conventional ankle and balance rehabilitation systems are built from a simple set of mechanical elements which lack sensory systems or networks. Current more advanced technologies do not combine ankle strength, mobility, motor control and coordinated balance training in one device that can retrain the patients in multiple positions from sitting to standing.

In this work, we present the Virtually-Interfaced Robotic Ankle and Balance Trainer (vi-RABT), a low-cost platform-based robotic system that is designed to improve overall ankle/balance strength, mobility and control. The system is equipped with two degrees-of-freedom (DOF) controlled actuation along with complete means of accurate force and angular measurements. Effective control techniques and virtual reality games were developed and interfaced into the system hardware. Under IRB approved protocol, the system was used to assess ankle force, mobility and motor control in a pool of healthy human subjects, while playing interactive virtual reality games on a large screen. In the next phase, an anisotropic assistive/resistive control paradigm has been implemented into practice, with realistic functionality consistent with the expectations of a Physical Therapy expert. A pilot experiment was conducted to investigate the feasibility of assistive control using vi-RABT.

The inspiring results on the pool of human subjects suggest that, in contrast to the upper extremity, subjects have better control over ankle’s position than the force they can regulate. The early results on the assistive control showed that, in the presence of objective force feedback, subjects finished the game in a shorter time and with fewer errors. The ankle rehabilitation aspect of the system is ready to be utilized in physical therapy. Further research is required to develop the balance rehabilitation paradigm. Vi-RABT has the potential to be used for variety of ankle and lower extremity neuromuscular impairments.

Dissertation Advisors:

Constantinos Mavroidis, PhD (deceased), Professor of Mechanical Engineering, Northeastern University (2004-2014)
Maureen K. Holden, PT, MMSc, PhD, Associate Professor of Physical Therapy, Northeastern University (2005-2014)
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Biographical Note

The author received his BS in Biomedical Engineering from Azad University in Tehran, Iran in August of 2003. He received his MS in Biomedical Engineering from Iran University of Science and Technology (IUST) in June 2006. In September 2008, he started the PhD program in Biomedical Engineering at University of Tehran under the mentorship of Prof. Fariba Bahrami. In 2010, he left the course and moved to US to restart his PhD in the Bioengineering program at Northeastern University. He joined the Biomedical Mechatronics laboratory in 2012 and worked under the supervision of Prof. Constantinos Mavroidis.
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Figure 98: Human subject results on assistive control condition along DFPF axis of rotation with d_{vel} = 2 (Deg/s) and G_v = 2, Subject 1 - Block 10. The desired angle (top - red), actual angle (top - blue); desired torque (mid - red), actual torque (mid - blue); and the control command (bottom - black) are shown.

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## Glossary of Terms

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<thead>
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<th>Definition</th>
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<tbody>
<tr>
<td>Lateral</td>
<td>To the side</td>
</tr>
<tr>
<td>Medial</td>
<td>Towards the center</td>
</tr>
<tr>
<td>Superior</td>
<td>Above</td>
</tr>
<tr>
<td>Inferior</td>
<td>Below</td>
</tr>
<tr>
<td>Proximal</td>
<td>Closer to the origin</td>
</tr>
<tr>
<td>Distal</td>
<td>Farther away from the origin</td>
</tr>
<tr>
<td>Anterior</td>
<td>Towards the front</td>
</tr>
<tr>
<td>Posterior</td>
<td>Towards the back</td>
</tr>
<tr>
<td>Inversion</td>
<td>Medially rotating the ankle about the subtalar joint</td>
</tr>
<tr>
<td>Eversion</td>
<td>Laterally rotating the ankle about the subtalar joint</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>The act of flexing the foot and phalanges upward, towards the leg, about the talocrural joint</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>The act of flexing the foot and phalanges (toes) downward, away from the leg, about the talocrural (between the tibia and talus) joint</td>
</tr>
</tbody>
</table>
Chapter 1 Introduction

1.1 Problem Statement

Stroke is a leading cause of long term disability in the United States; with approximately 795,000 survivors annually in US [1-2]. The projection by American Heart Association shows that by 2030, 40.5% of the US population will have some form of cerebrovascular disease (CVD) [3]. The total costs for stroke-related care in 2010 were estimated about $53.9 billion. This cost is projected to reach to $140 billion by 2030.

Every day in the United States, about 28,000 Americans suffer from an ankle sprain phalanges (10 million annually) [4-5]. Ankle sprains account for almost half of all sports-related injuries and its treatment was estimated about more than $4.2 billion/year [6-7]. Ankle disabilities are not only caused by ankle sprains but also by neurological impairments such as traumatic brain injury, cerebral palsy and stroke [2]. Such high incidence and cost show the need for making ankle and balance rehabilitation a compelling health care issue to be addressed.

Impaired control of gait and balance are frequent problems in patients with stroke [8-11]. Stroke causes loss of motor control, muscle weakness and spasticity in the ankle joint, which contribute to impaired balance and gait function in post-stroke patients [8, 12-14]. Such deficits interfere with overall functional independence and can place the patients at an increased risk of falls [15-16]. While balance training protocols are practiced at the later stages of rehabilitation, when patients have more ability to support (part of) the body weight, ankle strengthening/flexibility programs are the first to practice. Many treatments to improve gait and balance function in patients with stroke are aimed at controlling the ankle or including ankle and balance exercises as a component of treatment [17-18].

Conventional ankle and balance rehabilitation systems are built from a simple set of rigid and elastic elements [19-23]. Although these systems are very cost-effective and easy-to-use for the
physical therapist, they are not equipped with the primary mechanisms to objectively assess the effectiveness of the ongoing rehabilitation procedure. That is, these methods are not able to provide active rehabilitation and monitor patients’ progress. Due to the significance and varied severities of ankle injuries and impairments, a need exists for a rehabilitation device that offers assistive and resistive therapeutic mechanisms through different stages of rehabilitation. Recent advances in robotics and automation can be utilized to create a robotic system that provides objective ankle rehabilitation of individuals along more efficient rehabilitation process.

This study is focused on creating an ankle rehabilitation robot, called vi-RABT, which can be used to increase ankle strength, mobility, motor control and coordination in sitting or partial standing position. The vi-RABT will assist patients with ankle disorders similar to the way actual therapists would treat patients, though with enhanced augmented and quantitative feedback. The system will provide therapists with quantitative measures of patients’ performance and progress over time. It is expected that the robot will improve the quality of life of stroke survivors and sprained ankles by providing more effective methods to recover function. The system can also be used for balance training in standing posture with the footplate locked using previously developed software [32]. Future work will enable balance training in standing with robotic assistance or resistance to dynamic ankle movements.

1.2 Significance

The ankle joint plays a vital role in our simplest everyday activities such as standing, walking, running, and maintaining stability. This joint is usually under the stress of the entire body weight, and is the most common site of sprain injuries in the human body [24]. Ankle sprain occurs when the ankle is turned unexpectedly in any direction that is further than the ligaments can tolerate; an example is shown in Figure 1. Ankle disabilities are caused by mechanical disorders such as ankle sprain as well as neurological impairments such as traumatic brain injury, cerebral palsy
and stroke [7]. Stroke causes loss of motor control, muscle weakness and spasticity in the ankle joint which contribute to impaired balance and gait function in patient post-stroke [8].

Figure 1. The sprained ankle; the ligament is stretched excessively and torn, Reprinted with permission from Elsevier [45].

Rehabilitation is a must after stroke as insufficient therapy will markedly compromise subject’s ambulation and cause significant problems in the future [26-27]. Traditional rehabilitation routines require intensive cooperation and effort of therapists as well as patients over prolonged sessions [28]. Common ankle and balance rehabilitation systems are built from a simple set of mechanical elements [19-23]. Although these systems are very cost-effective and easy-to-use they do not have sensory systems, not being able to provide feedback regarding the status of the rehabilitation. These simple systems cannot be utilized at home setting, and hence patients need to travel repeatedly to clinics for evaluation and therapy.
Due to the significance and varied severities of ankle injuries and impairments, a need exists for a well-organized rehabilitation process that meets the expectations of therapists and patients. Recent advances in robotics and automation [29] can be utilized to create robotic systems that provide more efficient and objective ankle and balance rehabilitation process. Robotics can provide a transformation of rehabilitation from labor-intensive operations at clinics to technology-assisted interactions at home. For example, The Hand Spring Operated Movement Enhancer (HandSOME) is a lightweight wearable assistive robotic system that has been successfully implemented to assist the stroke patients at home with hand function during the activities of daily living [30]. The rapid growth in digital electronics and significant progress in computational methods can facilitate elaborate data collection process, provide advanced real-time control systems, deliver more effective diagnosis and offer tailored therapy to the individual patients [31].

In 2008-2012, our team developed the Northeastern University Virtual Ankle and Balance Trainer (NUVABAT) for ankle and balance rehabilitation [32-38]. This was a 2 degree-of-freedom (2-DOF) platform-based movable footplate that was instrumented with force and angle sensors. The system had a virtual reality (VR) interface with augmented kinematic feedback features for training active ankle motion (non-resisted) in sitting position [34, 37]. Standing balance games with a VR interface were also developed, using the footplate in the locked position, with augmented feedback from the load cells embedded in the footplate [34-37].

The initial design of the platform was movable around DF/PF and IN/EV axis of rotation but at that time, the system did not have actuation mechanism which was an inhibiting factor to explore dynamic exercises for active assistive and resistive therapy. This led to the design of our current device presented here, the virtually-interfaced robotic ankle and balance trainer (vi-RABT).
1.3 Contributions

Presently, no devices designed for ankle rehabilitation combine the ability to train balance function, ankle strength, mobility, and motor control into one system, nor do they typically allow for use of the device in multiple positions, such as sitting and standing. This multi-position ability is an important system feature because in early rehabilitation and due to weakness, patients may only be able to work on strength and mobility control of the ankle in a seated position.

The robotic actuated force-plates will allow extensive flexibility to train patients with lower extremity disorders at different levels of recovery in sitting (and standing) on key aspects of motor control that go beyond simple strengthening techniques; e.g., rapid reversal of movement, multi-planar movements that combine talocrural, subtalar, and transverse tarsal joint movements, timing, speed of torque production and bilateral coordination. Utilizing rich virtual reality environments, as patients gain motor control, we can simulate more advanced ankle training and rehabilitation.

Another crucial feature of the vi-RABT is the novel virtual reality (VR) games. The benefits of using virtual environments in rehabilitation are becoming more evident as these systems are being further developed and clinically validated [38]. VR can provide the motivation and enjoyment to the patient that can enhance their motor rehabilitation with the robotic system. The vi-RABT will be built with these advantages of VR, specifically to allow augmented feedback based on both kinematic and haptic features of the subject performance, and thus the facilitation of the motor learning through a wide variety of mechanisms.

The novel features of the proposed system are as follows:

- Designed for both ankle and balance exercise: Different technical specifications need to be met for ankle and balance exercises. The system is designed to cover both applications. This
dissertation is focused primarily on ankle training and motor control training in the sitting position.

- The actuated footplate is equipped with four force sensors so as to create a robotic force-plate. This will provide the possibility of measuring human-machine interaction forces in different foot angles and at the closest proximity to the end effector, and ultimately applying assistive/resistive force fields to the ankle through actuation.

- The system axis of rotation will be aligned with human ankle joint axis of rotation (talo-crural joint). This has significant importance from physical therapy perspective [39].

The long term goal for vi-RABT is to utilize it in clinics for variety of ankle and balance rehabilitation exercises. In this study, we are focused on the ankle rehabilitation aspect of this goal. However during the design phase, the future dynamic balance rehabilitation exercises involving robotically controlled movement of the two footplates were thoughtfully considered.

Some of the work presented in this thesis has been the subject of the following contributions:


In preparation:


As a result of this work, a patent application has been filed by Northeastern University:


The following awards were received from this study:

• The poster presented at the Northeastern University RISE expo (RISE 2013) was selected as the Greatest Entrepreneurial Potential, the people choice, and awarded $5000.

• The presentation at the Massachusetts Life Science Innovation Day (MALSI Day 2013) was selected as the best poster in a two round evaluation by participants and judges, and awarded $1000.
The electromechanical design, implementation, control system and human subject study of this contribution was realized in joint collaboration with students and faculty from mechanical engineering, physical therapy and bioengineering. The author was the lead design engineer on the electromechanical system as well as the lead researcher on data collection and analysis. The author of this dissertation had sole or significant contribution to the following areas of this work:

- Mechanical system,
  - The leader on the design, fabrication and assembly team,

- Electrical system
  - Actuators: selection, drivers, and calibration
  - Force and motion sensors: selection, circuit interface, data acquisition and calibration

- Real-time control system development for
  - Back-drivable condition
  - Assistive/resistive condition

- Virtual reality games
  - Contributed to the design

- Human subject testing, experimental design, data collection and analysis
  - Finding human subjects
  - Collecting data from all 20 healthy human subjects
  - Analyzing the data and providing the most meaningful perspective

1.4 Overview

This dissertation addresses the mechanical design and control system’s development, as well as human subject testing of the virtually interfaced ankle and balance trainer vi-RABT. In Chapter 2, the existing solutions for ankle and balance rehabilitation are presented, and prior work on the
previous prototype device (NUVABAT) is described. Chapter 3 describes the unique mechanical design of the vi-RABT and explains the electrical sensors and actuators. Chapter 4 presents the torque control design and game development of the vi-RABT. The system has been used to assess range of motion, strength and motor control about the ankle in healthy human subjects. We have studied whether healthy subjects have better control when using force or position feedback from ankle movements to drive a virtual avatar. Chapter 5 presents the details and rationale of the experiments and the acquired results that were conducted with 20 healthy human subjects that volunteered under a study approved by Institutional Review Board (IRB# 10-01-12). Chapter 6 presents the implemented impedance controller for assistive/resistive ankle training and the results of pilot experiment with two volunteer healthy human subjects. Chapter 7 provides a discussion of our findings and conclusions as well as suggestions for future work based on what we have learned through this endeavor.
Chapter 2  Background

In this chapter we review the pathologies of ankle and balance disorders. Then we will look into the ankle biomechanics to help the reader better understand the complicated problem of ankle rehabilitation. In the next step, the existing methods for ankle rehabilitation will be explained. We will look into the simple mechanical structures from commercial systems to research prototypes available for lower extremity, ankle training and balance rehabilitation. We will conclude by looking into potentials and openings in the existing solutions which has led to the design and introduction of vi-RABT.

2.1 Neurological and Mechanical Pathologies

A neurological impairment can happen due to a variety of dysfunctions or losses to the neural system. Additionally a mechanical damage to the ankle or surrounding areas (e.g. by accident or excessive external force) can cause an injury to different parts of the musculoskeletal system such as bones, joints and ligaments [48-49]. The quality of movements and life of an individual can be immensely compromised upon a neurological impairment (e.g. stroke) or mechanical injury (e.g. ankle sprain) [50].

Due to prolonged ageing, morbidity and disability rates in the elderly are growing [54]; and neurological impairments such as stroke are increasing [55]. On the more mechanical type of conditions, ankle sprain is the most common injury in athletic populations, accounting for up to 30% of sports injuries [51-53]. There are many types of disorders, injuries and diseases that require ankle flexibility or strengthening training. In this section, we will briefly review the most prevalent impairments, underlying mechanisms and consequences.
2.1.1 Stroke

Cerebrovascular accident (CVA), or stroke, is the loss of brain function(s) due to disturbances in the blood supply to the brain. Stroke is an acquired brain injury, which can be caused by a blood clot (ischemic stroke), or a burst open blood vessel (hemorrhagic stroke) [1-2]. Each year approximately 795,000 people experience a new or recurrent stroke in the US, and about two-thirds of these individuals survive and require rehabilitation. There are over 4.5 million stroke survivors in the population with the total estimated cost of $73.7 billion in 2010 [1-3].

The consequences of stroke depend on its type, location and intensity on the brain. In most common situations one cerebral hemisphere is affected resulting in contralateral sensory and motor paresis or paralysis [59]. This is commonly referred to ‘hemiparesis’ (weakness) or ‘hemiplegia’ (paralysis) [60-61]. The observable muscle weakness is not caused by an actual damage to the muscle; but rather the neural pathways leading to that muscle group, and also from disuse atrophy [62]. Motor control function of stroke patients are complex, and can involve weakened muscle tone, spasticity, degraded coordination, gait and balance disorders and impaired function of daily activities such as walking and maintaining stable posture. Additionally deficiencies in other functions such as speech pathology, and cognitive deficits are also other common symptoms [63-64]. One may recover completely from a stroke, but more than two thirds of survivors will have some form of disability [65].

2.1.2 Traumatic Brain Injury (TBI)

TBI occurs when a sudden mechanical force damages part(s) of the brain [66]. TBI is a major public health problem with estimated of 235,000 people hospitalized in the US every year. More than 80,000 of these survivors are left with a long-term disability [67]. According to the center of disease control (CDC), the annual total estimate cost of TBI (including those due to work loss and disability) is about $60 billion.
Long-term deficits of TBI are associated with motor control problems in upper and lower extremities, cognition, sensory processing, communication, and mental health or overall victim’s behavior [68].

2.1.3 Spinal Cord Injury (SCI)

The spinal cord is the neural pathway that carries electrical signals in between the central and the peripheral nervous system [69]. A trauma that damages these pathways will result in loss of function below the level of lesion. There are about 11,000 new SCI incidences every year in the US of which around half result in paraplegia [70-71]. Unlike stroke, which is typically an elderly disease (65+), the average age at SCI population is 32, which requires life-long specialized care. The estimated annual cost of SCI is about $9.73 billion in the US [71].

The nature of the post-SCI disability depends on the location and degree of the damage to the spinal cord [72]. The SCI severity can be at various levels of incomplete injury (i.e. no effect) to a complete injury (i.e. total function loss). An injury above the first thoracic vertebra may result in quadriplegia, disabling control over torso, arms and legs. Injuries below thoracic level can result in paraplegia, disabling legs only, or legs and torso [73].

2.1.4 Ankle Sprain

The ankle is the most common site of sprain injuries in the human body. Approximately 1 ankle sprain occurs per 10,000 person-days worldwide [56], and an estimated of 10,000,000 acute ankle sprains occur annually in the United States [3]. Ankle impairments contribute to balance perturbations and postural instabilities in humans.

Ankle sprain occurs when the ankle is turned unexpectedly in any direction that is further than ligaments tolerance, as shown Figure 1. A ligament is an elastic structure with limited length of operation. A severe turn of the foot causes the ligaments to stretch beyond the normal length. The
excessive amount of torque on the ankle joint can damage or tear the ligaments. The amount of force determines the grade and severity of the sprain as listed on Table 1. Instability occurs when there is complete tearing of the ligament or a complete dislocation of the ankle joint [57].

Table 1: Ankle sprain severity and consequences [58].

<table>
<thead>
<tr>
<th>Severity</th>
<th>Pathophysiology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade I</td>
<td>Slight stretching and some damage to the ligament fibers.</td>
</tr>
<tr>
<td>Grade II</td>
<td>Partial tearing of ligament. Ankle joint is subject to abnormal looseness (laxity).</td>
</tr>
<tr>
<td>Grade III</td>
<td>Complete tear of the ligament. Ankle joint is subject to gross instability.</td>
</tr>
</tbody>
</table>

Table 2 is a summary of the more prevalent ailments and their association with ankle injuries and rehabilitation.

Table 2: Common pathologies/ailments associated with ankle and balance rehabilitation [74].

<table>
<thead>
<tr>
<th>Pathology/Ailment</th>
<th>Symptoms and Main Rehab Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>Unilateral paralysis; Shift in COG from midline; Inability to bear weight on the affected limbs; Poor balance and weight shift to the affected leg and ankle</td>
</tr>
<tr>
<td></td>
<td>Impaired/lost ability to dorsiflex, e.g. ‘drop foot’</td>
</tr>
<tr>
<td></td>
<td>Spasticity, e.g. in plantarflexors, leading to stiff legged</td>
</tr>
<tr>
<td></td>
<td>Low recovery rate for ankle strength and stability</td>
</tr>
<tr>
<td>Lou Gehrig’s Disease (LGD)</td>
<td>Muscles weakness (due to severe atrophy) reduces patient’s automatic postural reflexes</td>
</tr>
<tr>
<td>Muscular Dystrophy (MD)</td>
<td></td>
</tr>
<tr>
<td>Brain injury</td>
<td></td>
</tr>
<tr>
<td>Multiple Sclerosis (MS)</td>
<td>Increased muscle tone and spasticity, e.g. reduces ability to plantarflexors/dorsiflex; ataxia and tremors</td>
</tr>
<tr>
<td>Arthritis</td>
<td>Weakness of affected areas result in compensation by other limbs that displaces balance</td>
</tr>
<tr>
<td>Slow reaction times (Fall)</td>
<td>Inability for fast reaction to maintain stability in the presence of balance perturbation</td>
</tr>
<tr>
<td>Long-term bedridden patients</td>
<td>Position of resting-plantarflexion reduces ability to dorsiflex</td>
</tr>
<tr>
<td>Ankle sprain</td>
<td>Over stretched/torn soft tissue, broken bones; decreased stability and strength in lower limbs</td>
</tr>
<tr>
<td>Shin-splints</td>
<td>Improper muscle control/balance in a static position; affects gait and dynamic stability</td>
</tr>
</tbody>
</table>
2.2 Ankle Biomechanics

In order to treat pathologies and injuries within the human ankle joint effectively, it is necessary to know and understand the ankle anatomy. Each injury will have a different effect on the bones and soft tissues (muscles, ligaments, joint capsules, tendons) of the ankle joint [40]. By knowing the specific components that are affected in each pathology, a more effective therapy plan can be prescribed to every patient.

Figure 2: Bones of the leg, ankle, and foot, modified from, Reprinted with permission from Lippincott Williams [40].

2.2.1 Bones and Joints

As shown in Figure 2, the human ankle joint is in between the bones of the lower leg (i.e. tibia and the fibula) and the forefoot [40]. Tibia is the weight-bearing bone of the leg, medial to the fibula which serves mainly for muscle attachment [41]. The talus (ankle bone) articulates with tibia and fibula and transmits the weight to the calcaneus (heel bone) and the forefoot. The
The forefoot consists of the cuboid, navicular, three cuneiforms, five metatarsals, and the phalanges [42]. The summary of ankle bones and associated functions in motion are in Tables 3 and 4.

**Table 3: Bones of the ankle and foot [40-42].**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tarsals</strong></td>
<td></td>
</tr>
<tr>
<td>Talus (ankle bone)*</td>
<td>Transfers weight from tibia to foot</td>
</tr>
<tr>
<td>Trochlea of talus</td>
<td>Articulates with tibia and fibula</td>
</tr>
<tr>
<td>Head of talus</td>
<td>Articulates with navicular bone</td>
</tr>
<tr>
<td>Calcaneus (heel bone)*</td>
<td>Articulates with talus superiorly and cuboid anteriorly</td>
</tr>
<tr>
<td>Navicular*</td>
<td>Between talar head and three cuneiforms</td>
</tr>
<tr>
<td>Cuboid*</td>
<td>Most lateral tarsal bone</td>
</tr>
<tr>
<td>Cuneiforms*</td>
<td>Three wedge-shaped bones</td>
</tr>
<tr>
<td><strong>Metatarsals</strong></td>
<td></td>
</tr>
<tr>
<td>Numbered 1 to 5, great toe</td>
<td>Possess base, shaft, and head</td>
</tr>
<tr>
<td>Two sesamoid bones</td>
<td>Associated with flexor hallucis brevis tendons</td>
</tr>
<tr>
<td>Three for each digit except</td>
<td>Possess base, shaft, and head</td>
</tr>
<tr>
<td>great toe</td>
<td></td>
</tr>
</tbody>
</table>

*Tarsal bones

**Table 4: Joints within the ankle and their features [40-42].**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Bones connected</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talocrural (Uniaxial Synovial Hinge) Joint</td>
<td></td>
<td>Stabilizes the ankle joint during plantarflexion/dorsiflexion</td>
</tr>
<tr>
<td>Capsule</td>
<td>Tibia and fibula to talus</td>
<td></td>
</tr>
<tr>
<td>Medial ligament</td>
<td>Medial malleolus to talus, calcaneus, and navicular</td>
<td>Limits inversion of foot; maintains medial long arch; has four parts</td>
</tr>
<tr>
<td>Lateral ligament</td>
<td>Lateral malleolus to talus and calcaneus</td>
<td>Resists inversion of foot; Is weak</td>
</tr>
</tbody>
</table>

**Talocalcaneal (Subtalar Plane Synovial) Joints**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Bones connected</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsule</td>
<td>Margins of articulation</td>
<td>Stabilizes subtalar joint during inversion and eversion</td>
</tr>
<tr>
<td>Talocalcaneal</td>
<td>Talus to calcaneus</td>
<td>Has medial, lateral, and posterior parts</td>
</tr>
<tr>
<td>Interosseous talocalcaneal</td>
<td>Talus to calcaneus</td>
<td>Binds bones together; Is strong</td>
</tr>
</tbody>
</table>
2.2.2 Ligaments

Ligaments are the soft elastic tissues in the musculoskeletal system in between the bones [43]. The primary ankle ligaments are the medial and lateral ligaments. As shown in Figure 3, the lateral ligament is composed of three individual ligaments as anterior talofibular ligament (ATFL), on the neck of the talus, the posterior talofibular ligament (PTFL), on the lateral tubercle of the talus, and the calcaneofibular ligament (CFL), on the surface of the calcaneus. Medial ligament is composed of four individual ligaments as tiobionavicular part, which connects the tibia to the navicular bone, the tibiocalcaneal part, which connects the tibia to the calcaneus, and the anterior and posterior tibiotalar parts, connecting the tibia to the talus [43].

![Figure 3: Medial and lateral ligaments of the ankle joint, Reprinted from [41] in public domain.](image)

2.2.3 Muscles and Tendons

Muscles are connected to bone via soft tissues called tendons who share the same name as the muscle they are originating from [44]. Muscles are classified by their location in one of three different compartments of the leg. Each muscle contributes to specific motion (i.e. plantarflexion/dorsiflexion and inversion/eversion). Individual muscles and their primary functions/motions are summarized in Table 5.

<table>
<thead>
<tr>
<th>Posterior Compartment Leg Muscles</th>
<th>Posterior Compartment Leg Muscles</th>
</tr>
</thead>
</table>

Table 5: Leg muscles and their respective actions [44].
<table>
<thead>
<tr>
<th>Muscle</th>
<th>Primary Function/Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrocnemius</td>
<td>Plantarflexes foot; Raises heel during walking; Flexes leg at knee joint</td>
</tr>
<tr>
<td>Soleus</td>
<td>Plantarflexes foot at ankle; stabilizes leg on foot</td>
</tr>
<tr>
<td>Plantaris</td>
<td>Assists gastrocnemius in ankle plantarflexion and knee flexion</td>
</tr>
<tr>
<td>Popliteus</td>
<td>Flexes knee and unlocks knee joint</td>
</tr>
<tr>
<td>Flexor hallucis longus</td>
<td>Flexes great toe at all joints and plantarflexes ankle</td>
</tr>
<tr>
<td>Flexor digitorum longus</td>
<td>Flexes lateral four digits and plantarflexes ankle</td>
</tr>
<tr>
<td>Tibialis posterior</td>
<td>Plantarflexes/inverts ankle</td>
</tr>
</tbody>
</table>

**Anterior Compartment Leg Muscles**

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Primary Function/Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibialis anterior</td>
<td>Dorsiflexes/inverts ankle</td>
</tr>
<tr>
<td>Extensor hallucis longus</td>
<td>Extends great toe and dorsiflexes ankle</td>
</tr>
<tr>
<td>Extensor digitorum longus</td>
<td>Extends lateral four digits and dorsiflexes ankle</td>
</tr>
<tr>
<td>Fibularis (Peroneus) tertius</td>
<td>Dorsiflexes ankle and aids in eversion</td>
</tr>
</tbody>
</table>

**Lateral Compartment Leg Muscles**

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Primary Function/Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibularis (Peroneus) longus</td>
<td>Everts/weakly plantarflexes ankle</td>
</tr>
<tr>
<td>Fibularis (Peroneus) brevis</td>
<td>Everts/ weakly plantarflexes ankle</td>
</tr>
</tbody>
</table>

Figure 4: Distal attachment of leg muscles shown relative to axes of rotation, Reprinted from [41] in public domain.
2.2.4 Range of Motion

Human lower extremity can produce two primary motions about the ankle joint, shown in Figure 5. Accordingly, there are minimal ranges of motion (ROM) that the healthy ankle is able to produce, as listed in Table 6 [46]. Any system designed for ankle rehabilitation must be able to rotate about the same axes of motion throughout similar range of motion.

Figure 5: Primary motions of ankle joint; Top: Dorsiflexion/plantarflexion, bottom: Eversion/inversion, Reprinted with permission [45].
Table 6: Ankle range of motion [46].

<table>
<thead>
<tr>
<th>Action</th>
<th>Joints</th>
<th>ROM (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eversion</td>
<td>Subtalar (hindfoot)</td>
<td>5-9</td>
</tr>
<tr>
<td></td>
<td>Tarsal (forefoot)</td>
<td>11-12</td>
</tr>
<tr>
<td></td>
<td>Transverse tarsal</td>
<td>15-21</td>
</tr>
<tr>
<td>Inversion</td>
<td>Subtalar (hindfoot)</td>
<td>5-15</td>
</tr>
<tr>
<td></td>
<td>Tarsal (forefoot)</td>
<td>30-35</td>
</tr>
<tr>
<td></td>
<td>Transverse tarsal</td>
<td>35</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>Talocrural</td>
<td>20</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>Talocrural</td>
<td>40-50</td>
</tr>
</tbody>
</table>

2.3 Ankle and Balance Rehabilitation Devices

Rehabilitation is a must after ankle injuries as insufficient therapy will markedly compromise people’s ambulation and causes chronic problems in the future [75]. The available devices for ankle rehabilitation range from simple mechanical rubber bands at home to complex computerized robots in research laboratories. These systems are recommended and effective based on severity of ailment, a patient’s needs and progress. Here we review a set of these systems to show the potentials and needs in the area.

2.3.1 Simple Devices for Home Use

There are many commercially available devices used for balance training for patients with an ankle injury. Products such as the Wobble Board, BOSU Ball, Balance Pads, DynaDisc, and BAPS Board are passive mechanical devices sued for ankle balance rehabilitation [19-23]. These are simple systems that are widely used among physical therapists and patients in home settings. These systems are reviewed in details below.

2.3.1.1 Wobble Board

A wobble board is a balance board typically made of a round wooden platform with a small half-sphere below [20]. The patient stands on the board center with both feet practicing to maintain balance.
2.3.1.2 BOSU Ball

A BOSU ball is a half exercise ball with a plastic foam mounted on the flat rigid side [21]. The subject stands on the soft semi-sphere side attempting to maintain balance. The ball can be used in two orientations; 1) the flat rigid surface on the ground or 2) the hemispheric foam on the ground. The exercise difficulty can be changed by different positioning in combination with a variety of exercises and balance training.

2.3.1.3 Balance Pads

Balance pad is a square foam with about 2 inches of thickness. Patients attempt to maintain balance with one foot in the center of the foam [23]. The user is required to utilize ankle muscles to maintain balance on the unstable surface. Balance pads are frequently used to perform ordinary exercises such as squats.

2.3.1.4 Complete Ankle Rehabilitation Device (CARD)

The CARD was designed by therapists to aid in faster rehabilitation in clinical and home settings [19]. Used in a seated posture the device can provide resistance to ankle motion in multiple directions utilizing a series of elastic bands. It is simple device to use with minimal maintenance requirements. The axes of motion are in line with patient’s ankle. This is an essential feature that is not implemented in many rehabilitation devices. However, similar to most simple and conventional devices, CARD does not control the quality of motions as the patient moves. It also does not support training in standing posture, which decreases the quality of rehabilitation for stroke patients or subjects with chronic ankle instability.

Overall, the conventional passive ankle and balance trainers do not provide any quantitative measure of performance, which would help the therapist to assess progress over time, nor do they provide any augmented feedback about performance to the patient, which would enhance motor learning and motor recovery. This is primary disadvantage of simple devices, while lower cost, convenience and ease of use are their main advantages.
2.3.2 Advanced Systems and Research Prototypes

There are a number of robotic systems that have been developed for ankle and balance rehabilitation. These systems can be categorized as wearable exoskeletons for over-ground walking and platform-based systems to be used in stationary clinical settings. The exoskeleton systems have the advantage of training the patient while walking. Theoretically, patients can wear the system and walk around, which is the closest possibility to real life condition. However in reality, the exoskeleton systems are usually bulky and heavy. Patients who experience functional disorders at the end effector (e.g. the foot) may not easily tolerate the additional load of the system hardware. Moreover this practice differs from real walking experience as the patients are controlling an augmented limb. The platform-based systems provide the possibility of minimum additional load to the patient limb, but they are stationary and cannot be used during walking under patient’s full body weight. However, they allow practice of many balance, weight shifting and pre-gait activities, necessary pre- cursors to walking control.

While the platform-based systems can be more effective at the early stages of rehabilitation, the exoskeletons can be utilized in the later phases after partial recovery to train the patients in the closer conditions closer to everyday walking activities. This is why exoskeleton and platform-based systems can be prescribed at different stages of therapy.

2.3.2.1 Ankle Foot Orthosis at University of Delaware (AFOUND)

Developed by the University of Delaware AFOUND is a 2-DOF orthosis that records ankle joint’s torques and angles during walking. Most of available ankle-foot orthoses on the market are single axis (along DFPF) but AFOUND has added the additional degree of freedom (along INEV) to reduce discomfort and provide a more natural motion to the ankle [76]. It is designed for patients with peripheral or central nervous system dysfunctions that have experienced weakened dorsiflexor muscles.
The orthosis is made of lightweight telescopic aluminum to accommodate for various subjects, and use ball bearings at the two joints. Optical encoders were used to measure the joint angles; and two force/torque sensors are placed on the device, one beneath the sole and the other between the human and device shank. AFOUND is an under-actuated system that has a spring-damper system about the inversion/eversion (INEV) joint. This simple viscoelastic property was used to create an angular limit and restrict the range of motion about INEV. The dorsiflexion/plantarflexion (DFPF) movement is actively assisted with a DC servomotor as shown in Figure 6 [77].

The AFOUND cannot train balance and does not actively train the inversion/eversion motion. The adjustability of the DFPF axis is an important advantage of the device, but its bulky nature makes it difficult for patients to use. The system has more assessment capabilities, and is good for advanced recovery level patients to practice walking, but it has less ability to actively train the ankle strength and range of motion in patients with lower levels of motor recovery.
2.3.2.2 Robotic Gait Trainer at Arizona State University (RGTASU)

A Spring Inside Muscle (SIM) actuator was developed and incorporated into a rehabilitation device in the Human Machine Integration Laboratory at Arizona State University (ASU) [78-79]. The device allows the patient to receive therapy around inversion/eversion and dorsiflexion/plantarflexion axes while walking. The SIM actuator is a two-way pneumatic actuator made of a compression spring and an air muscle.

An air muscle produces force only in one direction, similar to a human muscle. Accordingly two actuators are usually needed to provide flexion and extension in an opposing configuration. The use of a compression spring in parallel with the SIM actuator eliminated the need for the second actuator. As shown in Figure 7, the RGT is set up in a typical tripod configuration with two SIM actuators and a flat plate beneath the foot. Linear potentiometers were used to monitor the deflection in actuators, which was correlated to the foot angle along dorsiflexion/plantarflexion axis. The RGT provides input only for dorsiflexion/plantarflexion, and like most other devices is passive for the inversion/eversion movement.

![Figure 7: Robotic Gait Trainer at Arizona State University [78], Copyright © 2007, IEEE.](image)
2.3.2.3 **AnkleBot**

Developed as a research robotic system at MIT, AnkleBot is a two-degree of freedom (DOF) wearable exoskeleton used in walking that provides assistance/resistance to plantarflexion/dorsiflexion and inversion/eversion, as shown Figure 8. It is capable of measuring ankle kinematics and kinetics, and can be used as a diagnosis or training device. It is equipped with interactive video games that allows for assistive/resistive training protocols.

Pilot studies using AnkleBot demonstrated improvements in short-term motor learning and adaptation [79]. Further studies are needed to determine the long-term improvements in ankle strength and motor control. The AnkleBot does not provide the possibility of static and dynamic balance training bilaterally on both legs.

![Figure 8: MIT Anklebot; the exoskeleton to improve ankle and balance function in walking [80], Copyright © 2007, IEEE.](image)

2.3.2.4 **Sammons Preston Kinetic Breva Ankle CPM**

Breva is used to apply continuous passive motion (CPM) exercise to the patient foot. It provides rehabilitation and mobilization exercise of the ankle with movements along plantarflexion/dorsiflexion and eversion/inversion [81]. Breva is designed for use in seated posture to help patients recover from foot or ankle surgery or post-injury. The system aids in
reducing pain and joint stiffness, preventing the cycle of trauma, inflammation, and loss of range of motion and it provides a quicker recovery.

However, Breva is designed for passive motion without patient’s intention/input. This eliminates the patient’s active participation in therapy to use the muscles, and therefore does not improve patient’s ankle strength. Breva is also not designed for applications in balance training.

![Image of ADPED ankle rehabilitation system](image)

Figure 9: The ADPED ankle rehabilitation system [82], Left: first prototype, Right: third prototype, Copyright © 2007, IEEE.

### 2.3.2.5 Ankle Dorsiflexion Plantarflexion Exercise Device (ADPED)

The ADPED, shown in Figure 9, is an ankle training device for patients with complicated forms of ankle joint deformity [82]. Contracture deformity in joints is a secondary consequence after one is diagnosed with cerebrovascular disease (CVD). Continuous passive motion (CPM) exercises can aid in preventing joint deformity in early CVD or improving range of motion at later stages. Patients with contracture deformity have uneven deformity in the foot which is a significant limitation in rehabilitation with conventional techniques. ADPED has an adjustable footplate that rotates around inversion/eversion to adjust to the patient’s foot angle to host deformities, shown in Figure 10-(a). This additional level of adjustability reduces pain and increases the efficiency of the patient’s exercise. The difference of pressure distribution in the
patient’s foot with and without an adjustable footplate is shown in Figure 10-(b). The patient with contracture deformity experience more uniform pressure with ADPED.

![Diagram](image)

Figure 10: The ADPED [82]; (a) adjustable footplate (b) pressure distribution for a foot without the adjustable plate (left) and the ADPED adjustable plate (right) [82], Copyright © 2007, IEEE.

The ADPED is an actively controlled machine used in the sitting position that provides continuous passive motion (CPM) exercises for the patients. It applies a low operation speed to avoid muscle spasticity. The therapist can enter and choose the motion pattern, operating speed, length of the hold time, number of repetitions, and range of motion in the system control software. ADPED is for unilateral ankle rehabilitation and it does not support balance training.

### 2.3.2.6 STABLE and V-Gait

The STAbility BAalance Learning Environment (STABLE) and V-Gait, are the two commercial systems offered by Motek Medical for training and assessment of balance-related disorders [83-84], shown in Figure 11 and 12. Both systems are equipped with virtual reality interface to challenge the patients in an entertaining environment with the final goal of ankle stability, strength and balance training.
The STABLE is a force-plate that can be used for force measurement and does not have actuators to provide active training. It is composed of a force-plate with virtual environment and 6 motion-capture cameras to provide real-time visual feedback to the user. At the same time, the therapist receives real-time feedback on patient’s performance during tests such as functional reach or one-legged stance.

Figure 11: human subject exercising with STABLE balance trainer by Motek Medical, Reprinted from [83] Open access.

Figure 12: V-Gait by Motek Medical for balance training, Reprinted from [84] Open access.
V-Gait was designed for balance and gait training which requires a large space of about 170 square feet, Figure 12. The system is composed of an instrumented treadmill and a virtual reality display unit. Using motion capture cameras, the system provides feedback on stride length, width, and symmetry as well as joint kinetics and other gait related parameters [83]. One interesting feature of the system is the use of hand motions to challenge patient’s balance. V-Gait does not provide assistive/resistive ankle or balance training and is well suited for patients in more advanced levels of recovery. Motek Medical is a European (Netherland) medical device company that has a variety of gait and balance monitoring devices. They do not provide solutions for active training and rehabilitation exercises of ankle and balance disorders.

Figure 13: Biodex System 4 Pro for ankle rehabilitation, Reprinted from [90] Open access.

2.3.2.7 Biodex System 4 Pro

This is a dynamometer robotic system available for ankle rehabilitation, as shown in Figure 13. The device provides patient assessment and progress reports as through the therapy period [85]. It has five different modes of operation: Isokinetic Resistance Mode, Reactive Eccentric Mode, Passive Motion Mode, Isometric Mode, and Isotonic Mode that allow for a wide variety of rehabilitation programs tailored to patient’s needs. The system has high-level open source software for physicians to program more advanced desired protocols. It is designed for ankle
injuries which can also be used for knee and hip rehabilitation. It can be used in early to later stages of therapy to regain range of motion and strength. The major downsides of Biodex 4 Pro are cost and size (64 square feet), and that the device can only be used in sitting. It cannot be used for balance training and does not provide augmented feedback to facilitate motor learning.

2.3.2.8 Rutgers Ankle (RA)

The Rutgers Ankle rehabilitation system is the most referred system in the area of ankle and balance rehabilitation. It is a 6-DOF Stewart platform robotic system that incorporates a haptic interface in conjunction with virtual reality therapeutic games, shown in Figure 14. The platform uses double acting pneumatic cylinders, 6-DOF force sensor, and linear potentiometers. Therapeutic games include a baseline test for measuring ankle mobility, optional haptic functions, and a breakout 3D game focused on dorsiflexion/plantarflexion movement [86].

Figure 14: The 6-DOF Rutgers Ankle rehabilitation system [86], Copyright © 2011, IEEE.

The RMA robot is the improved version of the Rutgers Ankle (RA) trainer [87] with enhancements in design and dual Rutgers Ankle robots, Figure 15. The system includes a large projection screen and an unweighing support system. The RMA is equipped with 6-DOF and is made up of two triangular plates connected by six double-acting pneumatic cylinders. A linear potentiometer is mounted on each piston to measure the displacement and a 6-axes force sensor is mounted on each footplate.
The RMA can be used to simulate different uneven surface conditions by applying programmable haptic effects. The variables in virtual environment such as speed and time of walking can be altered by physical therapist. Other adjustable variables are season, time of day, type of community, level of traffic, length of traffic light, and width of the street for a patient’s walk.

Each platform in RA can lift 300 kg in static condition with limited 50 kg maximum torque capability in dynamic exercises. As a result, an unweighing support system is supplemented to overcome this limitation and promote patient’s safety during practice training. Other challenge in this system is the application of large size electro-pneumatic actuators, which requires certain infrastructure for regular operation.
2.3.3 Prior Work on NUVABAT

The Northeastern University Virtual Ankle and Balance Trainer (NUVABAT) was created over several years by Profs M. Holden and C. Mavroidis advising a series of undergraduate capstone teams and graduate students in the Biomedical Mechatronics Laboratory [32-37]. The early goal of this project was to create a portable ankle rehabilitation device that would allow for various ankle training exercises in the clinic [33]. In the later stages of research, and due to need in the field, the concept for the device evolved into ankle and balance training system that can be used in multiple positions from sitting to standing [37].

![Figure 17: The model of 2-DOF NUVABAT and the schematic for ankle and balance training](image)

[35], Copyright © 2010 IEEE.
NUVABAT houses a moveable platform that is able to rotate under the patient’s ankle, as shown in Figure 20-top. The footplate is able to rotate freely on both the anterior-posterior and medial-lateral axes to provide two degrees of freedom (2-DOF) around desired ankle motions, dorsiflexion/plantarflexion (DFPF) and inversion/eversion (INEV). The combinations of these 2-DOF contribute to supination (SUP) and pronation (PRON). The team also hypothesized to create controllable resistive forces along both axes by utilizing Magneto-Rheological Fluid (MRF) motors. This feature was not deeply studied.

NUVABAT allowed for use in stable (footplate locked) mode in sitting or standing and dynamic mode (footplate movable), in sitting position. The schematic of ankle training in sitting position and balance training in standing posture are shown in Figure 20-bottom. Later, a series of pre-gait, weight shifting and balance control tests were studied by looking into the individual’s center of pressure (COP) in standing position interacting with virtual reality games on the screen [34-37]. The developed games were unique in design as the COP was derived unilaterally using the measurement from one leg. This is a useful feature for patients with stroke which was absent in other systems with bilateral design (using both legs).

While NUVABAT had the advantage of ankle and balance derived measurements, it was not able to provide active controlled force feedback to the patient’s lower extremity. This was an inhibiting factor in exploring the dynamic exercise for active assistive and resistive therapy. Another problem with the design of NUVABAT was the footplate’s axis of rotation that was assembled in the middle of footplate whereas ankle’s physiological axis of rotation. These problems became the contributing factors to the research of 2-DOF ankle and balance rehabilitation robot that is subject of this research.
2.4 Conclusion

Ankle disabilities are caused by neurological impairments such as stroke, traumatic brain injury and spinal cord injury as well as mechanically imposed problems such as ankle sprain. Rehabilitation is a must after any kind of ankle injury as insufficient therapy will markedly compromise people’s ambulation and causes significant problems in the future. Traditional rehabilitation routines require intensive cooperation and effort of therapists and patients over prolonged sessions.

In this chapter we have reviewed a variety of available ankle and balance rehabilitation systems. Common ankle and balance rehabilitation systems are built from a simple set of mechanical elements but they are not equipped with the necessary mechanisms to assess the effectiveness of the ongoing rehabilitation process, nor do they provide patients with any type of augmented feedback to enhance motor learning. This augmented biofeedback can be useful for patients with neurological deficits as well as athletes in the gym or home settings.

Moreover, to the best of our knowledge, none of the advanced and research prototypes combine the ability to train balance function, ankle strength, mobility, and motor control into one system, nor do they typically allow for use of the device in multiple positions, such as sitting and standing. This multi-position ability is an important system feature because in early rehabilitation and due to weakness, patients may only be able to work on strength and mobility control of the ankle in a seated position.

The goal of this research is to develop a 2-DOF rehabilitation system that provides actuated assistive and resistive therapy to patients with ankle and lower extremity disorders. The system will be equipped with angle and force sensors and can be used in sitting as well as standing posture. The sensors will allow quantitative measurement of patient performance, which will allow evaluation of progress over time. The novel VR interface and related games will provide
engaging methods of providing augmented feedback about performance to the patient, a proven way to enhance motor learning. This is thus a useful way to facilitate motor recovery in those with neurological impairments affecting ankle function and balance, and to speed up functional recovery in those with only orthopedic impairments of ankle function.
Chapter 3  Electro-Mechanical Design

In this chapter we will review the hardware of the virtually interfaced robotic ankle and balance trainer (vi-RABT). We will start by looking into the challenging problem of having two independent mechanical degrees of freedom embedded within a compact small size platform. Then we will explain the electrical design including the choice of sensors, actuators and peripheral circuit. We will review the system software in the next chapter. The early electromechanical design, fabrication and assembly of this system were achieved in joint collaboration with undergraduate MIE capstone students at Northeastern University [131].

3.1 Design Specifications

There is a need for a system that can apply desired torque profiles and motion trajectories to the patients’ ankle joint in the standing and sitting positions. The system should be low-cost, lightweight and easy-to-use both for patients and physical therapists. It should be able to compensate the human weight and provide the possibility of effective rehabilitation experience for the patients with variety of lower extremity and control disorders.

Table 7: The specification of the virtually interfaced robotic ankle and balance trainer (vi-RABT).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Design Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of Motion (º)</td>
<td>Dorsiflexion (DF) 25</td>
</tr>
<tr>
<td></td>
<td>Plantarflexion (PF) 60</td>
</tr>
<tr>
<td></td>
<td>Eversion (IN) 30</td>
</tr>
<tr>
<td></td>
<td>Inversion (EV) 40</td>
</tr>
<tr>
<td>Torque (N-m)</td>
<td>DF/PF 200</td>
</tr>
<tr>
<td></td>
<td>IN/EV 50</td>
</tr>
<tr>
<td>Speed (Deg/sec)</td>
<td>DF/PF 120</td>
</tr>
<tr>
<td></td>
<td>IN/EV 150</td>
</tr>
</tbody>
</table>
Based on the current systems in the market and research level [19-23, 76-87], and by integrating the interviews from the experts in physical therapy (n = 5), we have derived the electromechanical specification of the system as listed in Table 7.

<table>
<thead>
<tr>
<th>Maximum user weight (Kg)</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footplate size (shoe size)</td>
<td>Women 6 - Men 14</td>
</tr>
</tbody>
</table>

Figure 18: Overall design of the virtually interfaced robotic ankle and balance trainer (vi-RABT):

The support frame (1) provides room for stepping forward/backward; Subjects feet will be strapped on the robotic force-plates (2); The surrounding rails (3) provides safety features to the patients during practice; The system can be used in standing or sitting posture using the adjustable chair (4); and patients will be instructed to play the VR game on the screen (5) (modified from [131]).

3.2 Overall Architecture

The building components of vi-RABT are shown in Figure 21. The system is composed of an electromechanical platform-based hardware in contact with the patient and a video screen to
present the interactive games. The system is equipped with force/angle sensors as well as actuators to apply 2-DOF rehabilitation exercises to each foot. Patients can use the system in a seated or standing posture. They face the large screen and are encouraged to engage in goal-oriented VR games, to improve their ankle function.

As shown in Figure 21, the ultimate system design is composed of 1) a stationary platform; 2) two robotic force-plates; 3) an adjustable seat; 4) the wide 3D projection screen and safety features. In the scope of this thesis, we are focused on a single robotic platform, used in the sitting position.

### 3.3 Stationary Platform

This subsystem serves as the housing for the robotic force-plates and the safety rails. The stationary platform provides additional space around the robotic footplates for the patients to step on. This might be needed based on the specific training protocol, for example during standing pre-gait activities such as stepping practice or weight shifting in semi-tandem position. The overall area of the platform is 110cm (L) x 100cm (W) and the surface is at the same height as the robotic footplates.

Human subjects have different stance widths. This component is subject to change due to variability in humans’ anatomy (e.g., pelvic width, femoral version, Q angle of knee) and comfort. Accordingly, the stationary platform has been designed so that it can accommodate variable stance widths in between two robotic force-plates, or subject’s feet. The current design allows for the stance width of 15-35cm.

### 3.4 Robotic Footplate

The essential contribution of this system is to provide 2-DOF controlled actuation that will deliver assistive/resistive rehabilitation to the lower extremities. The vi-RABT is composed of two robotic footplates (currently only one is implemented with actuators) to provide objective
manipulation to the human legs bilaterally. The footplate is the most important subsystem of the vi-RABT as it must provide controlled rotation, speed and torque with accuracy and precision. It will be controlled by a motor/gearbox combination for each degree of freedom, inversion/eversion and plantarflexion/dorsiflexion. The gearbox is necessary to provide a torque amplification and speed reduction. In order to decide on the motors necessary for each rotational direction, calculations were performed for speed and torque.

Figure 19. The robotic force-plate with 2-DOF actuation (TOP: CAD drawing; BOTTOM: Experimental Prototype). The cubic support frame (1); internal and external layers of the footplate (2); the PF/DF motor and transmission system (3); the IN/EV motor and transmission system (4); the encoders (5); the foot strap (6); and mechanical stop (7).

The 2-DOF actuation was provided by a two layer design for the footplate. As shown in Figure 22, the robotic footplate is composed of an internal force-plate surrounded by an external housing. The internal layer (i.e. the force-plate) was considered for the IN/EV movement and the
external layer for DF/PF, hence the robotic force-plate. As shown in Fig 22, the patients’ feet will be strapped onto the acrylic footplate and subjects can interact with the system in standing or seated posture.

The force-plate is supported on the cubic support frame via plates, load cells, bars and ball bearings. The support frame is 73cm (L) × 33cm (W) × 33cm (H) with a 36.5cm (L) × 16.5cm (W) footplate. It is made of 3.8 cm (1.5 inch) aluminum bars, which was shown to have minimal deflection and stress under our maximum weight application (150 Kg).

3.4.1 Mechanical Design

The mechanical design and early system fabrications were achieved in collaboration with undergraduate mechanical engineering students as a capstone project [131]. The robotic footplate is composed of a support platform (Figure 23) to host the rotating footplate (Figure 24). The finite element analysis was conducted to choose the materials for the support frame to provide safe and effective operation with minimal deflection and minimal stress under maximum weight application. The support frame of the robotic footplates is of 1.5” aluminum (80/20® Inc.), Figure 23.

Figure 20: 3D CAD image of the robotic footplate support frame built of 1.5” aluminum [131].
The interior and surrounding components of the robotic footplate that are driven by the transmission system were designed as custom parts. The surrounding frame of the robotic footplate needed to be robust and precisely fit together. Other than the length of each piece, there was no customization required so this simplified the assembly process. The requirement of fitting the two rectangular interior frames together such that they each rotated around a different axis (providing 2 DOF motion) was achieved using uniquely shaped components. Figure 21 shows the sub-assembly of the rotating portion of the robotic platform.

Figure 21: Image of the interior frame; Left: INEV axis of rotation, right: INEV built in within the DFPF axis [131].

As shown in Figure 24, the inversion/eversion frame is designed to rotate around the two shafts that has extruded from the both ends of the footplate. There were significant alignment challenges in fabrication of these components. Single shaft design was tried and found to require much more precise fabrication process to ensure proper rotation. The process of machining/fabricating these parts was done with high accuracy, within one-thousandth of an inch (0.001”) to ensure proper alignment. The internal footplate must have been perfectly square to prevent contact with the support frame during rotation.

In order to increase the system stability and also measure the applied force on the footplate, the internal layer is built of five different components: an acrylic plate, an aluminum plate, load cells, metal crossbars and aluminum beams as shown in Figure 25. The patient’s foot is strapped on the
acrylic plate. Acrylic was chosen because it is significantly lighter than aluminum and provides a relatively high rigidity. The aluminum plate was attached to the acrylic plate to support and strengthen the footplate and ensure minimal deflection. Four load cells (53CR from Honeywell Inc., Morristown, NJ) were inserted symmetrically in the four corners of the footplate, in between the aluminum plate and the two metal crossbars. The metal crossbars are connected to the surrounding aluminum beams.

Figure 22: The robotic force-plate, load cells and sensing mechanism (TOP: experimental prototype; BOTTOM: CAD drawing). The load cells (1); acrylic plate (2); aluminum plate (3); metal crossbar (4); aluminum beams (5); the linear spring to create a preload (6).

One of the design needs was the possibility to measure tensile force (for dorsiflexion) as well as compressive force (for plantarflexion). This was achieved by utilizing a preload structure in the force-plate. Accordingly, a bolt was passed through the aluminum crossbars to the acrylic and metal footplate and was secured by a nut on top of the footplate. A compression spring (k =
10,000 N/m) was inserted in between the bolt head/washer and the crossbar. The same structure was applied to the second crossbar. The preload on each pair of load cells (back and front) can be adjusted by tightening the bolts. The subject’s foot will be strapped to the footplate and by applying the voluntary force along dorsiflexion will relax the load cells and lead to tensile force measurement.

### 3.4.2 Motors and Transmission System

The final product is intended to rehabilitate patients with neurological impairments to exercise the ankle joint. The actuation system is composed of electrical motors, gearbox system and transmission mechanism that is elaborated in the following section. Since this is a medical device, the system must account for a worst case scenario and be able to safely handle such a situation with confidence and reliability.

![Foot Diagram](image)

*Figure 23: Torque calculation of the subject’s foot on the footplate about DFPF axis [131].*
Patients with neurological impairments can utilize a safety harness as well as the safety rails to steady themselves. This will take part of the weight off of the robotic footplate. It was decided that the worst case scenario is a healthy patient of 300 lbs applying 75% of the total weight on the ball of the foot [88]. The torque calculation is based on a rated output, which indicates what the motor/gearbox assembly can apply continuously for an indefinite amount of time.

Figure 26 shows an exemplary model of the patient foot on the footplate. This is the extreme case of a Men’s 14 shoe size, which is 12 inches in length.

75% of 300 lbs is applied at a distance of 9 inches from the pivot point, acting as the lever arm. Accordingly the following torque calculations for plantarflexion were developed:

\[
Torque = Force \times Distance
\]

\[
Torque = (0.75)(300 \text{ lbs}) \times (9 \text{ in}) = 2025 \text{ lb} - \text{in} = 228.8 \text{ N} - \text{m}
\]

Figure 24: Torque calculation of the patient foot on the footplate about INEV axis [131].
The same approach was used for the inversion/eversion axis of rotation, shown in Figure 27. The axis of this degree of freedom is in the center of the foot, in line with the 2nd metatarsal. The end range of a Men’s 14 foot size was taken as maximum 5 inches.

\[ Torque = (0.75)(300 \text{ lbs}) \times (2.5 \text{ in}) = 562.5 \text{ lb} - \text{in} = 63.6 \text{ N} - \text{m} \]

The speed calculation was based on the total range of motion (ROM) along each degree of freedom. Dorsiflexion/plantarflexion is a total of 90° and inversion/eversion is a total of 60°. This was converted to an RPM value using 1 second as the marginal time desired for a full range of motion rotation. Accordingly the RPM of dorsiflexion/plantarflexion and inversion/eversion are calculated using the following formula.

\[
RPM = \left( \frac{(\text{Desired ROM})}{360^\circ} \right) \times \left( \frac{60 \text{ seconds}}{1 \text{ minute}} \right) \left/ \frac{1 \text{ second}}{1 \text{ minute}} \right)
\]

Using the above equation, the speed along the DFPF and INEV axes were computed as 15 RPM and 10 RPM respectively. These were the marginal high values which were even increased in the final specification table (Table 7) to 20-30 RPM and 15-20 RPM. This ensures the motor/gearbox combination can provide at least the marginal speed, but gives room for flexibility in selecting the components.

The next step in the selection of a motor was to find a motor with the appropriate total rated power that fits to these variables. These variables are listed in Table 8.

\[
Power = Torque \times Speed
\]

\[
Power_{DFPF} = 230Nm \times (20 - 30) \times \frac{2\pi}{60} \left( \frac{\text{Radians}}{RPM} \right) = 480 - 720 \text{ Watts}
\]

\[
Power_{INEV} = 64Nm \times (15 - 20) \times \frac{2\pi}{60} \left( \frac{\text{Radians}}{RPM} \right) = 100 - 135 \text{ Watts}
\]
Table 8: Summary of motor requirements.

<table>
<thead>
<tr>
<th>Axis of Rotation</th>
<th>Rated Torque</th>
<th>Speed</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorsiflexion/Plantarflexion</td>
<td>230 N-m (2036 lb-in)</td>
<td>20-30 RPM</td>
<td>480-720 Watts</td>
</tr>
<tr>
<td>Inversion/Eversion</td>
<td>64 N-m (567 lb-in)</td>
<td>15-20 RPM</td>
<td>100-135 Watts</td>
</tr>
</tbody>
</table>

The torque requirements are very high and speed requirements very low. Accordingly, a gearbox is needed to provide the high torque multiplication and speed reduction along each axis of rotation. In general motor speeds are very high, in the thousands of RPM, and torques are very low, typically less than 5 Nm. The 100:1 gearbox ratio was selected to bring the output speed of the footplate down to the appropriate range and the torque output at the footplate up to meet our specification.

The other consideration in gearbox selection was backlash. Minimizing the backlash is required as the user should not be able to rotate the footplate a noticeable amount in a fixed position. The high amount of backlash will increase the play in the footplate in fixed position, which can create a perception of instability of the device and thus a lack of confidence for the user to operate the device safely. The selected gearboxes have 11 arcmin backlash. Converting this value to radian and multiplying that by the radius of the pulley (1.7”) will result in vertical shift of 0.005 inches on the footplate along DFPF axis.

Considering the factors of output power, size, weight and ease of use and programming, we selected brushless DC motors. Our compact design has the inversion/eversion motor mounted underneath the footplate. Accordingly it was necessary to keep the motor weight as minimal as possible so as to minimize the rotational inertia of the footplate. This will effectively minimize the wear on the DFPF motor that will have to counteract the rotational inertia of the footplate. The motor and gearbox were purchased from the same company (Anaheim Automation) to guarantee the compatibility.
Table 9: Calculation of output rated torques and maximum speeds of each axis of rotation.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Rated Motor Torque (N-m)</th>
<th>Maximum Motor Speed (RPM)</th>
<th>Gear Ratio</th>
<th>Rated Output Torque After Gear Multiplication (N-m)</th>
<th>Output Max Speed After Gear Reduction (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantarflexion/dorsiflexion</td>
<td>2.1</td>
<td>3200</td>
<td>100</td>
<td>210</td>
<td>32</td>
</tr>
<tr>
<td>Inversion/eversion</td>
<td>0.71</td>
<td>3000</td>
<td>100</td>
<td>71</td>
<td>30</td>
</tr>
</tbody>
</table>

Two motors were selected based on the required torque / speed, as specified in Table 8, and the response time in this application. Accordingly the 660 W brushless DC motor (BLY-344S-48V-3200 from Anaheim Automation, Anaheim, CA) was connected to the gearbox (GBPH-0902-NP-100) with a 100:1 ratio to gain the mechanical advantage and provide the required characteristics along the PF/DF axis. Similarly the 220 W brushless DC motor (BLY-342S-160V-3000) was connected to the gearbox (GBPH-0902-NP-100) to actuate the IN/EV axis. The motors have 300% maximum producible torque (rated torque) which is a secure enough margin for this application. Table shows the calculated rated torques and motor speeds when combined with the selected gearbox.

![Figure 25: The transmission systems about both axes; pulley and timing belts [131].](image)

The robotic force-plate is actuated by electrical gear-motors along 2-DOF. The method of driving the shafts from the motors was chosen as a pulley and timing belt assembly. The ratio of the “drive” pulley to the “driven” pulley is 1:1. The mechanical advantage that is needed comes from
the gearboxes, so the pulleys were kept at the same radius for each respective DOF system. The sprocket of the pulley assembly is mounted to a coupler, which fits on to the steel drive shaft.

The power from both gear-motors was transmitted by a pulley (with 1:1 ratio in both axes) and timing belt to the footplate axes of rotation. The belt and pulley were selected to match the required torque and RPM. The IN/EV motor is connected to the bottom of the external layer via an aluminum plate (Figure 2). The power from this motor is transmitted through a pulley (8MX-45S-36) and poly chain timing belt (8MGT-1120-36, from Gates, Denver, CO) to the internal acrylic plate. As shown in Figure 28, the DFPF motor is located in the bottom corner of the support frame. Similarly the power from DFPF motor is transmitted through a pulley (8MX-45S-36) and poly chain timing belt (8MGT-1120-36, from Gates, Denver, CO) to the robotic footplate. This setup allows for maximum efficiency and minimal backlash as well as enough flexibility to deal with misalignment issues. The actual backlash on the footplate is higher than the imposed value by the gearbox due to the play in the pulley and timing belt. In order to minimize this effect an idler pulley was built-into each axis of rotation, as shown in Figure 28. This will provide a better tuning mechanism on the timing belt assembly so as to reduce the amount of slippage or backlash.

### 3.4.3 Motor Controllers

Since the speed/power of the DC motors is a direct product of the current, each motor needs its own current controller. The values for each motor’s rated current in Table 1 were calculated using the rated power and voltage in the following equation:

$$\text{Rated Current} = \frac{\text{Rated Power}}{\text{Rated Voltage}}$$
Accordingly the rated current for the DFPF motor was calculated as \((660/48 = 13.75 \text{ Amp})\) and \((220/160 = 1.375 \text{ Amp})\) for the INEV motor. The values for the peak motor current, as well as the controllers’ peak and rated currents, were obtained from the respective data sheets.

The commutation sequence of brushless DC motors are controlled electronically, due to lack of mechanical brushes that automatically alternate the magnetic field in regular DC motors. The brushless DC motor requires the Xenus servo amplifier for operation. This digital amplifier can be programmed to operate in three different modes: position, velocity or force. Servo amplifiers (shown in Figure 29) are used for the sinusoidal commutation, and torque control of brushless motors along both DOF. Traditional “six-step” (or trapezoidal) commutation relies on hall-effect sensors for its phase information. However, this method is prone to cogging, particularly at low velocities. On the other hand, sinusoidal commutation relies on higher resolution phase information, and consequently generates smoother torque output.

![Figure 26: The linear motor controllers by Copley Controls.](image)

Table 10: Comparison of motor and controller electronic specifications.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Manufacturer</th>
<th>Part Name</th>
<th>Motor Rated Current</th>
<th>Motor Peak Current</th>
<th>Controller Rated Current</th>
<th>Controller Peak Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFPF</td>
<td>Copley Controls</td>
<td>XSL-230-40</td>
<td>13.75 A</td>
<td>55 A</td>
<td>20 A</td>
<td>40 A</td>
</tr>
<tr>
<td>INEV</td>
<td>Copley Controls</td>
<td>XSJ-230-10</td>
<td>1.375 A</td>
<td>5.6 A</td>
<td>5 A</td>
<td>10 A</td>
</tr>
</tbody>
</table>

It was necessary to select a controller with electrical specifications that were compatible with the motors. The motors are electrically driven by power controllers as shown in Table 10. Xenus
features a built-in PI controller for servo torque control (Figure 30). The desired torque output of the motor is commanded by an external analog voltage command.

In the torque – mode, the torque command (volt) is sent to the Xenus servo – amplifier. It will be scaled by a preprogrammed constant voltage to current factor. The flown current into the motors will be monitored and a proportional – integral (PI) controller adjusts the voltage sent to the actuator in order to coax the requested current draw. The built-in PI controller in the Xenus architecture will stabilize the instantaneous amount of current into the motor windings, out of Xenus.

For sake of convenience, the amplifier will be excluded from the diagrams from this point on. The Xenus amplifiers will be controlled by the commands sent out from the computer through the data acquisition board.

![Figure 27: The block diagram of the Xenus servo amplifier in torque control mode.](image)

### 3.4.4 Data Acquisition and Control

The system is equipped with torque and angular measurement units (explained in 3.5 & 3.6). It is continuously collecting the data from the sensors and drives the motors to achieve desired rehabilitation task, shown in Figure 31. The communication between the system and the computer
program is performed using the built-in PCI data acquisition board (NI PCI-6251) inside the LabVIEW real-time target.

![Diagram](image)

Figure 28: The real-time machine is in continuous communication with the robotic footplate to read the sensors and drive motors.

As shown in Figure 31, the force data is collected from the four built-in load cells in the footplate. After pre-amplification and hardware filtering, the data are acquired by the PCI data acquisition board (NI PCI-6251) inside the LabVIEW real-time target. The real-time target is the host of the control software that drives the actuators. This machine is used to ensure deterministic sampling rate of the force and angle data, which is an essential aspect of the ongoing rehabilitation task. The acquired data will be processed and the computed control commands ([-10:10] analog voltage) will be sent to Xenus controllers. Xenus controllers drive the actuators along DFPF and INEV axis of rotation. The data in the real-time target will be also communicated to the desktop host computer via Ethernet protocol. The desktop computer hosts the physical therapist interface and other non-critical applications such as data logging.
Figure 29: The schematic of human subject during ankle rehabilitation.

Figure 32 shows the higher level diagram of the system interfaced with the patient. The patient will be seated on the chair system, her foot strapped into the robotic footplate. She will play the interactive game on the screen while receiving the therapeutic regimens.

### 3.4.5 Stress Analysis

Users might feel unsafe or insecure in case of high amount of deflection in the footplate. Accordingly, a finite element analysis was performed to ensure system strength and stability in response to dynamic forces in extreme conditions [131]. The amount of maximum stress and incurred deformation under the maximum weight of 300 pounds was computed.

On the center, the footplate experiences less than 10.6 MPa stress while the peak value of 47.6 MPa was computed on DFPF drive shaft. The tolerable threshold by aluminum 6061 frame was 172.4 MPa, the DFPF driver shaft 2.07 GPa and acrylic plate (48 MPa). It was also determined that the maximum deflection on the footplate is limited to 0.275 mm, which is below the 2 mm sensible amount by subjects. The robotic footplate and the support frame showed the necessary stress requirements for this rehabilitation application.
3.4.6 Foot Straps

In order to transfer the exerted force or motion trajectory to the patient’s foot, a foot binding mechanism was used. Accordingly a foot strap (Flow Flite, from CA, USA) was attached to the acrylic footplate to embrace and secure the patient’s foot on the robotic footplate during a variety of demanding training protocols. This is an adjustable foot binding that can be fitted to a variety of patients with different shoe sizes. The binding also has a release mechanism that will be activated in rare situations of high pressure on the locks.

![Figure 30: The robotic force-plate and the foot strap mechanism to secure the subject’s foot on the footplate.](image)

Additionally a heel cup and strap mechanism was utilized to support the back of the foot, as shown in Figure 35 right. Two straps were passed through the locks to secure the foot during practice. Two air pillows were inserted in between the subject’s foot (top) and the foot strap to ensure the maximum and effective mechanical interaction.

3.5 Torque Measurement Mechanism

One of the most essential requirements for the ankle and balance rehabilitation system is the ability to measure human interaction force. In order to address this need, four compression load cells were
installed in the footplate and a unique mechanical design was utilized to measure both tensile as well as compressive loads. Load cells were separately calibrated, dually preloaded, and the accuracy of force-plate was measured experimentally.

Figure 31. The robotic force-plate, the force measurement mechanism (A: system prototype, top view; B: CAD drawing, side view; C: system prototype without footplate, top view). Load cells are placed in the Anterior(A)/Posterior(P) and Medial(M)/Lateral(L) planes with respect to the human ankle. The load cells (1); acrylic plate (2); metal plate (3); metal crossbar (4); aluminum beams (5); the linear spring to create preload (6).

3.5.1 Mechanical Design

As shown in Figure 36, the force-plate is composed of five different layers: (1) four compression load cells, (2) an acrylic footplate, (3) metal plate, (4) two metal crossbars and (5) surrounding aluminum beams that are connected to the system ground. The patient’s foot is strapped on the acrylic plate. Four load cells were inserted symmetrically in the four corners of the footplate, in between the metal plate and metal crossbars. The metal crossbars are connected to the surrounding aluminum beams which are connected to system body.
The footplate is composed of two layer rectangular plates: acrylic and metal plate. It is 36.3 cm × 16.2 cm (14 5/16” × 6 3/8”) and weights 2.295 Kg. Acrylic was chosen as it is significantly lighter than metal and provides a relatively high rigidity. The metal plate was attached to the acrylic plate to support and strengthen the footplate and ensure minimal deflection. Plastic shimmer paper was used in between the plate and two specific load cells to compensate for the uneven metal surface.

Figure 32. The force-plate structure: acryclic plate connected to the metallic plate. Shimmer papers were used in between the footplate and (AL and PM) load cells to further even the contact.

Four compression load cells are inserted in a “sandwich” configuration in between the footplate and system body, i.e. mechanical ground. The tensile force measurement was achieved by utilizing a preload configuration as shown in Figure 38. One spring (Steel Compression Spring, from Mcmaster, Part No. 9657K318, k ≈ 10000 N/m) was used for each pair of load cells in the anterior and posterior plane of the footplate. The spring was inserted in between the bolt head/washer and the metal crossbar below the force-plate. The bolt was screwed into a nut which is welded on top of the footplate.

The amount of preload on each pair of load cells can be adjusted by tightening/loosening the bolts. The preloaded force measurements will be set to zero and consequently subject’s dorsiflexion will,
relax the load cells and, lead to tensile (negative) force measurements. Considering the maximum applicable load to the springs (600 N), the anterior and posterior springs were preloaded by 220 N and 390 N respectively. These values were acquired experimentally to achieve a better accuracy in force measurement.

Figure 33. The mechanism of tensile force measurement. The springs were used to create a preload on the load cells.

3.5.2 Load Cells

Four compression load cells (53CR from Honeywell Inc., Morristown, NJ, 226 Kg) were used to measure the subject’s interaction forces with the footplate. The load cell signals were amplified and sampled at 1 KHz into the real-time machine target (using the NI PCI 6251), as shown in Figure 39. Each load cell was connected to the corresponding external amplifier and analog channel on data acquisition board.

Load cells produce 10 mv output (2 mV/V × 5 V excitation voltage) at the full load condition (226 Kg). Using the built-in potentiometers, the amplifier gain was adjusted to 1000 (to create a 10 V output) and the offset voltage was removed. Considering the 16-bit data acquisition board, the minimum load resolution can be theoretically estimated as 3.5 g.
3.5.3 Filtering

In the presence of active motors, significant amount of radio frequency interference (RFI) was observed on the load cells. This noise, which appeared as a high dc value at the output, was generated due to the inability of the precision amplifier (AMP04) to reject the common mode high frequency (30 KHz) interference. Accordingly two capacitors (1.5 µf, R = 266 Ω) were used at the amplifier input to suppress the RF noise (fc = 408 Hz). Additionally, the amplifier output signals were also filtered using an analog anti-aliasing low-pass RC filter (2.2 nf, R = 222 kΩ) with a cutoff frequency of 325 Hz. This will help to remove undesired high frequency components and improve the quality of output signals.

3.5.4 Force-plate

Four load cells were placed in between the footplate and system ground to create a force-plate. The unique mechanical design provides the possibility of measuring tensile and compressive loads. The force data was collected in the computer and a standard experimental procedure was defined to measure the accuracy of the force-plate in terms of total force and center of pressure (COP).

Load cells were calibrated independently using the Instron machine, which was used to provide the test loads. Figure 40 demonstrates the response of each individual load cell to the applied standard loads provided by Instron machine. Six ascending test loads followed by 5 descending
points were considered to calibrate each load cell (11 points in total). The curve fitting procedure was conducted to find the best linear estimate \((R^2 > 0.998)\) for each load cell and the acquired equations were used to represent the corresponding load cells in the next steps.

![Figure 35](image)

Figure 35. Load cells calibration characteristics; test loads were applied to the load cells and the output voltages were recorded. Load cells are placed in the Anterior(A)/Posterior(P) and Medial(M)/Lateral(L) planes, with respect to the human ankle.

The total force was defined as a summation of readings from load cells on four corners:

\[
\text{Total Force} = F_{AL} + F_{AM} + F_{PL} + F_{PM}
\]

\(F_{ij}\): Reading from load cell positioned in Anterior/Posterior or Medial/Lateral plane.

Developing the momentum equations at equilibrium, the COP can be calculated as follows:

\[
X_{COP} = \frac{\sum_{i=1}^{4} x_i F_i}{\sum_{i=1}^{4} F_i}
\]
\[ Y_{COP} = \frac{\sum_{i=1}^{4} y_i F_i}{\sum_{i=1}^{4} F_i} \]

Where

\( x_i, y_i \) represent the distance from the center of origin (left-bottom of the plate) and they were measured as follows: \( x_1 = 13.33 \text{ cm}, y_1 = 32.41 \text{ cm}; x_2 = 3.175 \text{ cm}, y_2 = 32.46 \text{ cm}; x_3 = 13.15 \text{ cm}, y_3 = 4.52 \text{ cm}; x_4 = 3.175 \text{ cm}, y_4 = 4.52 \text{ cm}. \)

A LabVIEW program (NI LabVIEW 2013) was developed to read the load cell data from the data acquisition board and represent the values in the computer. The load cells’ estimated linear curves were used to convert the voltage readings to force values. Stacking a mixture of weights, two standard weights (93.4 N and 205 N) were created and used to test the total applied force and COP measurement on the force-plate. Sixty circles (\( r = 1.4 \text{ cm} \)) were drawn on a sheet of paper (36.3 cm × 16.2 cm) and placed on the footplate, as shown in Figure 41. The circles were drawn to mark the weight’s position. The bottom-left corner of the plate was chosen as the space origin (\( X = 0, Y = 0 \)).

For the center of each circle, the theoretical COP was calculated and compared with the acquired experimental values. The spatial errors represent the difference in theoretical reference model and those actually obtained from the force-plate:

\[ e = \sqrt{(X - X_{COP})^2 + (Y - Y_{COP})^2} \]

Where \( X: \) Acquired experimentally (cm); \( X_{COP}: \) The reference value as marked on the sheer (cm)

The distance and force errors are shown in Figures 43, 44 respectively.
Figure 36. The experimental setup for force-plate accuracy tests. A: The reference sheet was glued to the force-plate and the center of origin was considered as the bottom-left. B: Test loads were applied to circles on the plate.

Figure 37. Spatial accuracy map in application of two standard loads to the force-plate.
Accordingly the mean and standard deviation of associated errors are reported in Table 11.

Table 11. The foot-plate accuracy; COP and total vertical force measurements.

<table>
<thead>
<tr>
<th></th>
<th>$F = 93.4$ N</th>
<th>$F = 205$ N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error in COP (cm)</td>
<td>$0.64 \pm 0.24$</td>
<td>$0.49 \pm 0.27$</td>
</tr>
<tr>
<td>Error in W (N)</td>
<td>$3.00 \pm 1.85$ (3% ± 1%)</td>
<td>$6.58 \pm 5.03$ (3% ± 2%)</td>
</tr>
</tbody>
</table>

For this device it is necessary to employ sensors that supply feedback to the motors for precise control. The first of these is the positional feedback of the footplate, which can be provided by an encoder. Another sensor that we evaluated was a pressure map system for measuring peak pressure distributions under the foot surface (magnitude and location). Potentially this information could provide useful training to subject during balance and motor control training.
However, since we found a relatively high inaccuracy in the pressure mapping technology (±10%), we decided to utilize the information from the 4 load cells to monitor the weight percentage distribution and COP used by the patient in different training applications.

The vi-RABT is equipped with four load cells under the rectangular footplate to measure both compressive and tensile forces, as explained in Figures 36-38. Load cells were calibrated separately (out of the system) and mounted into the platform. Center of pressure and total applied force to the force-plate were acquired (as described in the prior section) to evaluate the accuracy of the prototyped platform.

The rectangular metallic plate in contact with four load cells is not perfectly straight and smooth. Shimmer papers in addition to unequal preloads (220 N vs. 390 N) were utilized to reduce this unbalanced contact and provide more even interaction between the footplate and load cells. Higher preload in the posterior plane has resulted in more accurate force measurements. The imperfections in mechanical elements as well as the imprecisions in the electrical circuits do not allow for the extremely high force resolution of 3.5 g in practice.

Load cell calibrations demonstrated a strongly linear profile. The applied test loads had a radius of 1.4 cm, which is the limit of our accuracy evaluation in center of pressure. The best case scenario was to apply point loads to the force-plate which was not practically possible in our lab. The error in center of pressure under both loads was less than 1.4 cm across the force-plate. The total applied force to the force-plate also showed less than 5% mean error value.

The acquired results are supportive and promising in pursuing the application of COP and force measurement. The force-plate can be used in any type of static force and COP measurement. Human subjects will be able to stand on the force-plate (unilateral at present) and play the previously developed pre-gait and balance activity virtual reality game previously developed for
the NUVABAT device [34-37]. These games are driven by the COP inputs derived from footplate load cell data.

### 3.6 Angle Measurement Mechanism

There is an encoder built-in on each motor shaft, but additionally there will likely be an encoder on the footplate shafts for each rotational direction. This serves the purpose that if there is an error in the transmission of rotation between the motor and the footplate shaft, the error can be read between the two encoders on each degree of freedom.

To maintain consistency, the encoders were also ordered from Anaheim Automation. The encoder selected is part number ENC-A5DI-1250-394-H-G. This encoder was used on both axes of rotation. It is a differential, optical rotary encoder. Its resolution is the maximum available at 1,250 counts per revolution. For the inversion/eversion axis, the encoder was directly mounted to the motor via a dual-shaft configuration. The same option was not commercially available for the plantarflexion/dorsiflexion motor, so an encoder was applied directly to the axis of rotation.

Real-time position measurement is a necessary requirement for the closed-loop control of the vi-RABT. The same data can also be fed to the virtual reality game interface. In order to achieve this goal, we have utilized an optical encoder along each axis of rotation. This section discusses encoder mountings, data collection and the bench test to compute measurement accuracy in each axis.

#### 3.6.1 Optical Encoder

Encoder is an electro-mechanical device that converts the angular displacement or motion of shaft to a digital code. Shaft encoders can be used for many sophisticated rotating machine where real-time position and control is needed. There are two main types of encoders: absolute and incremental (relative). The output of absolute encoders indicates the current position of the shaft, i.e. the position transducer. The output of incremental encoders provides information about
the relative position of the shaft, which is typically further processed elsewhere into information such as position and speed.

The standard components of incremental optical encoders are shown in Figure 44. The internal codewheel is made of glass or plastic with the adjacent transparent and opaque bands. The disc is placed in between a light source and a photo detector to read the motion.

![Figure 44. The schematic and mechanism of optical encoder.](image)

In this study, we have used two incremental optical encoders (ENC-A5DI-1250-394-H-G, from Anaheim Automation, Anaheim, CA) to conduct the required angular measurements.

### 3.6.2 Mechanical Attachment

Encoders are very accurate but also extremely sensitive to displacements and external vibrations. This is due to the internally sensitive optical circuit, shown above, that requires precise fixation and alignment specifications. In this endeavor, we have tried several scenarios to find the most optimal position of the encoders on the system. Our criterions were to attach the encoders in the closest and also most robust proximity to the footplate in order to have repeatable and accurate
angular measurements. We have found that mounting and assembly of encoders next to the end effector can be very challenging.

Figure 40. The footplate axis of rotation, where the encoders were installed in the early trials.

Figure 41. The optical encoder attachment to the DFPF axis of rotation: 1) the 3D printed pulley housing, 2) the optical encoder, 3) the extension rod, 4) the encoder electrical wiring to the data acquisition board.

In the early trials, we have placed the encoders close to the footplate. The dorsiflexion / plantarflexion (DFPF) and inversion / eversion (INEV) encoders were attached directly to the
footplate axis of rotation, as shown in Figure 45. The encoders were attached and assembled on
the shafts, which come out of the footplate through the pulleys. In order to install the encoders,
and also for safety considerations, two housings were designed and 3D printed. They were used
to cover the pulley transmission systems for the DFPF and INEV axes of rotations.

This design didn’t succeed due to the subtle play in the axes of rotations, attached to the footplate.
The play, which was caused by footplate deviations, was beyond the encoder tolerance and led to
the erroneous output measurements.

Figure 42. The optical encoder attachment to the INEV axis of rotation: 1) the pulley housing, 2)
the optical encoder, 3) the extension rod, 4) the encoder wiring to the data acquisition board.

As a result, we have mounted the encoders on the primary pulleys attached to the actuators,
shown in Figures 46 and 47. In order to achieve this goal on the DFPF axis, a second housing was
designed and 3D printed to support the encoder mechanical body and attachment. As shown both
encoders were assembled directly on the gear-motor shaft. We have also designed and fabricated
an extension rod to the pulley hole in order to transfer the rotation to the encoders’ codewheel.
3.6.3 Data Acquisition and Results

Both encoders were electrically connected to the wiring terminal and PCI data acquisition board (NI PCI-6251) built-in to the real-time machine, as shown in Figure 48. The data were recorded in LabVIEW 2013 for further processing and control.

![Electrical Circuit Diagram]

Figure 43. The electrical circuit to collect the encoder data into the computer.

The recruited encoders generate 1250 pulse per full revolution. Utilizing the quadrature settings, the smallest detectable angular displacement (i.e. resolution) can be calculated as follows:

Angular Resolution = \( \frac{360 \text{ (Deg)}}{1250 \times 4} = 0.072 \text{ (Deg)} \)

This value was verified in the collected data. Figure 49 presents the exemplary angular displacement of the robotic footplate along both axes of rotations. In this plot, the footplate was moved by hand along both axes of rotations subsequently, the DFPF and INEV.

3.6.4 Bench Testing

Real-time closed-loop control relies on accurate data acquisition from the sensors. This need is critical in our rehabilitation task, as the vi-RABT is interacting with patients, as well as healthy human subjects. Encoders are very precise sensors, which if installed and used correctly, can be relied on with high level of accuracy, repeatability and confidence.
In order to evaluate angular measurements we have used a precision 45 (Deg) miter with bubble level at different configurations, as shown in Figure 50. The bubble level is an instrument designed to indicate whether a surface is horizontal, vertical or in our application 45 (Deg). Accordingly, using this instrument, we have placed the footplate in three reference angular positions (-45°, 0°, +45°). The motors were used to move the footplate to the selected reference angles. Each time the actual data readouts from the LabVIEW were recorded to be compared with the reference value. This procedure was repeated for 10 consecutive trials along each axis of rotation (2 DOF ×10 trials ×3 reference values = 60 data points), and the results are provided in Table 12.
Figure 45. Using a 45° (Deg) bubble level to assess the accuracy of angular measurements. The reference tool (A: Precision 45° miter with bubble level) was used to set three different reference angles (B: 0°, C: 45° and D: -45°) and the data readouts were recorded in the LabVIEW program.

Table 12 summarizes the mean angular measurements (in LabVIEW) of ten trials. Data were collected in three different reference angles (as set by the 45° bubble level) along each degree of freedom. The reference points were selected randomly and the mechanical and software locks were released for the purpose of this test.

Table 12. The angular measurement accuracy; bench test results in each reference angle.

<table>
<thead>
<tr>
<th>Axis of Rotation/Reference Angle</th>
<th>$\theta = 45°$</th>
<th>$\theta = 0°$</th>
<th>$\theta = -45°$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inversion/Eversion (Deg)</td>
<td>45.807 ± 0.10</td>
<td>0.25 ± 0.15</td>
<td>-45.25 ± 0.29</td>
</tr>
<tr>
<td>Dorsiflexion/Plantarflexion (Deg)</td>
<td>45.81 ± 0.53</td>
<td>-0.06 ± 1.3</td>
<td>-45.23 ± 0.64</td>
</tr>
</tbody>
</table>
Accordingly on the average, we will have less than 0.8 (Deg) measurement errors. This inaccuracy can be due to the play in the transmission system or our visual recognition of the leveled bubble in each trial.

Encoders are highly accurate sensors which are also very sensitive to vibrations and external mechanical noise. In this study, we have found the most optimal position for the encoders along two degrees of freedom (DFPF, INEV) ankle rehabilitation system. Accordingly the angular resolution of 0.072 (Deg) with less than 1 (Deg) accuracy was achieved. The system follows the standards to be used as a robotic rehabilitation system in the follow up studies on human subject experiments.

3.7 Virtual Reality System

Another unique feature of the vi-RABT is the interactive gaming interface. The virtual reality (VR) allows for augmented feedback based on both kinematic and haptic features of the subject performance, and thus results in facilitation of the motor learning through a wide variety of mechanisms [38]. The VR system hardware includes two projectors (Hitachi's CP-SX1350) to create a 3D interface and speakers to augment the experience.

The wide projection screen (3×2 m) was used to increase the patient engagement in the rehabilitation procedure. A large screen display is a compelling and motivating input for subjects who may have difficulty feeling or seeing small movements in their ankle while practicing their exercises, especially in the presence of sensory impairments. Virtual reality games have been developed and used with human subjects that will be explained in the next chapter.

3.8 Chair Subsystem

Due to the severity and complexity of injuries, many patients (e.g., patients with stroke) may need to begin training in the seated posture. For those patients, an adjustable seat that allows training in incremental positions between sitting and standing is ideal. Accordingly we utilized a chair
system with adjustable height, as shown in Figure 51. The chair has an adjustable height of 17.5" - 23.5" with a fixed width (26.25") and depth (16"). In order to accommodate the force-plate height and further increase the height of the chair, two adjustable platforms (The Step Inc.) were used. The platforms were placed underneath the chair legs, on right and left sides, with the footplate of the vi-RABT in the middle. Each platform was 43" long, 16" wide and with adjustable height from 4" to 8".

Figure 46: The adjustable chair with risers.

The total adjustable height was 21.5"-31.5” which was high enough for subjects with different heights. Our current prototype was developed for regular seated posture only (i.e., hip and knee each at 90 degrees). The chair will require modification in the future to allow training of the ankle with the hip and knee at different angles to accommodate interim positions between sitting and standing.

3.9 Mechanical Safety Features

The ultimate goal of the vi-RABT is for the rehabilitation of the patients. We anticipate that the majority of the patients who use this device will have impaired ankle strength and/or balance control. Therefore, rigorous hardware and software safety features were considered in the design
phase. These features prevent excessive footplate rotation and extreme torque values. The hardware features include the mechanical stops to ankle rotation beyond any set position on either axis; foot straps, safety handlebars, and other features for the future including a harness or use in standing during standing.

![Image of safety mechanical stops]

Figure 47: The safety mechanical stops (in green color). Left: Inversion/eversion, Right: Dorsiflexion/plantarflexion [131].

In order to limit the maximum angle along each axis, mechanical stops have been implemented underneath the corresponding DOF, as depicted in Figures 52-53. These act as a hard-limiter to prevent over rotation of the footplate. Accordingly the maximum rotation on the INEV axis was limited to 40° of rotation, shown in Figure 52.

The maximum rotation on the DFPF axis is 60° of rotation. The stop on this axis was built into the frame using a cross beam from the 8020. The stop for this axis can be seen in Figure 47 and is highlighted in green. This is adjustable based on therapist decision and is a backup protection in case of software failure.

As explained in the previous section, the patient’s foot will be strapped into the bindings on the footplate. This is to provide the maximum control over the ankle joint. However having the patient’s foot tight on the footplate will raise the risk of damage to the tissue in uncontrolled
situations, such as falls or excessive power. This problem will become more serious by considering the maximum producible torque (300% of the rated toque) of the motors. We are envisioning use of the inherent quick release mechanism in the ski-board bindings. Using this feature the person can be quickly separated from the robotic footplate in many undesired situations. However, this will require rigorous testing in standing prior to use with patients.

In the future developments of the system while using in standing mode, the safety harness can be used to serve to protect the patient if they were to lose their balance, but can also be used to bear some of the patient’s weight. Due to limitations in cost and the high amounts of torque that a person can apply to footplate it may be necessary to employ an unweighing safety harness. The safety harness itself will be mounted directly onto the overall system and can easily be attached or detached.

3.10 Conclusion

This chapter described the design and architecture of the novel 2-DOF platform-based robotic ankle and balance trainer called the virtually-interfaced robotic ankle and balance trainer (vi-RABT). Vi-RABT can be used for measurement of ankle kinetics, kinematics and balance function, as well as for retraining standing balance, motor control and strength of the ankle during dorsiflexion/plantarflexion (DFPF), ankle inversion/eversion (INEV) and circumduction motions. Furthermore, the vi-RABT was designed for use in either a sitting or standing posture to accommodate early and late phases of rehabilitation training. By providing controlled force and angular profiles, the system can be used for lower-extremity training in variety of neuro-muscular disorders.

Special safety measures have been considered in the system hardware to prevent excessive rotation along each DOF. By hosting one DOF (INEV) into the other one (DFPF), we could
create a system that is relatively compact and lightweight. At the same time the robotic footplate is robust enough to tolerate the patient’s weight in different posture from sitting to standing.

vi-RABT is composed of A) a robotic force-plate to apply desired force profiles and motion trajectories to the human lower extremities; B) the chair to provide the possibility of following the exercise regimen in the seated posture; and C) a 3-D wide screen to project virtual reality games and create an entertaining, immersive therapy experience for the patient. In future developments the system will include: D) a second robotic force-plate to provide the possibility of balance perturbation to individual legs independently, E) a stationary platform to host both robotic force-plates and supply safety hand grips for the patients; F) the harness to increase the safety and selectively compensate the patient’s weight as needed by the therapeutic regimen.
Chapter 4  Interactive Games and Robotic Control Software

The vi-RABT hardware is interfaced with the virtual reality games and the control software. As shown in Figure 54, a subject interacts with the robotic force-plate while playing the game on the screen. Therapist can monitor the ongoing measures and adjust a number of variables. Two virtual reality games have been developed to train the ankle muscle strength, range of motion, coordination and motor control. The games were interfaced with the control software (in the real-time machine) so as to control the robotic force-plate along the desired goals of games. In this chapter, the games and control software will be explained. The performance results from a pool of human subjects following use of the VR games are explained in chapter 5.

Figure 48: The components of vi-RABT. Subject is seated on an adjustable chair (3); His foot is strapped into the robotic ankle trainer (1); The real-time machine (4) controls the 2-DOF robotic footplate (1); The 3-D display is used to project the virtual reality game (2); The subject is instructed to control the virtual avatar on the screen via moving the footplate (1); Therapist enters the required parameters and objectively monitors the ongoing experiment (5).
4.1 Virtual Reality Games

The focus of this study was on ankle rehabilitation. The virtual reality games were designed by the physical therapist to acquire the desired rehabilitation goals. The impaired ankle can be rehabilitated by particular strength and flexibility training protocols. The game development of this project was the subject of a master thesis at Northeastern University [130].

The subject’s foot is in physical contact with the robotic force-plate. Accordingly the system can measure the foot’s motion or applied torque to the robotic force-plate. These measures are transmitted to the game interface that is running on the therapist interface. The Board and Maze game were developed to train the ankle strength, motor control, coordination and range of motion. The games can be used either in isometric force or dynamic mode of operation. In Isometric mode the footplate axes are locked and the game avatar is controlled by subject’s isometric muscle contractions. In Dynamic mode, one or both axes is/are released, and the game avatar is controlled by concentric or eccentric ankle muscle contractions. The experimental design will be explained in the next chapter.

As shown in Figure 55, the Board Game is composed of three main components: 1) The blue board (plate), which represents the actual footplate under subject’s foot in veridical (but scaled) dimensions; 2) Horizontal and vertical box sets which demonstrate a guideline to the subject; and 3) the yellow and red box indicators to represent the current and desired position of the subject’s ankle position, respectively. The cubes located on the right demonstrate the plantar-dorsiflexion axis of rotation and the cubes on the bottom represent the inversion-eversion direction. The goal of the game is to move the yellow target along the guidelines and stay on or near the red target for a minimum of 1.1 sec, continuously. This time value can be increased to increase the level of difficulty for patient as they improve. As shown in Figure 55 and along the DFPF axis (y-axis), at the instant of reaching to the target, the three boxes in the target neighborhood turn into green. If the subject can keep the foot position for a short period (around 1.1 sec) in that area, then he will
acquire the goal and the next target will turn red. This game was utilized in three different scenarios: playing solely along the y-axis (DFPF); along x-axis (INEV) and along both DOFs simultaneously. In each case there is the total number of 30 goals to achieve.

Target distribution was performed by special considerations so as to avoid the repetition of the same target or close targets in the same proximity in successive targets. Accordingly each axis was categorized into 4 target-groups based on proximity. In every target selection, one group out of 4 was selected semi-randomly, as the same group was not allowed to be selected in successive trials. In the next step, a target was picked from the selected group following a uniform distribution. This routine was continuously repeated for all 30 goals along each axis.

Figure 49. The virtual reality Board game, as seen by the human subject. The y-axis represents the DFPF and x-axis represents the INEV. By using force/motion, the subject can move the yellow cursor to acquire the red target. Upon catching the red target, it will turn into green color.
Figure 50. The virtual reality Maze game, as seen by the human subjects. Using isometric force or dynamic ankle motion, the subject can move the purple avatar to acquire the green cubes.

The second game was developed based on the familiar concept of a maze game. In the developed Maze Game, subjects are instructed to move the avatar (purple ball shown in upper right of Figure 56) within the star-shape maze plane to pick up all green cubes. Subjects could self-select the sequence of acquisition. There were a total of 25 cubic goals to achieve in this game, including one target in the center that is already achieve in Figure 56.

There is an additional constraint in this game which is the concept of the wall, black areas surrounding the maze. Hitting the ball to the wall is considered as a collision and was accompanied by a negative score and an unpleasant high-pitch audio signal from the speaker. A pleasant low-pitch audio signal was played after each target was acquired. Subjects were encouraged to collect the targets in the minimum amount of time; and with the least number of
collisions in the maze game. The elapsed time, number of hits and collisions are shown on the
screen to the subject, shown in Figure 56.

The game boundaries were calibrated to each subject’s available maximum ROM and isometric
strength. These variables were measured at the beginning of every experimental session the
obtained values were used to set the dimension boundaries for the maze game. Further detail on
the experimental method may be found in Chapter 5. Later, we developed and implemented a
‘haptic wall’ which was produced by an active force from the actuator, preventing the subject
from moving the avatar (and thus the foot) past the wall position. This will be completely
explained in Chapter 6.

4.2 Real-time Control

The game is interfaced with the robotic force-plate, which needs to be effectively controlled so as
to acquire the rehabilitation objective. To achieve the ultimate rehabilitation goals of this
application, two robust and smooth controllers were developed so as to drive the system in the
back-drivable (free-running) mode. This was achieved by the force (torque) control mechanism.
As the subject pushes (pulls) the footplate, the system can sense the compressive (and tensile)
force and drive the actuators in the same direction so as to cancel out the interaction torque
experienced by the subject. This is a dynamic stabilization problem in control theory, where the
desired force (or torque) equilibrium point is zero.

The real-time target is the host of the control software that drives the actuators (explained in
Figure 31). The acquired data from the sensors will be processed to compute the control
commands ([-10:10] analog voltage) that will be sent to the Xenus linear controllers and both
motors. The desktop computer hosts the physical therapist interface and other non-critical
applications such as data logging.
Accordingly the next step in this study is to control the 2-DOF ankle rehabilitation device. A stable, robust and smooth PID (proportional-integral-derivative) controller needs to be developed for the ankle rehabilitation application. The system is equipped with accurate force and angular measurements. In order measure the subjects’ range of motion on the ankle joint, the system needs to operate in back-drivable mode. Accordingly the control objective is to create minimum force in human-machine interaction, i.e. foot-robotic force-plate. System identification algorithms were conducted, PID controllers were developed along each DOF and a mechanical bench-test setup was designed to test the system. This procedure is explained in the section below.

### 4.2.1 System Identification

The goal of system identification is to determine the system’s model and parameters by utilizing the set of experimentally acquired input/output data from the system [85]. Common system identification methods are introduced and recruited in time and frequency domain. Time-domain method is performed by applying a variety of statistical methods to the synchronized input-output time series. The frequency-response identification method is applied to the paired input-output series but in frequency domain and by analyzing the magnitude and phase of the system harmonic response. More advanced techniques include application of least square (LS) methods to determine a finite number of unknown parameters that optimally characterize the system model.

In this study and in order to design an effective enough controller for the 2-DOF ankle and balance robotic system, we have used the basic pulse response technique in time domain. The goal of this approach was to capture and model a significant portion of system’s behavior for control purposes.

In order to design an efficient PID controller along each axis of rotation, time-domain input-output techniques were used to model each axis of rotation by a 2\textsuperscript{nd} order linear model. The procedure consisted of applying a known voltage (i.e. pulse current) to the actuators and recording the system torque response on the robotic force-plate. The system transfer function was
estimated from the output/input characteristic. This process was repeated along each DOF, shown in Figures 57-58 as explained below.

The bench-test setup (explained in 4.3) was used. A 5V pulse voltage (period = 10 sec) was applied to the actuators and the resulted torque values were recorder along each axis of rotation. The system response to each stimulus was used as a basis to identify the underlying electromechanical dynamics. This data was analyzed in the system identification toolbox in Matlab (Matlab Corp. Natick, MA) and a second order system was estimated based on the acquired values.

The 2nd order transfer function of the DFPF actuation was estimated by 95.4% confidence interval as below:

$$H_{dfpf} = \frac{25.58}{s^2 + 4.17s + 8.53}$$

![Figure 51. System identification along the DFPF axis. The input voltage to the motor (blue), the actual torque (black) and the computed torque from the model (red) are plotted.](image-url)
Similarly, the 2\textsuperscript{nd} order transfer function along the INEV axis of actuation was estimated by 96.63% confidence interval as below:

\[ H_{\text{inerv}} = \frac{4.73}{s^2 + 3.29s + 4.78} \]

The computed transfer functions were used as a basis to design and tune the PID controllers in the next step. The system response including amplitude and time characteristics in two different axes were different due to the dissimilar underlying electromechanical dynamics along DFPF and INEV axes of rotation.

![Figure 52. System identification along the INEV axis. The input voltage to the motor (blue), the actual torque (black) and the computed torque from the model (red) are plotted.](image)

4.2.2 Proportional-Integral-Derivative (PID) Controllers

There are various control design techniques available for robust stability and performance of feedback systems. However, it was sufficient to use PID controller for this system to achieve the desired performance. Using the acquired models from the system identification method, the
proportional-integral-derivative (PID) controller was developed along each axis of actuation/rotation. The formulation of PID controller is considered as follows:

\[ e = T_d - T_a \]

\[ CI = K_P \times e + K_I \times \int e \, dt + K_D \times e' \]

\( T_a \): actual torque (Nm); \( T_d \): desired torque (Nm); \( e \): error; \( e' \): error derivative; \( CI \): control input to the motors (volt).

\( K_P \): proportional gain; \( K_I \): integrative gain; \( K_D \): derivative gain.

Accordingly, the error value was defined as the difference between the measured torque (Nm) and a desired set-point, which was zero in this application. The computed PID output will be low-pass filtered and sent to the actuators as the control input (CI), to accomplish the control objective.

The PID coefficients were optimized in SIMULINK (MATLAB) and implemented as follows:

DFPF: \( K_P = 3, K_I = 1.4, K_D = 0.48; \)

INEV: \( K_P = 3.7, K_I = 0.9, K_D = 0.55; \)

4.2.3 Stability Analysis

The electromechanical system of the robotic system was modeled with a 2nd order linear time-invariant transfer function along each axis of rotation with more than 95% confidence interval. In order to assess system stability and robustness, both time and frequency domain analysis was considered. While the frequency domain analysis reveals the system’s internal dynamics, the time domain analysis can shed more light on system’s response to bounded inputs [133]. In the following, the Nyquist frequency analysis and system’s step response in time domain is provided under both normal and perturbed conditions.
The stability analysis was performed to assess the system characteristics and safe range of operation. Figures 53-54 shows the Nyquist plot, applied to open loop characteristics along both degrees of freedom. As shown in both axes the system has not circled the \(-1 + j0\) and shows sufficient stability margins.

![Nyquist Diagram](image)

**Figure 53.** The Nyquist diagram of the control system along DFPF axis of rotation.

In order to further assess system stability margins beyond the limitations of the time-invariant model, we have also studied the system characteristics under uncertainty to parameters. Our approach was to add 10% random noise to the computed coefficients of the 2\(^{nd}\) order linear model as shown below:

\[
H_{\text{dfpf-perturbed}} = \frac{25.58}{(1 + \sigma)s^2 + (4.17 + \theta)s + (8.53 + \varepsilon)}
\]
\[ H_{inev-\text{Perturbed}} = \frac{4.73}{(1 + \sigma')s^2 + (3.29 + \theta') s + (4.78 + \epsilon')} \]

Where \( \sigma, \theta, \epsilon \) and \( \sigma', \theta', \epsilon' \) are uniform random variables within the \%±10 range of the corresponding coefficients.

Figure 54. The Nyquist diagram of the control system along INEV axis of rotation.

Figures 53-56 shows the Nyquist and step response plot of the perturbed system along DFPF and INVE axis respectively.
Figure 55. The Nyquist diagram of the control system along DFPF (left) and INEV (right) axis with 10% perturbation.

Figure 56. The time response characteristics of the control system along DFPF (left) and INEV (right) axis (right) in regular condition (…), and with 10% perturbation (-).

As shown in time response and frequency analysis in Figures 55-56, the perturbed characteristics of the system also demonstrated stable margins. Accordingly if the coefficients of the linear
model were subject to perturbation by 10%, the system is still in safe range of operation. The system is stable both internally as revealed by frequency analysis and bounded as shown in time domain.

4.3 Bench-test Setup

In order to assess and evaluate the performance of the controllers along each axis, the following test-bed was designed and developed, as shown in Figure 57. Two springs were attached to the front and back part of the footplate to resist the movement of force-plate and create an interaction torque similar to that produced by human subjects.

The bench-test was designed to evaluate the torque controllers. Two springs in the anterior lateral and posterior medial of the footplate provided the possibility of applying all combination of torques along both DOF. Using this mechanism, the actuators were controlled to drive the force-plate so as to experience particularly chosen desired torque values along each degree of freedom, i.e. dorsiflexion/plantarflexion (DFPF) and inversion/eversion (INEV).

![Figure 57. The control test bed utilizing springs to create interaction torques along INEV & DFPF axes of rotation. A: vertical view, B: horizontal view.](image)

4.4 Results

Controller design and bench tests were performed separately along INEV and DFPF degree of freedom. For generalization purposes, the desired torque values were set to 5 Nm for the INEV
and 10 Nm for the DFPF (instead of zero). These values were chosen based on the upcoming developments of the system to provide effective and strong enough assistive/resistive training in the virtual reality games.

Using the estimated 2\textsuperscript{nd} order models, the PID coefficients (K\textsubscript{P}, K\textsubscript{I}, K\textsubscript{D}) were computed in MATLAB. The acquired values were further tuned and implemented into the real-time LabVIEW machine to acquire the most optimal responses along each axis. Accordingly the following values were computed and utilized along each axis of rotation:

DFPF: K\textsubscript{P} = 3, K\textsubscript{I} = 1.4, K\textsubscript{D} = 0.48;

INEV: K\textsubscript{P} = 3.7, K\textsubscript{I} = 0.9, K\textsubscript{D} = 0.55;

Figure 58. Controlling vi-RABT along DFPF axis of rotation. The desired torque (top - red), actual torque (top - blue) and control command (bottom - black) are presented.
Figure 59. Controlling vi-RABT along INEV axis of rotation. The desired torque (top - red), actual torque (top - blue) and control command (bottom - black) are presented.

Results are presented in Figures 58-59. In the plotted results, motions toward the body (DF and IN) were considered positive and motions away from the body (PF and EV) were defined to have negative values. The controllers’ performance can be addressed using the following metrics:

DFPF: Rise time < 350 msec, Steady-state error < 0.25 Nm

INEV: Rise time < 450 msec, Steady-state error < 0.8 Nm

4.5 Conclusion

Two virtual reality games were developed to assess the subject’s ankle strength, range of motion and motor control. The controllers were developed to smoothly map the user’s physical input, on the footplate, to the game interface on the screen. The test-bed was utilized to design and evaluate
controllers along each DOF more efficiently. Development of PID controllers along both axes of rotation was explained. The controllers drove the motors to follow the desired values, and minimized the error. Although the upcoming human subject experiment was based on a stabilization problem (zero-torque trajectory), more general regulation cases (i.e. INEV = 5 Nm and DPF = 10 Nm) were considered. This regimen can be applied in future experiments, when assistive/resistive forces will be latter provided to the human foot while playing the maze game in the virtual reality.

The control objectives of the current rehabilitation experiment are to avoid application of excessive amount of torque to the subject’s foot, i.e. overshoot, and yet follow the desired trajectory in a reasonable time period (e.g. rise time and settling up to 1 sec). This is due to the critical sensitivity of the final application as patients with ankle injuries or motor control disorders may not be able to experience over-threshold torque profiles. The acquired results were stable, robust to 10% perturbation in the linear model, and smooth enough to meet the needs of the ultimate application of this system. New control techniques can be further explored in the future to achieve faster responses with lower amounts of steady state error.
Chapter 5  Experimental Results with Human Subject

The vi-RABT is purposed to be used for ankle and balance rehabilitation of patients with a wide range of neuromuscular disorders and injuries. In this study, we began walking toward this goal by assessing the preliminary measures in ankle biomechanics and human motor control in a series of experiments with human subjects. Our operational goal was to develop the required protocols for safe and smooth operation of this device with healthy human subjects that can pave the way for future patient tests. Our technical objective was to assess the ankle biomechanics including the rotational forces (torques) and range of motion (ROM), and also studying human motor control in the presence of augmented force and position biofeedback in the virtual reality environment. Objective measures were extracted from human-machine interaction and additionally the individuals were asked to fill out subjective questionnaires for complementary analysis.

Rotational forces (torques) and range of motion (ROM) are the first and most common assessments by physical therapist. These measurements are required for early diagnosis and correct treatment planning and they are also used during therapy to evaluate progress over time [89-91]. We have developed the protocols and designed an experiment to recruit a group of healthy human subjects and assess ankle biomechanics and motor control. We were also looking for system’s safety, consistency and smooth performance under heavy load of working with pool of human subjects.

In the motor control studies, we have studied and compared the application of augmented force and position biofeedback to the individuals while playing the virtual reality Maze and Board games. We were interested to address the effect of biofeedback to human motor performance in lower extremity and ankle joint which might contribute to rehabilitation. Biofeedback enables an individual to learn how to change physiological activity for the purposes of improving health and
performance [92]. Biofeedback signals have been used to study and understand human motor functions [93-95] and it is suggested that biofeedback may enhance neural reorganization by engaging auxiliary sensor inputs through existing cerebral and spinal pathways [96]. Force and position based biofeedback have been applied in rehabilitation to extract human intention for control and navigation purposes of active arm supports [97], electrical wheelchairs [98] and exoskeletons [99].

Force-based control interfaces have been utilized in rehabilitation robots to regain control, mobility and strength [100]. Using an upper limb rehabilitation device, haptic force feedback was applied to patient’s hand to regain motor control [101]. The upper limb rehabilitation device included therapeutic libraries for object manipulations and therapist could modify VR parameters and rehabilitation goals based on patient’s progress. Force biofeedback was shown to have certain advantageous over position biofeedback to increase the efficacy and patient compliance in gait rehabilitation. Accordingly Lunenburger et al. have developed a gait rehabilitation robot and used the force feedback to support patient’s weight [102]. This was formerly performed using indirect measurements such as gait phase and lower limb muscle activity.

Position-based control using joystick was studied to control an upper extremity orthoses [103]. MULOS (motorized upper-limb orthotic system) is a five-degree-of-freedom electrically powered assistive robot attached directly to the arm to provide controlled movements for people with severe upper limb disability. The system has three degrees of freedom at the shoulder, one at the elbow and one to provide pronation/supination and a specialized five-degree-of-freedom joystick was developed for the control purpose of MULOS. This device combined the normally used side-to-side movements of a joystick together with axial movement and rotation about the long axis. It was shown that potential users found this design intuitive to use and were able to perform a number of appropriate tasks created for assessment purposes.
The combination of force and position biofeedback was used to increase the reliability of an exoskeleton system that was used to assist nurses during patient transfer [104]. The system was made of aluminum shoulders, arms, waist and legs driven by the pneumatic rotary actuators that help nurses to carry patients around the hospital environment. Obviously any failure in accurate detection of user intent could have severe consequences and probable injuries and the high reliability of the force and position based inputs were required.

The existing literature to date, does not specifically address the scope, effectiveness and limitations of the lower extremity position versus force augmented feedback on motor control and rehabilitation. Force, position and electromyography (EMG) control in upper extremity control task has been addressed in [105]. In this study, healthy human subjects were instructed to track a 1-D goal on the screen by generating force, moving a joystick at the hand or producing the arm EMG. The force signal was generated by elbow flexion and extension to move the 1-D cursor up and down respectively. A forward tilt of a generic joystick moved the cursor up and a backward tilt moved it down. The isometric EMG control signal was measured from the envelop of electrical activities in biceps (move up) and triceps brachii (move down) muscles. Results show that subjects had lower tracking error in EMG control than the force control which was better than position control condition. While in the natural situation, healthy human subjects use both position and force sensory inputs simultaneously, the use of specific inputs is task dependent, and may switch depending on the environmental conditions during the task [106].

The choice of most effective biofeedback with respect to the user needs and capabilities can be crucial for the usability and success of any rehabilitation robotic system. In this study, and in addition to the assessment and operational objectives, we were interested to study the lower extremity force versus position motor control. We have designed an experiment to compare isometric force control and isotonic motion control of ankle joint in the goal oriented virtual reality environment. Results could address this fundamental question of whether healthy human
subjects have better motor control over the ankle joint with augmented position or force biofeedback. This might contribute to the appropriate selection of control interface in rehabilitation robotic systems and exoskeletons.

5.1 Methods

For the purpose of these experiments, the system was used in static mode (motors off) as a force-plate or controlled in dynamic back-drivable mode (motors on). In the static mode, the force-plate was locked by mechanical locks and it was used as an isometric force measurement unit. In the dynamic mode, one or both footplate axes were unlocked and the system was used in free-running mode where the controllers were used to steer the motors and the robotic force-plate along the subjects’ motions. In this condition, the motors were only used to counter the resistive the internal friction and inertia of the force-plate, so that the subject does not experience any significant resistance while moving the force-plate. In later tests we plan to examine device operation under conditions where the robotic motors provide resistance to ankle movements. The experimental design, measures and procedure are explained in the followings.

5.1.1 Design

An experiment was designed to study different characteristics of human ankle joint, as shown in Figure 60. Human subjects went through a single session of experiment consisting of 2 conditions and 20 blocks to assess ankle range of motion (ROM), isometric strength and motor control. The tests were conducted in the Dr. Holden’s Neurorehabilitation Laboratory (Dept. Physical Therapy, Northeastern University).
Figure 60. The experimental design diagram; each subject went through 20 Blocks (B) of exercise in 2 Conditions (C). In the diagram PF: plantarflexion, DF: dorsiflexion, IN: inversion, EV: eversion, BG: Board game, and MG: Maze game.

The goal of Familiarization blocks were to give subjects enough practice trials to learn how to interact with the system in Force and ROM conditions. In this phase, each subject went through one sample experiment of each condition. Accordingly subjects practiced isometric force (footplate locked) and ROM (back-drivable) measurements across single and both axes. Passing the Familiarization tests, subjects started the actual experiment with the Force condition. The explanation of experimental conditions and blocks are as follows:

- **Condition I (C-I):** Isometric Force measurement, footplate locked as a static force-plate
  - Blocks 1-4: Assessing maximum force along four directions: DF, PF, IN, EV
    - Subjects were instructed to perform 5 contraction trials along each axis
  - Block 5: Playing Board game solely along DFPF axis
    - Subjects were instructed to achieve 30 goals along the DFPF axis
  - Block 6: Playing Board game solely along INEV axis
    - Subjects were instructed to achieve 30 goals along the INEV axis
  - Blocks 7-8: Playing Board game along both axes DFPF, INEV
    - Subjects were instructed to achieve 25 goals along both axes
  - Blocks 9-10: Playing Maze game along both axes DFPF, INEV
Subjects were instructed to achieve 25 goals along both axes

- Condition II (C-II): Range of Motion (ROM) measurement, footplate in free-running
  - Block 11: Assessing maximum ROM along DFPF axis of rotation
    - Subjects were instructed to perform 7 movement trials around DFPF axis
  - Block 12: Assessing maximum velocity along DFPF axis of rotation
    - Subjects were instructed to perform 7 movement trials around DFPF axis
  - Block 13: Assessing maximum ROM along INEV axis of rotation
    - Subjects were instructed to perform 7 movement trials around INEV axis
  - Block 14: Assessing maximum velocity along INEV axis of rotation
    - Subjects were instructed to perform 7 movement trials around INEV axis
  - Block 15: Playing Board game solely along DFPF axis of rotation
    - Subjects were instructed to achieve 30 goals around DFPF axis
  - Block 16: Playing Board game solely along INEV axis of rotation
    - Subjects were instructed to achieve 30 goals around INEV axis
  - Blocks 17-18: Playing Board game along both axes of rotation DFPF, INEV
    - Subjects were instructed to achieve 25 goals along both axes
  - Blocks 19-20: Playing Maze game around both axes of rotation DFPF, INEV
    - Subjects were instructed to achieve 25 goals around both axes

5.1.2 Human Subjects

The experiments were approved by the institutional review board at Northeastern University (IRB# 10-01-12). Twenty healthy human subjects were recruited and went through each block of the experiment. Each individual filled the screening questionnaire as attached in Appendix B. The purpose of screening was to give preliminary information regarding the experiment and also assure subject’s health history with an emphasis in lower extremity. Eight females and 12 males, in the range of 20-40 years old all affiliated with Northeastern University passed the screening
test. In the next step, subjects were asked to sign the consent form as attached in Appendix C, and then participate in the study. All subjects were informed of the procedure and signed the consent form before participation in the experiment.

5.1.3 Measures

The goal of this experiment was to evaluate vi-RABT and measure subject’s ROM, forces and motor control on the ankle joint. Accordingly the following measures have been collected during the experiment and after each experiment as a questionnaire:

- **Objective data:** Measurements that were acquired from subject’s interaction with device.
  - Range of Motion (ROM): This variable was used to describe the amount of movement about the ankle joint around both axes.
  - Force: The amount of force (or torque) that subjects applied around both axes.
  - Game completion time (Time): The amount of time that subjects used to finish the virtual reality games.
  - Collision: This variable was defined in the Maze game. The game environment is surrounded by walls and subjects are instructed to avoid collision.

- **Subjective data [Appendix H]:** The measures that were acquired at the end of each block via subjective questionnaires.
  - Borg’s Rating of Perceived Exertion (Appendix D): This is a measure of physical fatigue experienced by a subject.
  - Visual Analog Scale (Appendix E): This is an indication of cognitive understanding and game requirements/complexity.
  - Usability Questionnaire (Appendix F): This was an indication of whether subjects understood the tasks, if the testing took too long or caused excessive fatigue, and how the subjects perceived their performance.
The objective of collecting the assessment blocks were to find out the range as well as peaks of the subjects’ ability. These values were later on used to set the boundaries of the virtual games. Accordingly %80 of the maximum values was set as the game boundary in the next section. The following equation was used for computing the maximum values along each axis of rotation:

\[ I = \text{mean} (Y); \quad Y = X(t), \forall X(t) \geq 0.70 \max(X) \]

X: Variable in use, e.g. rotational force, range of motion, or velocity.

In order to compute these measures, the maximum generated values (force or ROM) were selected; next, a subset of all the points more than %75 of this value were integrated (red circles in Figures 63-70) to measure to determine the mean value of that block.

In the normally distributed data, 99.7% of data population is within the three times the standard deviation from the mean population [132]. The same rule was applied to this experiment to identify the outliers. The following criterion was used:

Subject exclusion criteria: \( T > \mu_t \pm 3 \sigma_t \); and \( C > \mu_c \pm 3 \sigma_c \);

\( T \): Game completion time; \( \mu_t \): mean (T); \( \sigma_t \): standard deviation (T)

\( C \): Number of collisions; \( \mu_c \): mean (C); \( \sigma_c \): standard deviation (C)

Accordingly, out of 20 subjects 4 were eliminated due to excessively poor outcomes. The performance was evaluated based on subjects’ completion time and/or the number of collisions in the virtual reality games. If the subject had one block of experiment with three times deviation from the average population, he/she was identified as an outlier.

5.1.4 Procedure

Subjects were tested in the Neurorehabilitation Lab of Dr. Holden at Northeastern University. Upon arrival, they were asked to read and sign the consent form. As shown in Figure 61, they
were seated on the adjustable chair, with dominant foot strapped securely into the robotic footplate. To protect subject’s knee joint and to increase measurement accuracy, subjects’ legs were stabilized with pads and straps to minimize hip internal and external rotation. The chair height was adjusted to place the hip and knee in 90 degrees of flexion, and ankle joint in neutral.

As diagramed in Figure 60, the experiment started with familiarization blocks, in which subject were given enough practice trials to learn how to interact with the system in different conditions. Afterwards, subjects were tested in a series of four different tasks. Task one involved assessing the subject’s isometric force while the footplate was locked into the platform and it worked as a force-plate. Subject’s force output in plantarflexion (PF), dorsiflexion (DF), inversion (IN), and eversion (EV) were measured by having the subject perform 5 maximal contractions of 3 second duration for each of the desired directions. Mean values for strength for each subject were then used to set the game boundaries (%75 of maximum strength). In the second task subjects played a series of 4 games (BG-DFPF, BG-INEV, BG-2 DOF, and MG-2 DOF) that required single or double axis force output from the subject’s ankle in order to reach the targets and complete the games.

Figure 61. Exemplary human subject in the experiment. Left: Subject seated on the chair, Right: the foot placed into footplate using the pad and straps.
After completion of force control games the subjects maximum ROM was assessed in task three. The mechanical locks on the footplate were removed. The system was driven in the back-drivable mode, so it followed the subject motions rotating the ankle up, down, in or out. The subjects performed 7 trials along a sagittal and frontal axis at a comfortable pace along each axis (DFPF, INEV) followed by the same movement at as fast as possible (DFPF Fast, INEV Fast). Mean values for ROM for each subject were then used to set the game boundaries (%75 of maximum ROM). Subject maximum velocity was also measured. Subjects then completed task four by playing the same series of games as they did in task two (force control) however this time controlling the games via movement of the ankle (ROM).

Every session included two conditions of force and ROM measurements. Each condition was composed of 10 blocks. The whole session was composed of 388 trials, with total number of 190 trials in force condition and 198 trials in ROM conditions. Subjects finished the session in about 2 hours. All 20 subjects have sequentially gone through the explained 20 blocks. Standard rest period of 10 seconds were given after each trial in force assessments, and 15 seconds after each block during the whole experiment. Additional rest periods were given upon subject’s request. The experimental protocol is attached in Appendix G.

The subjective questionnaires were collected simultaneously, by Amber Hartman in [Appendix H]. Upon completion of each task as explained above, subjects were asked to complete a Borg's Rating of Perceived Exertion scale and a Visual Analog Scale (VAS). The actual questionnaires can be found in Appendix D and E respectively. At the completion of the vi-RABT testing subjects were also asked to complete a usability questionnaire, as attached in Appendix F.

5.1.5 Virtual Reality Games

Figure 62 shows the virtual reality games that were used in the study. The Board game is composed of three main components: 1) The blue board (plate), which represents the actual
footplate under subject’s foot; 2) Horizontal and vertical box sets which demonstrate a guideline to the subject; and 3) the yellow and red box indicators to represent the current and desired position of the subject, respectively. The goal of the game is to move the yellow target along the guidelines and stay next to the red target for about 1.1 sec continuously.

As explained in Chapter 4, this game was utilized in three different levels: playing solely along the y-axis (DFPF); along x-axis (INEV) and along both DOFs in both isometric force and ROM conditions. In each case there was total number of 30 goals along each axis to achieve. Target distribution was performed by special considerations so as to avoid the repetition of the same targets in successive trials. Accordingly each axis was categorized into 4 target groups. In every trial, one group out of 4 was selected to host the next target which was selected randomly within that group. This routine was continuously repeated for 30 goals along each axis.

Figure 62. The virtual reality games from subject’s perspective. Left: Board game, Right: Maze game.

Using a similar concept, in the Maze game, subjects were instructed to move the avatar (purple ball) within a star-shape maze plane to pick up all green cubes. They were also instructed to avoid the walls. Hitting the ball to the wall is considered as a collision and accompanied by an unpleasant high-pitch audio signal. There was the total number of 25 cubic goals to achieve in
this game. Target selection was not random and it was in a predictable order in this game. The games are completely explained in Chapter 4 of this dissertation.

5.2 Results

Each subject went through the total of 20 blocks of experiment, as diagramed in Figure 60. We have used the vi-RABT to characterize the ankle force, ROM and motor control. The initial 4 blocks (in both conditions) were preliminary assessment tests to measure maximum force, ROM and velocity. In the next step, and in the virtual reality games, the ankle ability to acquire targets in a VR game using position versus force augmented biofeedback was studied across 20 subjects and the results are provided.

In the following the acquired results from each block is demonstrated. Figures 63-66 represent the collected force assessment values. Throughout the whole study, dorsiflexion and inversion were considered positive and plantarflexion and inversion was defined with negative value.

![Figure 63. The force assessment experiment; block 1; subject 20. The solid (blue) line represents the acquired isometric torque value along the plantarflexion axis. The (red) dots represent the selected peaks that were integrated to compute the maximum torque value. In this block the maximum torque value was measured to be -22.0 Nm.](image-url)
Figure 64. The torque assessment experiment; block 2; subject 20. The solid (blue) line represents the acquired torque value along the dorsiflexion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum torque value. In this block the maximum torque value was measured 11.2 Nm.

Figure 65. The torque assessment experiment; block 3; subject 20. The solid (blue) line represents the acquired torque value along the inversion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum torque value. In this block the maximum torque value was measured 6.7 Nm.
Figure 66. The torque assessment experiment; block 4; subject 20. The solid (blue) line represents the acquired torque value along the inversion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum torque value. In this block the maximum torque value was measured -4.7 Nm.

The mean and standard deviation (SD) values of these variables for all subjects are reported in Table 13.

Table 13. Assessment Tests. Mean values ± SD for 16 human subjects for isometric torque, active range of motion (ROM) and velocity (V) about the ankle joint.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Biomechanical Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Torque (Nm)</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>18.26 ± 12.08</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>-19.82 ± 10.71</td>
</tr>
<tr>
<td>Inversion</td>
<td>7.11 ± 3.45</td>
</tr>
<tr>
<td>Eversion</td>
<td>-6.07 ± 3.24</td>
</tr>
</tbody>
</table>

As shown in Table 13, a similar approach was used for the angular measurement and velocity assessments. Exemplary results are shown in Figures 67-70.
Figure 67. The angle assessment experiment; block 11; subject 8. The solid (blue) line represents the acquired angular displacement along the Dorsiflexion /Plantarflexion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum. In this block the maximum angles were measured [30.0; -30.3] Deg respectively.

Figure 68. The velocity assessment experiment; block 12; subject 14. The solid (blue) line represents the acquired velocity along the Dorsiflexion/Plantarflexion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum. In this block the maximum velocity was 74.21 Deg/s.
Figure 69. The angle assessment experiment; block 13; subject 8. The solid (blue) line represents the acquired angular displacement along the Inversion/Eversion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum. In this block the maximum angles were measured [30.7; -20.7] Deg respectively.

Figure 70. The velocity assessment experiment; block 14; subject 14. The solid (blue) line represents the acquired velocity profile along the Inversion/Eversion axis of rotation. The (red) dots represent the selected peaks that were integrated to compute the maximum. In this block the maximum velocity was 113.62 Deg/s.
After conducting assessment trials, every subject played four different games, in the isometric and isotonic conditions (12 blocks per subject). Subjects first played the 1-DOF Board game along DFPF axis, and then the Board game along INEV axis. Next they performed the 2-DOF Board game; followed by the 2-DOF Maze game. They played the 2-DOF games each twice. The results are reported below in the order of experiment.
Figure 71. Subject’s torque profile while playing the Board game along DFPF; block 5. The solid (blue) line represents the acquired torque measurements along the dorsiflexion(+)/plantarflexion(-). The (green) dots represent the goals on the screen that was achieved. The game completion time was 73.00 sec.

Figure 72. Subject’s torque profile while playing the 1-DOF Board game; block 6. The solid (blue) line represents the acquired torque measurements along the inversion(+)/eversion(-). The (green) dots represent the goals on the screen that was achieved. The game completion time was 53.35 sec.
Figure 73. Subject’s torque profile while playing the 2-DOF Board game (top) and the self-selected sequence of achieving goals (bottom); block 7. The solid (blue) line represents the acquired torque measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 172.91 sec.
Figure 74. Subject’s torque profile while playing the 2-DOF Board game (top) and the self-selected sequence of achieving goals (bottom); block 8. The solid (blue) line represents the acquired torque measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 161.77 sec.
Figure 75. Subject’s torque profile while playing the 2-DOF Maze game (top) and the self-selected sequence of achieving goals (bottom); block 9. The solid (blue) line represents the acquired torque measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 305.69 sec.
Figure 76. Subject’s torque profile while playing the 2-DOF Maze game (top) and the self-selected sequence of achieving goals (bottom); block 10. The solid (blue) line represents the acquired torque measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 181.81 sec.
Figure 77. Subject’s angular displacement while playing the 1-DOF Board game; block 15. The solid (blue) line represents the angular measurements along the dorsiflexion/plantarflexion axis of rotation. The (green) dots represent the goals on the screen that was achieved. The game completion time was 65.15 sec.

Figure 78. Subject’s angular displacement while playing the 1-DOF Board game; block 16. The solid (blue) line represents the angular measurements along the inversion/eversion axis of rotation. The (green) dots represent the goals on the screen that was achieved. The game completion time was 56.60 sec.
Figure 79. Subject’s angular displacement while playing the 2-DOF Board game (top) and the self-selected sequence of achieving goals (bottom); block 17. The solid (blue) line represents the angular measurements along both axes. The (green) dots represent the goals on the screen that subject was trying to achieve. The game completion time was 108.05 sec. Goals 15, 27 and 7, 25 are shown close and on top of each other.
Figure 80. Subject’s angular displacement while playing the 2-DOF Board game (top) and the self-selected sequence of achieving goals (bottom); block 18. The solid (blue) line represents the angular measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 120.47 sec.
Figure 81. Subject’s angular displacement while playing the 2-DOF Maze game (top) and the self-selected sequence of achieving goals (bottom); block 19. The solid (blue) line represents the angular measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 46.84 sec.
Figure 82. Subject’s angular displacement while playing the 2-DOF Maze game (top) and the self-selected sequence of achieving goals (bottom); block 20. The solid (blue) line represents the angular measurements along both axes. The (green) dots represent the goals on the screen that was achieved. The game completion time was 46.01 sec.

The 12 blocks of game trials were further analyzed to assess individuals’ motor control. The essential question was whether motor performance in VR game was better with augmented force feedback or position feedback. The specific instruction in each game was to finish the games as fast and as accurately as possible. Additionally in the Maze game subjects were advised to have
the minimum number of collisions with the surrounding walls. Accordingly the game completion time (Sec) in all games and the number of collisions in the Maze game were selected as the primary variables for further analysis and comparison. The mean game completion times of 20 subjects across game blocks are shown in Figure 83-84. The complete results of game completion time and number of collisions of all participants in the game blocks are reported in Appendix A.

Overall, there is the total number of 6 games in each condition (force and ROM). Figure 83, displays the time completion time across each game in force and ROM conditions. Subjects first went through the 1-DOF game and then the 2-DOF games.

![Figure 83. The game completion time in six blocks of virtual reality games in 20 subjects. “B-1” represents Board game block 1 and “M-2” represents Maze game block 2. Error bars indicate standard deviation across subjects in each block.](image)

In Figure 84, the 2 blocks of 2-DOF games are averaged together. The summary of game completion time across different control modes are reported in Table 14.
Figure 84. The game completion time in 4 separate virtual reality games in 20 subjects. “B” represents Board game in 1-DOF and 2-DOF, and “M” represents Maze game in 2-DOF. Error bars indicate standard deviation across subjects in each block.

Table 14. Game completion time in force control vs. position control conditions in 20 subjects.

<table>
<thead>
<tr>
<th>Game \ Mode</th>
<th>Force Control</th>
<th>Position Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board game - DFPF (1-DOF)</td>
<td>66.72 ± 9.71</td>
<td>63.57 ± 4.90</td>
</tr>
<tr>
<td>Board game - INEV (1-DOF)</td>
<td>63.08 ± 7.06</td>
<td>58.72 ± 4.55</td>
</tr>
<tr>
<td>Board game - 2 DOF</td>
<td>156.73 ± 50.91</td>
<td>109.73 ± 12.45</td>
</tr>
<tr>
<td>Maze game - 2 DOF</td>
<td>132.18 ± 111.25</td>
<td>49.54 ± 14.13</td>
</tr>
</tbody>
</table>

Figure 85, shows the total number of collisions in Maze game in force versus ROM conditions across 19 subjects. The number of collisions in the first subject was not recorded due to technical difficulty. The summary number of collisions in force versus position control mode is reported in Table 15.
Figure 85. The number of wall collisions in the Maze game in 20 subjects. “M-1” represents Maze Game block 1; and “M-2” represents Maze game block 2. Subjects controlled the footplate in isometric (force control) and isotonic (position control) conditions. Error bars indicate standard deviation across subjects in each block.

Table 15. The number of collisions across different experimental conditions in 20 subjects.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Maze Game - Block 1</th>
<th>Maze Game - Block 2</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Control</td>
<td>22.05 ± 26.82</td>
<td>13.36 ± 16.48</td>
<td>17.97 ± 21.65</td>
</tr>
<tr>
<td>Position Control</td>
<td>3.31 ± 2.23</td>
<td>3.52 ± 2.75</td>
<td>3.42 ± 2.49</td>
</tr>
</tbody>
</table>

The provided results were from all subjects across different experimental blocks. Following our exclusion criteria (T > μ ± 3σ; or C > μc ± 3σc), subjects with one or more blocks of deviation with average population were identified. Accordingly subjects 8, 10, 13 and 20 showed one or more blocks out of average population [Appendix A]. Excluding these four subjects from the pool of 20 subjects, the final results of 16 subjects shows the same trend. This result is reported in Figures 86-87 and Tables 16-17.
Figure 86. The game completion time in 4 separate virtual reality games across 16 subjects. “B” represents Board game in 1-DOF and 2-DOF, and “M” represents Maze game in 2-DOF. Error bars indicate standard deviation across subjects in each block.

Figure 87. The number of wall collisions in the Maze game across 16 subjects. “M-1” represents Maze Game block 1; and “M-2” represents Maze game block 2. Subjects controlled the footplate in isometric (force control) and isotonic (position control) conditions. Error bars indicate standard deviation across subjects in each block.
Table 16. Game completion time in force control vs. position control conditions in 16 subjects.

<table>
<thead>
<tr>
<th>Game \ Mode</th>
<th>Force Control</th>
<th>Position Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board game - DFPF (1-DOF)</td>
<td>64.86 ± 9.81</td>
<td>63.37 ± 5.23</td>
</tr>
<tr>
<td>Board game - INEV (1-DOF)</td>
<td>62.93 ± 6.94</td>
<td>57.96 ± 4.34</td>
</tr>
<tr>
<td>Board game - 2 DOF</td>
<td>148.99 ± 43.81</td>
<td>107.68 ± 12.78</td>
</tr>
<tr>
<td>Maze game - 2 DOF</td>
<td>93.84 ± 40.41</td>
<td>47.09 ± 12.98</td>
</tr>
</tbody>
</table>

Table 17. The number of collisions across different experimental conditions in 16 subjects.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Maze Game - Block 1</th>
<th>Maze Game - Block 2</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Control</td>
<td>12.33 ± 8.36</td>
<td>10.06 ± 8.47</td>
<td>11.19 ± 8.41</td>
</tr>
<tr>
<td>Position Control</td>
<td>3.40 ± 2.19</td>
<td>3.13 ± 2.82</td>
<td>3.26 ± 2.51</td>
</tr>
</tbody>
</table>

The detailed results of individuals are reported in Appendix A of this dissertation. Additionally, the subjective results were collected and analyzed by Amber Hartman [Appendix H].

5.3 Discussion and Conclusion

Twenty healthy subjects performed variety of early assessment and virtual reality game conditions. Results from isotonic and isometric tests were reported. In the isometric tests, the footplate was locked using mechanical locks. In the isotonic tests, the footplate was controlled in back-drivable mode. During the ROM tests, the RMS torque values experienced by the subjects were 1.3 ± 0.26 Nm along DFPF and 0.7 ± 0.12 Nm along INEV axis. This was an acceptable result, not more demanding than walking with a winter boot. The game completion time and number of collisions in the maze game were recorded. We had to eliminate four subjects due to their significantly poor performance in terms of game completion time and number of collisions.
We could not find assessment studies on ROM and force with the same or even close experimental apparatus or procedure to vi-RABT in the literature. Accordingly the normal active range of motion of ankle joint measured in supine posture are reportedly 15°-20° dorsiflexion, 45°-55° plantarflexion, 20°-30° inversion, and 5°-15° eversion [89]. As reported in Table 13, we have achieved similar results using vi-RABT. The observed difference in plantarflexion can be explained by different postures in the two experiments. In our setup, subjects’ seated and strapped posture on the chair contributes to the lower ROM along plantarflexion axis or rotation. The reported torques in healthy human subjects with the same demography are 25.4 ± 6.9 Nm dorsiflexion, 54.2 ± 10.3 Nm plantarflexion, 15.6 ± 3.7 Nm inversion, and 14.3 ± 2.1 Nm eversion [90]. This result was collected with the participant leaned back on a chair with Biodex System 4 Pro with 90 degrees hip and knee flexion. Again the higher amount of reported values in this case can be accounted by the subject’s posture during measurements. Having the subject leaned back with right angle hip posture could directly contribute to higher amounts of generated torques.

We have studied the effect of augmented position versus force biofeedback to shed more light on human motor control as well as provide suggestions for the most effective biomarker for rehabilitation purposes. The choice of most effective biofeedback with respect to the user needs and capabilities can be crucial for the usability and success of any rehabilitation robotic system. We have specifically instructed the healthy human subjects to play the virtual reality games with rotational forces or motions of the ankle joint in a seated position and while having the hip and knee at 90-90 posture. As shown in Figures 87-88, subjects did not show significant difference in the position versus force augmented control in the 1-DOF games. However the position control was better than force control in both 2-DOF games as subjects finished the isotonic games significantly faster than isometric games. This result is also consistent with the number of collisions in the Maze game. As shown in Figure 89, subjects collided more frequently with the
walls in force based control versus position based control. Correspondingly the subjective data analysis also revealed the same patterns. Subjects reported higher amount of physical and cognitive fatigue in force versus position based games. The results of perceived exertion in Borg and cognitive VAS tests show significant difference in the 2-DOF force versus position conditions which is in line with objective data analysis. This significant difference did not hold in the 1-DOF games.

We could not find any similar study in lower extremity that compares the effectiveness, accuracy or compliance of force-based versus position-based control of a manipulator. Our results are in contrast with reported result in upper extremity [102]. This difference can be explained by the higher level of dexterity in human upper extremity [108], or the effects of everyday practice and feedback on human motor performance [109]. It is suggested that biofeedback may enhance neural reorganization by engaging auxiliary sensor inputs through existing cerebral and spinal pathways [96]. The higher level of accuracy and force perception in upper extremity can be due to the higher level of practice, reinforcement and reorganization in the contributing neuromuscular components. In the everyday examples of holding a cup or writing we directly train the neuromuscular function of upper extremity for tuned force perception and control which does not have equivalent counterpart in lower extremity. Human lower extremity is primarily responsible for posture control and ambulation with the everyday examples of ankle control in walking or climbing the stairs. In a regular task such as climbing the stairs or walking on the street, it is of vital importance to correctly perceive and control the position of the foot. However the amount and degree of force perception during these tasks is not of equivalent importance. The closer example in everyday force and position control of the ankle joint might be in driving and controlling the gas or brake pedals. These are augmented force and position control tasks, mostly along 1-DOF (DFPF), and using the same rational it poses insignificant difference in the force
versus position control in the 1-DOF (DFPF) ankle control tasks. Our result was in agreement with this observation.

Review of the usability questionnaire indicated that subjects found the interface to be user friendly, the length of the testing session not too long or too short, and that extreme fatigue was not experienced in the ankle or leg throughout the conduction of the experiment [Appendix G]. The subjective information can be used to recognize the most fatiguing or challenging tasks and provide ample rest period for subject’s recovery before moving on to another task. Overall subjects had more cognitive challenge than physical difficulty doing the tasks. They found the force games more difficult and challenging than position games.

Running long and rigorous tests on an electromechanical hardware could potentially reveal any operational or safety issue associated with the system. Following our operational objective, we have closely observed system’s operation and performance and analyzed the subjective questionnaires. Healthy human subjects did not report excessive fatigue or injury during the experiment, and they found the system interface to be user friendly. We observed that healthy subjects were trying to move the knee joint from the 90-90 advised fixed position. This might be reconsidered in patient’s diagnosis tests by giving them more flexibility. Our observations and subjective results confirmed that system had a safe, smooth and consistent operation over total period of experiment. We have successfully achieved our operational goal to develop the required protocols to work with healthy human subjects and the system is recommended to be used with patients in the next step.

This was the first step in using the vi-RABT for ankle assessment and rehabilitation purposes. The ROM and force measurements were accurate and along the reported values in the literature. Our motor control study suggest that, in the lower extremity and in the task with 2-DOF, individuals have better control over the position rather than force control. This effect was not
observed in the task with 1-DOF and force based control was similar to position based control. This outcome can be useful in robot assisted therapy where there is a question for the most effective biological marker to trigger/control an external manipulandum. Our results support the application of ankle position as a more refined control variable to show the user intent and trigger/control the presumable exoskeleton.
Chapter 6  Assistive-Resistive Control

In the field of rehabilitation robotics, and along with technological advancements in systems’ hardware, significant amount of work has been invested on developing novel therapeutic assistive methods. These include impedance, adaptive and EMG-based methods to control rehabilitation robotic systems [110-112]. The desired goal of therapeutic control algorithms is to control robotic systems so as to provoke motor plasticity, and therefore improve motor recovery [113-115]. The field is at the very early stage, but there is clinical evidence supporting the effectiveness of robotic training strategies over more conventional therapy in patients [116-118]. The control algorithms have usually been designed on an ad hoc basis, based on the understandings from the rehabilitation, neuroscience, and motor learning.

Impedance control has been extensively used in rehabilitation applications [119-120], which was first introduced as a method for stable contact execution between a robot and the environment [110]. The advantage of impedance control is that, instead of separately specifying the desired kinematics or kinetics (as in position control and force control), one defines the mechanics of human-robot interaction. This contributes to the creation of a stable regime in a complex contact task where there is no prior knowledge of the environment. The general framework of impedance control is relied on constant viscoelastic properties in force-position interaction; however the more dynamic control architectures and detailed implementation has been a subject of further research.

Variable impedance control in rehabilitation robotics was suggested based on the dynamic and time-varying characteristics of human impedance during cooperative tasks [121-124]. There are many studies to show that the viscoelastic properties of the neuromuscular system are task dependent, i.e. the musculoskeletal impedance is modulated based on specific task and environment. Joint stiffness depends on the direction of external loading during posture maintenance; and direction of movement in a reaching task [125-129]. Practical and simulation studies have shown the advantages of variable impedance control [121-124] in rehabilitation.
robotics. In [121], variable mechanical characteristics of human arm was estimated in a human-human task and applied to a human-robot cooperation doing the same task. Results showed that the variable impedance parameters obtained from humans give the best characteristics to the robot in cooperation with the human. Equipping robots with variable impedance control will make them adapt to human behavior and contribute to more human-friendly paradigm.

In another attempt and in upper extremities, variable impedance control was developed to perform an assistive calligraphic task in human-robot cooperative writing [122]. Accordingly the robot arm viscosity was adjusted continuously in proportion to the estimated stiffness of the human arm which resulted in stable and easy task execution. Experimental results on this device showed the effectiveness of control method in the human-robot interaction.

There are few studies in human lower extremity and ankle joint that have evaluated the effectiveness of variable impedance control in assistive control of human-robot interaction [123-124]. The potential advantages of using a variable impedance controller was investigated in a simulation study of a robotic ankle trainer [123]. An exoskeleton was modeled as the ankle rehabilitation robot and the impedance parameters were selected using the ankle compliance at different foot configurations during walking. The variable impedance controller had better performance as it reduced force application in stiff directions such joint limits.

A wearable active ankle-foot orthoses (AAFO) with variable impedance modulated based on the walking cycle was developed for drop-foot patients [124]. The orthotic joint stiffness was actively adjusted to prevent forefoot collisions with the ground during plantarflexion, and lift the foot to provide toe clearance during dorsiflexion. These results from two drop-foot participants wearing the AAFO indicated that, in comparison with zero or constant stiffness joint behaviors, a variable-impedance method may have certain clinical benefits for the treatment of drop-foot patients.

The vi-RABT, as explained in Chapter 5, had no functionality to provide active assistive training to individuals. In this study we were trying to assess the feasibility of assistive/resistive training using this electromechanical hardware. This is one more step toward the ultimate goal of using vi-
RABT for assistive training of patients with variety of neuromuscular disorders. In close collaboration with physical therapy expert (Dr. Holden), a novel task-dependent variable impedance controller has been developed and implemented into vi-RABT. The control system was developed heuristically and based on the controllers in chapters 4 and 5. A modified Maze game was introduced which was different from the Maze game as explained in chapters 4 and 5. The new Maze game, controller development, and acquired results on two human experimenters are reported in this chapter.

Figure 88. The Sequenced Maze game that was used in assistive/resistive control; the purple avatar was in subject’s control to acquire the target (red cubes). After achieving each target, the next target turned red.

6.1 Sequenced Maze Game

The modified Maze game is shown in Figure 88. There were two changes in this revision: 1) the goals were presented in a sequence; and 2) the origin was always the next target, after every non-origin target. The goal of the game was to achieve the goals in sequence as fast as possible while
avoiding wall collisions. Considering the origin as the frequently repeated target, there were 50 targets in each block of game. In the regular Maze game as used in Chapter 5, there was no order and subjects had 25 goals in total.

6.2 Anisotropic Impedance Controller

The system control hardware with the Proportional-Integral-Derivative (PID) force controller was explained in Chapter 4. The system was used in static condition for force measurement and controlled in back-drivable condition for range of motion (ROM) measurements, as explained in Chapter 5. During force measurements the system was utilized as a static force-plate without the use of actuators. In ROM measurements the electrical motors were utilized in back-drivable mode for minimizing resistance to the user’s movements.

In order to create assistive-resistive control, and as shown in Figure 89, the position/velocity control loop has been added to the existing internal PID force controller. The Sequenced Maze game was used and subjects were instructed to acquire a specific position (goal) and follow a specific velocity. A geometrical algorithm was developed and a variable impedance control technique was implemented to provide a smooth assistance to the subjects along the Sequenced Maze paths.

![Figure 89. The schematic of the impedance control in the 2-DOF ankle device. The PID force control loop is inside the position/velocity control algorithm.](image-url)
6.2.1 Geometrical Algorithm

The Sequenced Maze game is defined by specific hexagon geometry, walls, set of goals and an avatar in user’s control. In every movement trial, the subject is required to move the avatar from the starting point to the specific final position at a certain velocity (each game block includes 50 trials). In each movement trial, there is an optimally shortest path that links the starting point to the goal, Figure 90. A desired velocity was defined and subjects were instructed to perform the task at this speed.

A geometrical algorithm was developed to force the movement trajectory on the shortest line while following a certain desired speed. As shown in Figure 90, lateral and longitudinal directions were defined relatively with respect to the start and final position on the screen. The goal of the lateral error ($e_{\text{lateral}}$) component was to provide resistance in reaction to subject’s lateral deviation from the shortest line. The longitudinal velocity error ($e'_{\text{Longitudinal}}$) component was defined to provide assistance if the subject is moving below the speed threshold and resistance if the movement is happening faster than the speed threshold.

Figure 90. The lateral ($e_{\text{lateral}}$) and longitudinal ($e'_{\text{Longitudinal}}$) error components in an exemplary movement trial. The subject starts (at $t = 0$) moving toward the red cube as the next target. Deviation from the optimal direct line as well as the desired speed is corrected by the applied force fields.
The shortest line in the plane between the initial point and target is given by the equation $ax + by + c = 0$, where $a$, $b$ and $c$ are real constants with $a$ and $b$ not both zero. Based on the current position $(x_t, y_t)$, the closest orthogonal point on the line has coordinates $(x_0, y_0)$ as follows:

$$x_0 = \frac{b(bx_t - ay_t) - ac}{a^2 + b^2}$$

$$y_0 = \frac{a(-bx_t + ay_t) - bc}{a^2 + b^2}$$

The lateral position error components are calculated:

$$e_x = x_0 - x_t$$

$$e_y = y_0 - y_t$$

Accordingly the following assistive torque profile has been created along both axes to respond to this type of error.

$$N_i = 1.64 \frac{G_k}{\alpha} \frac{e_t}{e^{2/2\alpha^2}}$$

$i$: $x$, $y$; inversion/eversion (x), and dorsiflexion/plantarflexion (y)

$G_k$: proportional stiffness gain (N/m)

$N$: assitive lateral torque (Nm)

$e$: the lateral position error (m)

$\alpha$: the center of the Gaussian function (Deg)

The semi-Gaussian function in Figure 91 was selected to provide smooth corrective force profiles to the subject. Our goal was to create a smooth and continuous function to secure patient’s safety and prevent any probable injury. The developed function provides sharp and smooth force corrections in the lower amounts of error ($e \leq \alpha$). If the patient passes the error threshold ($e = \alpha$), on purpose or by accident such as at initial point, then there is a smooth resistive force gradually correction the movement trajectory. The computed function has a steep slope around the zero
error and smoother profile in the larger error values. As shown the maximum possible assistive/resistive torque gain ($G_k$) is applied in the center of bell shaped Gaussian function ($\alpha$), and the system cannot amplify the torque values more than $G_k$ on the patient’s limb. This will increase the safety margin of the system, in case if the error exceeds to very high values ($e \gg \alpha$). The developed impedance controller is in continuous search for the minimum position error.

The velocity error component ($\sigma$) was considered along the longitudinal axis. This was calculated based on the derivative of the displacement along both axes:

$$\sigma_i = d - v_i$$

$$\sigma_y = d - v_y$$

The longitudinal assistive torque component ($M$) is defined as follows:

$$M_i = G_v \sigma_i$$

$G_v$: proportional damping gain (Ns/m)
Additionally in order to guarantee the smooth operation of the system, a ramp up mechanism for the velocity was considered. The velocity component \(d\) was gradually ramped up to the final desired value based on the specified Rise Time (sec) variable that also can be adjusted in the therapist interface. The complete block diagram of the developed controller is shown in Figure 95.

### 6.2.2 Controller

The developed algorithm is physically equivalent to recruiting a spring and damper along the lateral and longitudinal axes respectively, as shown in Figure 92. The spring and damper are responding to deviations from the desired position and velocity values respectively to create a smooth movement for the patients. The summation of the error components along the lateral and longitudinal axes creates a force sensitive to displacement and velocity components, shown in Figures 92-93.

![Figure 92. The equivalent spring-damper mechanism of the developed algorithm in the Sequenced Maze game. The subject feels the spring force in response to the lateral deviations and the damping effect in response to the change in velocity.](image-url)
This mechanism is equivalent to the impedance control paradigm, which is developed along each axis of actuation/rotation to provide assistance to the subject while playing the Sequenced Maze game. As shown in Figure 95, the impedance controller consists of a force control loop within a position/velocity control loop. While the internal loop is trying to achieve the desired force trajectory, the position/velocity loop is achieving the desired movement kinematics.

Playing the Sequenced Maze game, the subject is expected to interact with the robotic footplate and achieve separate cubic goals as shown on the screen (Figure 90). The game is in sequential mode in which the targets are highlighted sequentially one after another. The desired force (torque) trajectory is defined as the outcome of the position/velocity controller calculated as follows:

\[
T_d = N_i + M_i
\]

\[
e_T = T_d - T_a
\]

\[
CI = K_P \times e_T + K_I \times \int e_T \, dt + K_D \times e_T'
\]
N_l: lateral torque profile (Nm); M_l: longitudinal torque profile (Nm);

T_a: actual interaction torque (Nm); T_d: desired interaction torque (Nm); e_T: Interaction torque error;

CI: control input (volt) to the motors

K_P: proportional gain; K_I: integrative gain; K_D: derivative gain.

This represents the virtual characteristics of a spring (N/m) and damper (Ns/m) elements, as shown in Figure 94. The ultimate outcome of the torque control loop is sent to the actuators as the control input (CI), to accomplish the control objectives. The developed impedance controller is in continuous search for the minimum position and force errors.

6.3 Human-Machine Interaction

Another important variable from the physical therapy perspective is the amount of active effort (i.e., muscle activation) that patients exert while practicing in a specific paradigms. This is because patient’s active effort is much more effective for motor learning than passively assisted movement. In order to address this variable, a mechanism is needed to measure human voluntary movement or applied force versus machine’s contribution. This analysis was not possible in the existing vi-RABT setup. However, using the human-machine interaction torque we can provide an estimate of the level of collaboration and engagement between human and the robot. This might help our understanding of the amount of contribution/engagement across different subjects. It is predicted that in the case of full human-robot collaboration, lower amount of interaction torque is produced. This is because human closely follows the commanded trajectories and applied forces by robot and does not provide resistance. In the opposite case scenario, if the human cannot follow the robot’s trajectories there will be high amount of counteracting forces between the two. This will increase the amount of recorded interaction torque.
This measure can be used in comparing subjects with each other at certain conditions and blocks. This might be useful to design games or change the level of difficulty for a specific subject. We will compare the level of contribution of the two subjects using this criterion.

6.4 Methods
The goal of the experiment in this chapter was to evaluate the developed assistive controller. Comparing to the former experiment (explained in Chapter 5), we have conducted a simple pilot experiment on two human subjects as explained below.

6.4.1 Design
Three conditions of 5 blocks of were performed by two experimenters. Total of 15 blocks of Sequenced Maze game was conducted. The first five blocks was in the back-drivable mode; in blocks 6-10 subjects played the game at comfortable speed; and in blocks 11-15, we have doubled the proportional damping gain to study the effect of over-assistance.

Figure 94. The experimental design of the assistive control in vi-RABT; two subjects went through 3 Conditions (C) of playing Sequenced Maze game across 15 Blocks (B).

The explanation of experimental conditions and blocks are as follows:

- Condition I (C-I): Back-drivable
  - Blocks 1-5: Sequenced Maze game with no force feedback.
- Condition II (C-II): Assistive
  - Blocks 6-10: Sequenced Maze game with force feedback, $G_v = 2$.
- Condition III (C-III): Over-Assistive
Blocks 11-15: Sequenced Maze game with strengthened force feedback, \( G_v = 4 \). In back-drivable condition, subjects experienced no assistance, and slight resistance from friction of the motors, similar to moving with a winter boot on. During assistive modes, subjects received corrective force vectors at different rate from the device.

### 6.4.2 Human Subjects

Two experimenters were recruited and instructed to play the modified version of virtual reality Maze game, i.e. Sequenced Maze game. The Maze game was adapted to the assistive control experiment.

### 6.4.3 Measures

The target positions were fixed in the Sequenced Maze game across both subjects. In each block, the corresponding proportional damping (\( G_v \)) was changed to simulate normal assistance versus over assistance. We have also studied the human-machine interaction torque to understand the level of subject engagements.

- **Game completion time (Time):** The amount of time that subjects spent to finish the Sequenced Maze game.
- **Collision:** The number of events that subjects collided with the walls while playing Sequenced Maze game.
- **Human-machine interaction torque (IT):** The amount of recorded force/torque in the robotic force-plate due to human interface.

The human-machine interaction torque was computed using the mean absolute value of torques along DFPF and INEV as follows:

\[
IT = \text{Mean} (T_a)
\]

\[
T_a = |T_{DFPF}| + |T_{INEV}|
\]
IT: Mean interaction torque in both axes

$T_{INEV}$: Recorded torque along INEV (Nm); $T_{DFPF}$: Recorded torque along DFPF (Nm)

### 6.4.4 Procedure

Two healthy human subjects (i.e. the investigators) were recruited to conduct a pilot study on the paradigm. Both subjects had already participated in the assessment and motor control studies explained in Chapter 5 and were familiar with the system and procedure. Subjects were tested in the Biomedical Mechatronics Lab of Prof. Mavroidis at Northeastern University. Similar to the procedure in former experiments, and as shown in Figure 65, subjects were seated on the adjustable chair with dominant foot strapped securely into the robotic footplate. To protect subject’s knee joint and to increase measurement accuracy, subjects’ legs were stabilized with pads and straps to minimize hip internal and external rotation. The chair height was adjusted to place the hip and knee in 90 degrees of flexion, and ankle joint in neutral.

In the first preliminary blocks, subjects were instructed to familiarize themselves with the newly developed assistive-resistive controller. In the next step and upon subject’s approval, we have started assessing their comfortable speed. Subject’s comfortable speed was acquired heuristically by letting the subject explore a range of options. Accordingly each subjects went through a few preparation blocks in which they played the game at different speed (d) and reported the most comfortable one. Interestingly both subjects confirmed a value around $d = 2$ Deg/s as the comfortable speed. This value was used as a reference in the controller formulation in the next steps.

After the initial familiarization and speed investigations and in the actual experiments subjects were instructed to play the Sequenced Maze game in three difference conditions. They were instructed to move the avatar toward the highlighted cubic (red) goals on the screen and achieve the goals in sequence as fast as possible while avoiding the collision with walls.
6.5 Results

The 2-DOF robotic system assisted the subjects to achieve the sequence of targets on the maze scene. The results of three tested conditions are presented here in order. In the following plots, motions/torques toward the body (DF and IN) were considered positive and motions away from the body (PF and EV) were defined as negative values. Results on the back-drivable condition are presented first followed by assistive condition and over assistive condition.

The controller parameters were tuned heuristically in human subject tests; and the following are the final values that were implemented into the anisotropic impedance controller and used in three conditions:

\[
G_k_{\text{DF/IN}} = 2 \text{ (N/m)}; \quad G_k_{\text{PF/EV}} = 1 \text{ (N/m)}; \quad \alpha = 3 \text{ (Deg)}; \quad \text{Rise Time} = 1 \text{ sec}
\]

DFPF: Torque controller: $K_P = 0.5$, $K_I = 1.4$, $K_D = 0.2$;

INEV: Torque controller: $K_P = 1$, $K_I = 1.5$, $K_D = 0.3$;
6.5.1 Back-Drivable Condition

Figure 95. Human subject results on back-drivable condition along INEV axis of rotation in (all \( G_i = 0 \)), Subject 1 - Block 5. The desired angle (top - red), actual angle (top - blue); desired torque (mid - red), actual torque (mid - blue); and the control command (bottom - black) are shown.

The robotic footplate is programmed to minimize the resistance to the subject’s movement. Subject is moving the footplate along DFPF axis to achieve the presented goals on the screen. In this block the human-machine interaction torque was 1.22 ± 0.82 Nm along INEV.
Figure 96. Human subject results on back-drivable condition along DFPF axis of rotation in (all $G_i = 0$), Subject 1 - Block 5. The desired angle (top .. red), actual angle (top - blue); desired torque (mid .. red), actual torque (mid - blue); and the control command (bottom - black) are shown.

The robotic footplate is programmed to minimize the resistance to the subject’s movement. Subject is moving the footplate along DFPF axis to achieve the presented goals on the screen. In this block the human-machine interaction torque was $1.55 \pm 1.14$ Nm along INEV. The interaction torque (IT) along both axes was $2.78 \pm 1.4$ Nm.
6.5.2 Assistive Condition

Subjects’ comfortable speed was estimated in the preliminary blocks as \( d_{vel} = 2 \) (Deg/s) and applied as desired velocity in the succeeding assistive conditions.

The robotic footplate was programmed to provide assistive force feedback and steer the subject toward maze goals. Subject is collaborating with the robot along INEV axis to achieve the presented goals on the screen. In this block the human-machine interaction torque was \( 2.36 \pm 1.77 \) Nm along INEV.
Figure 98. Human subject results on assistive control condition along DFPF axis of rotation with $d_{vel} = 2$ (Deg/s) and $G_v = 2$, Subject 1 - Block 10. The desired angle (top .. red), actual angle (top - blue); desired torque (mid .. red), actual torque (mid - blue); and the control command (bottom - black) are shown.

The robotic footplate was programmed to provide assistive force feedback and steer the subject toward maze goals. Subject is collaborating with the robot along DFPF axis to achieve the presented goals on the screen. In this block the human-machine interaction torque was $4.09 \pm 2.89$ Nm along DFPF. The interaction torque (IT) along both axes was $6.46 \pm 3.28$ Nm.
6.5.3 Over-Assistive Condition

Subjects’ comfortable speed was estimated in the preliminary blocks $d_{vel} = 2$ (Deg/s) and applied as the desired velocity in the succeeding assistive conditions.

![Figure 99](image)

Figure 99. Human subject results on over-assistive condition along INEV axis of rotation with $d_{vel} = 2$ (Deg/s) and $G_v = 4$, Subject 1 - Block 15. The desired angle (top - red), actual angle (top - blue); desired torque (mid - red), actual torque (mid - blue); and the control command (bottom - black) are shown.

The robotic footplate was programmed to provide over-assistive force feedback and steer the subject toward maze goals. Subject is collaborating with the robot along INEV axis to achieve the presented goals on the screen. In this block the human-machine interaction torque was $3.80 \pm 3.03$ Nm along INEV.
Figure 100. Human subject results on over-assistive condition along DFPF axis of rotation with \( d_{\text{set}} = 2 \) (Deg/s) and \( G_v = 4 \), Subject 1 - Block 15. The desired angle (top - red), actual angle (top - blue); desired torque (mid - red), actual torque (mid - blue); and the control command (bottom - black) are shown.

The robotic footplate was programmed to provide over-assistive force feedback and steer the subject toward maze goals. Subject is collaborating with the robot along DFPF axis to achieve the presented goals on the screen. In this block the human-machine interaction torque is \( 6.24 \pm 4.47 \) Nm along DFPF. The interaction torque (IT) along both axes was \( 10.04 \pm 5.21 \) Nm.
Figure 101. Subject’s angular displacement while playing the 2-DOF Sequenced Maze game in 3 conditions: back-drivable, assistive control, over-assistive control. Dorsiflexion and Inversion are positive; Plantarflexion and Eversion are negative.
Table 18. Game outcomes across experimental conditions.

<table>
<thead>
<tr>
<th>Variable / Condition</th>
<th>Back-drivable</th>
<th>Assistive</th>
<th>Over-Assistive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion Time (Sec)</td>
<td>111.18 ± 3.54</td>
<td>62.55 ± 9.49</td>
<td>54.33 ± 4.61</td>
</tr>
<tr>
<td>Wall Collisions (#)</td>
<td>12.9 ± 3.19</td>
<td>1.6 ± 1.52</td>
<td>0.8 ± 0.8</td>
</tr>
</tbody>
</table>

The human subjects went through 15 blocks of Sequenced Maze game and summary results were provided in Table 18. The first five blocks were performed in back-drivable condition (1-5); the second five blocks (6-10) in comfortable assistive condition ($G_v = 2$); and the last three blocks (11-15) in over-assistive condition with doubled proportional damping gain ($G_v = 4$).

### 6.5.4 Human-Machine Interaction

Figure 102 shows a comparative measure of the subjects mean interaction torque (IT) across 15 blocks of experiment.

![Figure 102. Comparing the interaction torque of two subjects across 15 blocks of experiment.](#)
6.6 Discussion

Human sensorimotor system has variable and task-dependent characteristics depending on the limb direction, position and velocity [125-129]. Located in muscle spindles, human neural system is equipped with sensory afferent fibers II and Ia that respond to the change in muscle position and velocity differently [125]. This variability in human sensorimotor system is encouraging the use of variable controller as a better suit to the patient's need. We have developed a controller that has visco properties along the relative diagonal direction and viscoelastic properties in perpendicular lateral direction.

The primary concern in rehabilitation robots is to ensure system safety, smooth and effective operation with patients. The control objectives of the rehabilitation experiment are to avoid application of excessive amount of assistance (i.e. torque) to the subject’s foot, i.e. overshoot, and yet follow the desired trajectory in a reasonable time period. This is due to the critical sensitivity of the final application as the patients with variety of injuries and ankle disorders may not be able to experience over-threshold torque profiles safely without injury.

Elaborate considerations from physical therapy perspective were integrated and formulated into the geometrical algorithm to provide a safe and effective rehabilitation experience. Different formulations and set of parameters were considered for movements along the longitudinal and lateral directions in the Sequenced Maze geometry. Deviations from the lateral component were corrected by a virtual spring while damping effect was utilized along the longitudinal axis.

Two healthy human subjects were tested and results were provided. Figures 97-102 shows individuals performance in three different experimental conditions. The recorded interaction torque, and movements had no overshoot and the settling times/movement velocity were in the desired range condition for the rehabilitation problem. As shown in the game angular space, in Figure 101, in back-drivable condition both subjects inefficiently explored the whole workspace to acquire the goals. This was not the case in assistive training conditions where subjects received
goal-oriented force feedback. In assistive conditions, the undesired movement variations were assisted / resisted and corrected back to the defined position / velocity trajectories. Subjects seem to have lower variability in over-assistive comparing with assistive condition. The results on game completion time and number of collisions in Table 14 also show the same pattern. Subjects spent significantly more time in completing the game in back-drivable condition; and they had collided with the walls much more in the back-drivable condition. The objective assistive controllers reduced the number of undesired collisions. The game completion time in assistive condition was close to the over-assistive condition. This can be explained by the fact that the desired velocity was the same under both conditions. The major difference between the controllers was rooted in the specified proportional damping gain in each block of experiment. This mean there was more strict condition (doubled) in the over-assistive condition to follow the desired speed value. The anisotropic controllers drove the motors to follow the desired impedance between the robot and the robot. Both subjects verbally confirmed the comfortable experience in playing with the robotic ankle trainer in both assistive training and back-drivable mode. Subjects reported less control over the footplate as well as smoothness in the higher speeds.

We also had another question of the subject’s effort during practice. Looking into the results, both subjects had the minimum interaction torque in the back-drivable condition. This can be explained as in the ideal case scenario and in the back-drivable condition, the machine is following the human movements without any resistance. Subjects are able to easily move and control the footplate toward any desired goal on the screen. As a result and theoretically, the calculated interaction torque will be minimum. The high torque values are an indication of human-machine disagreement. This can be due to the subjects’ inability to follow the exercise, or an indication of higher skill level requirements by the game. As expected, the assistive and over-assistive conditions showed higher amount of interaction torques. This result is not comparable for a single subject across different conditions, but can be meaningful across multiple subjects. As
shown in Figure 102, in the most of blocks subject 2 had lower amount of interaction torque. This can be interpreted as this subject had higher skill level or the game is better designed for his condition.

### 6.7 Conclusion

The assistive control architecture of the 2-DOF robotic ankle trainer is described and the early assistive training results from two human subjects are presented. A virtual reality Sequenced Maze game was designed specifically for the assistive training paradigm. A physiologically plausible task-dependent anisotropic impedance controller was developed and implemented into the robotic footplate. The acquired results experimentally showed the implemented concept. The 2-DOF robotic system assisted the subjects to achieve the targets sequentially in assistive and over-assistive conditions.

The acquired results are stable, robust and smooth enough and they are addressing the need for the ultimate application of this system. Our early results confirmed the feasibility of assistive ankle training using virtually interfaced robotic ankle and balance trainer (vi-RABT). Our future work includes patient tests to see whether acquired improvements on the Maze game carryover to performance, and more importantly, to functional gains such as improved walking ability and standing balance. The system and the introduced controller will be further explored in the future investigations on variety of ankle and balance disorders.
Chapter 7 Conclusions

This dissertation addressed the electromechanical design, control system development, virtual game interface, and human subject testing of the virtually interfaced robotic ankle and balance trainer (vi-RABT). In this chapter, we present a summary of the significance, methods and acquired results out of this work. We also provide recommendations for future work.

7.1 Summary

Ankle and balance control is of vital importance in our everyday activities such as standing, walking, running, and maintaining stable posture. This functionality is impaired by range of neuromuscular disorders such as stroke, cerebral palsy, traumatic brain injury and also ankle sprain. Stroke is the leading cause of long term disability in the United States with 795,000 victims every year; and about 10 million people annually sprain their ankles. Traditional ankle and balance rehabilitation methods are costly and physically demanding and the conventional therapy is based on using a combination of simple mechanical elements. These methods are not able to provide automated rehabilitation or assess patient’s progress over the course of therapy. There is no research prototype or commercial device in the market that combines the ability to train ankle and balance training in one system. A need exists for an ankle and balance rehabilitation setting that offers monitoring and assessment features as well as active assistive/resistive therapeutic mechanisms through different stages of rehabilitation.

The virtually interfaced ankle and balance trainer (vi-RABT) was developed and built to be a comprehensive rehabilitation system that monitors patient’s progress and combines the ability to train balance function, ankle strength, mobility, and motor control into one system. Vi-RABT is a platform-based 2 degree-of-freedom (2-DOF) robotic footplate that is equipped with complete means of force and angle measurement as well as two strong actuators to compensate for the patient’s weight in standing posture. The system can be used in either sitting or standing posture.
for ankle and balance training and the footplate’s axis of rotation is aligned with the ankle joint. The control system and virtual reality games were developed and the system was used for assessment purposes of ankle force, mobility and motor control in the study with 20 healthy human subjects. In the next step, a task-dependent anisotropic assistive-resistive impedance controller was developed and the feasibility of automated rehabilitation by vi-RABT was studied on two healthy human subjects.

Vi-RABT was successfully used in the long and rigorous experiments with 20 healthy human subjects assessing ankle force, mobility and motor control while playing interactive games on the screen. The system had accurate force and mobility measurements and the results from motor control study contribute to the lower extremity rehabilitation. The task-dependent anisotropic assistive-resistive controller provided corrective force feedback to the subjects while playing the virtual reality games on the screen. The acquired results were stable, robust and smooth enough over total period of experiments. Healthy human subjects did not report excessive fatigue or injury during the experiments, and they found the system interface to be user friendly. Our study confirmed the feasibility of an ankle and balance trainer (vi-RABT) with monitoring features and automated assistive training.

7.2 Future Work

The future work includes further hardware development and more experiment with patients in clinic. The recommended future hardware developments are: 1) the second robotic force-plate. This will provide the possibility of coordinated balance perturbation to individuals, which can be the subject of a study to further our understanding of human proprioception, vestibular and sensorimotor system; 2) a stationary platform to enclose and host both robotic force-plates and also supply safety hand grips for the patients; 3) a harness to support patient’s weight. This will promote safety and may be performed gradually to compensate part of the patient’s weight as needed by the therapeutic regimen; and 4) a novel chair subsystem to accommodate the knee and
hip at desired angles, provide safety release mechanism, and also offer the most comfortable experimental setup for the patients. As shown in Chapter 5, the hip and knee fixture was used to limit the degrees of freedom in human movements to focus on the contributions by the ankle joint. The safety release mechanism is also needed to provide the possibility of quick discharge in case of any unpleasant situation. The current chair has 1-DOF along the heave axis and we used manual straps and bindings to minimize the hip and knee contribution and focus on the ankle joint. The future chair can have the built-in mechanism to fix the hip and knee angles at specific desired values. The chair can also facilitate the patient setup by allowing the patient be seated on the chair away from the footplate and then moved close to the setup. The adjustable height and orientation will accommodate the full range of sitting to standing phase. Accordingly a 4-DOF chair is recommended with more DOF along surge, yaw and pitch axes.

Another outlook in this study was to create a low-cost portable system so that it can be the first interactive lower extremity rehabilitation robot for home setting. This was not realized in the current system due to the specific requirements of balance training. However, relaxing the balance training aspect of the system one can introduce a home-based ankle rehabilitation robot. Accordingly a portable version of the system is suggested to specifically target the population with ankle impairments. This is a 2-DOF (or 1-DOF) robotic system for virtual reality-based home-centered ankle rehabilitation only in seated position. Control algorithms to achieve these goals need to be developed and implemented in a portable circuit board using the microcontroller technology.

Our early results on healthy human subjects confirmed the feasibility of assistive ankle training using vi-RABT. The future experiments include patient tests to evaluate the application of assistive controller in motor recovery and rehabilitation with the population in need. More importantly we would like to investigate the effectiveness of vi-RABT in helping patients acquire functional gains such as improved walking ability and standing balance.
Bibliography


[23] M. Kemery, T. N. Guild, and Z. Rapaport, “Inflatable structure and method of


call: 800 940-0195


### Appendix A. Detailed Experimental Results

<table>
<thead>
<tr>
<th># Subject</th>
<th>Game Completion Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force Condition</td>
</tr>
<tr>
<td></td>
<td>Board Game</td>
</tr>
<tr>
<td></td>
<td>DFPF</td>
</tr>
<tr>
<td>1</td>
<td>76.00</td>
</tr>
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<td>61.55</td>
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<td>20</td>
<td>73.00</td>
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Subjects with one or more blocks of \((T > \mu_t \pm 3\sigma_t)\) difference are highlighted.
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<thead>
<tr>
<th># Subject</th>
<th>Number of Collisions (#)</th>
</tr>
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<tr>
<td></td>
<td>Force Condition</td>
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<td>24</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
</tr>
</tbody>
</table>

* The data number of collisions in subject 1 was not recorded.

Subjects with one or more blocks of \((C > \mu_c \pm 3\sigma_c)\) difference are highlighted.
Appendix B. vi-RABT Study Screening Questionnaire

Name: __________________      Subject #:_________
Age:         Date:
Gender:        Height:
Contact Info:        Weight:
    Primary Phone Number:
    Secondary Phone Number:
    E-mail Address:
    Mailing Address:

1. Are you able to commit to one session that is two hours in length?   Yes / No

2. Have you had any leg (hip, knee, foot/ankle) injuries in the past 3 months?  Yes / No
   If yes, please explain:

3. Do you have any pain in either leg?       Yes /  No
   If yes, please explain:

4. Do you have any numbness, tingling, or weakness in either leg?   Yes / No
   If yes, please explain:

5. Do you have any balance problems, or had an injury affecting your balance
   in the past 3 months?        Yes / No
   If yes, please explain:

6. Have you fallen in the past 6 months?      Yes / No
   If yes, please explain:

7. If you had to kick a ball, which foot would you use?    R / L

8. Do you play any sports or exercise on a regular basis?       Yes / No
   If yes, please list sports or type of exercise and frequency:

9. While standing on 1 leg, can you go up and down on your toes 10 times?   Yes / No

10. Can you walk 10 steps on your heels without touching your toes to floor?    Yes/ No
Appendix C. Human Subject’s Consent Form

Northeastern University: Departments of Mechanical and Industrial Engineering & Physical Therapy
Investigators: Prof. Constantinos Mavroidis & Prof. Maureen Holden
Human Testing on Northeastern University Virtually-Interfaced Robotic Ankle and Balance Trainer (vi-RABT)

Informed Consent to Participate in a Research Study
We are inviting you to take part in a research study. This form will tell you about the study, but the researcher will explain it to you first. You may ask this person any questions that you have. When you are ready to make a decision, you may tell the researcher if you want to participate or not. You do not have to participate if you do not want to. If you decide to participate, the researcher will ask you to sign this statement and will give you a copy to keep.

Why am I being asked to take part in this research study?
We are asking you to be in this study because you are a healthy person between the ages of 18 and 80 and have no history of stroke, neurological problem, or problems with leg function.

Why is this research study being done?
The purpose of this research is to test some features of a new mechanical device with a virtual reality interface called the vi-RABT. This device is designed for ankle and balance rehabilitation in patients who have had a stroke, to help them improve their ankle strength, motor control, balance and walking function. It may also help athletes and others who have suffered ankle injuries to regain similar abilities.

What will I be asked to do?
These tests will be done in the sitting position. You will be seated in an adjustable chair with one foot positioned on the force plate of the device. A strap will be placed over the top of your foot to secure it to the device. You will then perform the following activities:

1. We will ask you to pull against the strap or push your foot down against the plate in a number of different directions (e.g., up, down, to the side). The force plate will not move, but as you push or pull against it, the device with measure the force you can produce in different directions with your ankle muscles. You will repeat this several times in each direction, resting after each try.
2. Next we will release the locks on the ankle platform so that it will move along with your foot as you bend your ankle up, down, in or out. You will be given a few minutes to get a feel for how the device moves with your foot attached to the plate. No outside resistance will be applied, but you will feel a slight resistance due to the weight of the footplate itself. This should be similar to moving your foot with a winter boot on. Once you feel comfortable moving your ankle, we will ask you to perform specific ankle movements in different directions (e.g., up, down, inward, outward) at a speed that feels comfortable to you. After you have repeated these movements several times, we will ask you to perform the same movements as fast as you comfortably can. You will be given practice trials so that you feel comfortable with the task. You will also rest after each trial, so your muscles will

168
not fatigue. During this task, we will measure the speed and distance of your ankle motions.

3. Next, we will turn on the large video screen in front of you. Here you will see a scene that looks like a maze. Your task will be to move a small dot through the maze by moving your foot in various directions. No outside resistance will be applied, but you will feel a slight resistance due to the weight of the footplate itself, as in the prior task. You will see a score of your performance displayed on the side of the screen. This task will be repeated a number of times with different mazes. Some mazes may require faster movement speed to move the dot, but the maximum speed will be adjusted to your ability, so that you should not feel fatigued.

4. Next we will again lock the platform so that your ankle does not move. You will again try to move the dot representing your foot through the maze. This time, to move the dot you will pull against the strap or push against the platform to move in the various directions. For example, pulling straight up will move the dot up, lifting the outside of your foot will move the dot sideways, pushing down with the toes will move the dot downward, and so on. Even though your foot is not moving, the plate will sense your force and use this reading to move the dot. You will see a score of your performance displayed on the side of the screen. The task will be repeated a number of times with different mazes. Some mazes will require more force to move the dot, but this will be adjusted to your ability, so you should not feel any strain in your ankle.

After you finish these tests, we will ask you to complete a few questionnaires that ask you to judge the how difficulty of each task, whether you felt any fatigue, how you liked the various games, and how easy it was to understand what you were supposed to do based on the computer display and instructions.

Where will this take place and how much of my time will it take?
The study will be conducted at Northeastern University, in Dr. Holden’s Neurorehabilitation Laboratory in Robinson Hall, Rm. 402. This is a one-time test that will take about two hours.

Will there be any risk or discomfort to me?
Although unlikely, it is possible that participants may experience fatigue or soreness of the leg or foot during or after the test session. If this happens, it should get better in a day or two. If you do experience any discomfort during or after the test, please let the researchers know. If you feel fatigued, you may take a break to rest at any time. You will be seated during the test so it is unlikely you will lose your balance. However we will have an assistant stand by to guard you to prevent a fall in the unlikely event that you should lose you sitting balance, to prevent any chance of injury to your ankle. We will check with you by phone or email a few days after the study to ask about any soreness in your ankle or leg.

Will I benefit by being in this research?
There is no direct benefit to you for taking part in the study. However, by participating in this research you may help neurological patients or athletes who are injured by contributing to the development of this ankle rehabilitation system which has the potential to benefit their health.

Who will see the information about me?
Your part in this study will be confidential. Only the researchers on this study will see the information about you. No reports or publications will use information that can identify you in any way. Every participant will be associated with a code. Instead of referring to the participants’ names they will be stored as coded letters or numbers. In rare instances, authorized people may request to see research information about you and other people in this study. This is done to insure that research is done properly. We would only permit people who are authorized by organizations such as the Northeastern University Institutional Review Board to see this information.

What will happen if I suffer any harm from this research?
In the unlikely event that you suffer any harm, we will obtain emergency assistance for you through the Northeastern University Public Safety Division.

Can I stop my participation in this study?
Your participation in this research is completely voluntary. You do not have to participate if you do not want to. Even if you begin the study, you may quit at any time. If you do not participate or if you decide to quit, you will not lose any rights, benefits, or services that you would otherwise have [as a student, employee, etc].

Who can I contact if I have questions or problems?
For questions about the device you may contact: Amir Farjadian at the Northeastern University Biomedical Mechatronics Laboratory, Egan Rm.061, Boston, tel. 617-373-7733; email: farjadian.a@husky.neu.edu. For questions related to human testing procedures you may contact Prof. Maureen Holden, PT, MMSc,PhD at 407C Robinson Hall, Northeastern University, Boston, tel. 617-373-5274; email: m.holden@neu.edu.

Who can I contact about my rights as a participant?
If you have any questions about your rights as a participant, you may contact Nan C. Regina, Director, Human Subject Research Protection, 960 Renaissance Park, Northeastern University Boston, MA 02115 tel. 617-373-4588, email: irb@neu.edu. You may call anonymously if you wish.

Will I be paid for my participation? There will not be any payment for participation.

Will it cost me anything to participate? There are no costs for participation.

Is there anything else I need to know? You must be at least 18 years old to participate.

I agree to take part in this research.

______________________________________________
Signature of person agreeing to take part   Date   Printed name

______________________________________________
Signature of person who explained the study to the participant above and obtained consent   Date   Printed name
## Appendix D. Borg’s CR-10 scale of Perceived Exertion

Please rate your overall exertion on the activity you just performed, using the scale below. The number 10 implies an extremely strong perceptual intensity, as in the perceived intensity in extremely heavy physical exercise like running for some minutes as fast as possible or lifting and carrying extremely heavy weights. Ten is defined as the strongest effort and exertion a person has ever experienced.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nothing at all</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>Extremely weak</td>
<td>(just noticeable)</td>
</tr>
<tr>
<td>1</td>
<td>Very weak</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Weak</td>
<td>(light)</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
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</tr>
<tr>
<td>4</td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>Strong</td>
<td>(heavy)</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Very strong</td>
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</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Extremely strong</td>
<td>(almost max)</td>
</tr>
<tr>
<td>•</td>
<td>Maximal</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E. Visual Analog Scale

Please rate how difficult you found it to maintain your balance during each task by marking the bar at the appropriate spot.

0 Limits of Stability Task:

<table>
<thead>
<tr>
<th>Very very easy</th>
<th>Almost impossible</th>
</tr>
</thead>
<tbody>
<tr>
<td>to balance</td>
<td>to balance</td>
</tr>
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</table>

2. Dot Moving Task A:

<table>
<thead>
<tr>
<th>Very very easy</th>
<th>Almost impossible</th>
</tr>
</thead>
<tbody>
<tr>
<td>to balance</td>
<td>to balance</td>
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</table>

3. Dot Moving Task B:
<table>
<thead>
<tr>
<th>Very very easy</th>
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</tr>
</thead>
<tbody>
<tr>
<td>to balance</td>
<td>to balance</td>
</tr>
</tbody>
</table>

4. **Bar Task A:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Very very easy</td>
<td>Almost impossible</td>
</tr>
<tr>
<td>to balance</td>
<td>to balance</td>
</tr>
</tbody>
</table>

5. **Bar Task B:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>Almost impossible</td>
</tr>
<tr>
<td>to balance</td>
<td>to balance</td>
</tr>
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</table>
Appendix F. Usability Questionnaire

Please give us your opinion on the usability and computer interface aspect of the system.

1. I found the computer interface for the balance task easy to use:

   Strongly Agree    Agree    Neutral    Disagree    Strongly Disagree

2. It was difficult for me to use the computer interface for the balance task.

   Strongly Agree    Agree    Neutral    Disagree    Strongly Disagree

3. It was difficult for me to learn how to move my body while standing on the platform so that the dot on the screen would go where I wanted it to go.

   Strongly Agree    Agree    Neutral    Disagree    Strongly Disagree

4. I had no trouble understanding what to do in the study.

   Strongly Agree    Agree    Neutral    Disagree    Strongly Disagree

5. The screen graphics displays sometimes confused me.

   Strongly Agree    Agree    Neutral    Disagree    Strongly Disagree
6. The experiment took too long.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

7. My ankle and/or leg became extremely tired in the experiment.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

8. I made many errors.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

9. It was very easy for me to move and hold the dot representing my balance point on the screen.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

10. I did not have any difficulty pressing the footplate with the correct force direction.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>
Appendix G. Protocol for Human Subject Testing vi-RABT Ankle

Strength and Motor Control Device

Equipment Needed:

- Robotic Footplate device
- Main VR computer (Hewlett-Packard)
- VR screen and Crestron controller software (on VR computer)
- Real-time computer (named Jaxon)
- Data acquisition (DAQ) terminal
- Output cables from optical encoders (#2) and load cells (#4) to the DAQ terminal
- Output connections from the DAQ terminal to motor controllers (Junus)
- Plastic bench with height adjustable legs
- Aerobic steps and risers for chair height adjustment
- Snowboard strap with heel guard

Supplies:

- Duct tape
- Masking tape
- Magic marker
- Plastic goniometer
- Velcro straps and towel roll to secure thigh and prevent hip external rotation
- Foam leg separator pad w/ Velcro strap to prevent hip internal rotation
- Velcro strap for patient toe stabilization- prn

Forms:

- Screening Questionnaire
- Informed Consents (2 copies/subject)
- Borg Rating of Perceived Exertion (9 copies total, one for each test)
- Visual Analog Scale for Difficulty Rating – all 9 tests are on one form
- Usability Questionnaire

Test/Game Names:

- Isometric Force assessment
- Game A: Force-controlled Board game; single axis, X and Y axes performed separately
- Game B: Force-controlled Board game; double axes, X and Y together
- Game C: Force-controlled Star Maze game; X and Y axes simultaneous control
- ROM assessment - self-selected speed
• ROM assessment – fast as possible speed
• Game A: Position-controlled Board game; single axis, X and Y axes performed separately
• Game B: Position-controlled Board game; double axes, X and Y together
• Game C: Position-controlled Star Maze game; X and Y axes simultaneous control

**Equipment Set-Up:**

- Ensure the real-time machine is powered on, as can be seen on the monitor
- Devices are plugged in, connected as indicated in the schematic
- Log on to VR computer
- Open *Crestron Control* software to activate VR screen
  - Power on only the Left eye (not right)

**Initial Software Setup:**

- Open *Unity* Software
  - Add how to select individual games [directories]
- Open *Labview* Software
  - Open the project file on desktop named *vi-RABT*
  - In the opened project file, open two files on the host and Jaxon
  - You will have three LabVIEW windows open
Outline of Subject Testing Sequence
(note- detailed instructions follow on next page)

Prior to Subject Arrival:

Ideally, review screening questionnaire and informed consent form with subject by phone or email prior to test date, to maximize time for testing during session.

A) Subject Arrival:

1. Initial Preparation: (Approximately 15-30 Minutes)
   1. Review and check screening questionnaire with subject
   2. Obtain Informed Consent
   3. Position subject in chair and device

B) Strength Tests:

1. Force production assessment:
   1. 4 directions (DF, PF, Inv., Evr)
   2. 3 second isometric hold
   3. 5 repetitions (n=20 repetitions total)

2. Force-controlled games
   1. Board Game: Single Axis – 30 reps each axis, n=60
   2. Board Game: Double Axis – 2 blocks of 30 trials each, n=60
   3. Star Maze: Double Axis – 2 blocks of 24 trials each, n=48

Total recorded trials for Strength + Force control games: 20+60+60+48 = 188;
Practice trials: 4+30+30+30+24 = 118

C) Motion Tests:

1. Range of Motion Assessment:
   1. Self-selected speed:
      A. 2 motions (DF-PF, INV-EVR)
      B. 7 repetitions each (middle 5 used for analysis) ; n= 14 repetitions total

2. Fast pace
   A. 2 motions (DF-PF, INV-EVR)
   B. 7 repetitions each (middle 5 used for analysis) ; n=14 repetitions total

2. Position-controlled games
   1. Board Game: Single Axis – 30 reps each axis, n=60
   2. Board Game: Double Axis – 2 blocks of 30 trials, n=60
   3. Star Maze: Double Axis – 2 blocks of 24 trials each, n=48

Total recorded trials for ROM + Position control games: 14+14+60+60+48 = 196
Practice trials: 10+10+30+30+30+24 = 134
TOTAL TRIALS RECORDED = 384
GRAND TOTAL = ~636 TRIALS
TOTAL PRACTICE TRIALS ~ 252
**Full Detailed Subject Testing Instructions**

**Prior to Subject Arrival:**
Ideally, review screening questionnaire and informed consent form with subject by phone or email prior to test date. At this time subject will receive a brief explanation of study, and a copy of the screening questionnaire and informed consent form. If contact is by phone, administer Screening questionnaire verbally over phone; if this is not possible, subject can return completed screening questionnaire via email. *Ensure that the subject passes the screening criteria prior to scheduling a test session.* Next, ask subject to review the informed consent form (sent via email) prior to coming to the test session. Answer any questions subject may have. These pre-test activities are designed to save time during the test session, but if scheduling does not allow, they can be done at start of the actual test session.

**A. Subject Arrival – Initial Preparation**

1. Review and check screening questionnaire with subject
2. Obtain Informed Consent – give subjects brief verbal overview (below), then give them written form to read, answer questions, obtain signature. Offer to give subject a copy of consent to take with them following testing.
3. Read *Initial Verbal Instructions* to subject (see below)
4. Properly position subject in chair and device (see below)

**Initial Verbal Instructions:**

*Thank you for participating in this study of the virtually interfaced robotic ankle and balance trainer device. This study will involve testing the strength of the muscles that move your ankle as well as your ability to control ankle movement. You will be seated throughout the study, and will use the projector screen for each task.*

*Prior to the start of each trial we need to set the foot plate to a value of zero. In order to do this we will lock the foot plate and ask you to hold as still as possible. During this time please relax your foot and try not to push, pull, or turn your ankle. This will take a few seconds and we will let you know when you no longer need to hold still and can relax.*

*So we can obtain measurements of your ankle strength you will be asked to push or pull forcefully on the footplate while it is locked in a stationary position. After we obtain strength information, you will complete three games using the projector screen and controlling the game by pushing and pulling on the locked plate. Once these games are complete, we will then unlock the foot plate and obtain range of motion measurements. These measures will then again be followed by the playing of three games in which you use the projector screen and move the footplate to control the game. These games are*
designed to present a precise level of difficulty tailored to your ability, based on the measurements of your personal strength and range of motion values.

Before we begin, please inform the investigators if there is any reason you feel you cannot or should not participate in these tasks. Because the tasks will involve use of a projector screen, any seizure history or sensitivity to flashing lights must be known before beginning the study. If you feel discomfort or require an additional rest period at any time, please let us know.

**Position Subject in Chair & Device**

- Position chair height & location based on subject size
- Lock the footplate in neutral position (use mechanical stops)
- Have subject sit in chair and adjust as needed:
  - Patient is sitting in the chair such that his/her back is against the backrest
  - Patients RIGHT hip and knee (of the testing ankle) are at 90 degrees of flexion
- Apply duct tape to plate or sole of shoe to minimize foot motion on plate
- Position subject’s foot (shoe on) on plate w/ malleoli lined up with PF/DF Axis
- Right ankle should be in neutral (90 degrees) along both DF-PF and INV-EVR axes
- Apply foot strap and heel guard; lock in place
- Apply additional velcro strap at toes if needed (for larger feet)
- Apply strap and towel roll to prevent hip external rotation
- Apply strap and foam knee separator to prevent hip internal rotation
- Explain to subject that this is to help prevent torque forces to their knee joint and to isolate ankle movements from hip movements

**B. Strength Tests**

**Task One: Isometric Force Assessment**

*Instructions to Subject:*

*For this task you will remain seated with your foot strapped into the device as we examine the strength of the muscles around your ankle. The foot plate will remain locked in place throughout this task. You will be instructed to push or pull your foot in four different directions, and the apparatus will record the strength with which you perform each action.*

- Software setup for this specific task –isometric plantarflexion (PF)
- Step-by-step for ensuring that the vi-RABT device is locked in stable, neutral
Instructions to Subject: **Plantarflexion**

At this time, with your foot locked into the foot plate, we will zero the load cells. Please hold still and keep your foot relaxed. Ok, relax.

For this trial push through your foot as though you are pushing down on a gas pedal. Push as hard as you can. You will hold this until we tell you to stop, about 3 seconds. You will rest for 10 sec, then repeat, for a total of 5 trials. We will now give you a few practice trials. Are you ready? OK, Push!* (Stop, rest).

Examiner reviews the 4 individual load cell inputs during this task to ensure the subject is mainly pushing down and not pulling up with heel (2 posterior load cells, blue and green traces) which could be caused by using hip flexor muscles vs ankle plantarflexors. If necessary, show subject these traces, and guide performance until you are sure subject is mainly performing the task using plantarflexor muscles.

We will now re-zero the plates, please hold still and keep your foot relaxed. OK, relax. We will now perform the 5 recorded trials. Do you have any questions? Are you ready? OK, Push! (Stop, rest, repeat).

- *Examiner guards the patient
- Examiner uses timer to control duration of isometric contraction (3 sec, + 10 sec rest)
- Record and save data for 5 trials
- Setup of next test (isometric dorsiflexion - DF) (software)
- Ensure that binding has not loosened and foot is immobile.

Instructions to Subject: **Dorsiflexion**

Now, with your foot locked into the foot plate, we will re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax.

For this trial try to lift the front of your foot as though you are pointing your toes towards your head. Please keep your hands in your lap, and sit up straight. It is important that you try to pull your toes toward your head and try not to push down through your heel or lift at your hip. Pull as hard as you can. You will hold this until we tell you to stop, about 3 seconds. You will rest for 10 sec, then repeat, for a total of 5 trials. We will now give you a practice trial. Are you ready? OK, Pull! (Stop, rest).
Examiner reviews the 4 individual load cell inputs during this task to ensure the subject is mainly pulling up (2 anterior load cells, red & white traces, negative direction) and not pushing down with heel (2 posterior load cells, blue and green traces, positive direction) which could be caused by using hip extensor muscles vs ankle plantarflexors. If necessary, show subject these traces, and guide performance until you are sure subject is mainly performing the task using dorsiflexor muscles. You may also need to check via palpation that subject is not activating hip flexors too much during task. (This would be more of a problem with patients who have weak dorsiflexors.)

We will now re-zero the plates, please hold still and keep your foot relaxed. OK, relax. We will now perform the 5 recorded trials. Do you have any questions? Are you ready? OK, Pull! (Stop, rest, repeat).

- Examiner uses timer to control duration of isometric contraction – 3 sec hold, 10 sec rest
- Record and save data for 5 trials
- Setup of next test (isometric inversion - INV) (software)
- Ensure that binding has not loosened and foot is immobile.

Instructions to Subject: Inversion

Now, with your foot locked into the foot plate, we will re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax. For this trial please keep your hands in your lap, sit up straight, and try keep your knee still. You will attempt to pull up, on the inside of your foot, as hard as you can. It is important that you try to pull up on the inside rather than trying to push the outside of your foot down. You will hold this until we tell you to stop, about 3 seconds. You will rest for 10 sec, then repeat, for a total of 5 trials. We will now give you a practice trial. Are you ready? OK, Pull! (Stop, rest).

Examiner reviews the 4 individual load cell inputs during this task to ensure the subject is mainly inverting via pulling up on the 2 medial load cells (red & green traces) and not pushing down the 2 lateral load cells (blue and white traces) which could be caused by using hip extensor muscles or ankle plantarflexors. If necessary, show subject these traces, and guide performance until you are sure subject is mainly performing the task using anterior tibialis muscle.

We will now re-zero the plate, please hold still and keep your foot relaxed. OK, relax. We will now perform the 5 recorded trials. Do you have any questions? Are you ready? OK, Pull! (Stop, rest, repeat).

- Examiner uses timer to control duration of isometric contraction – 3 sec hold, 10 sec rest
Instructions to Subject: **Eversion**

Now, with your foot locked into the foot plate, we will re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax.

For this trial you will try to lift the outside edge of your foot up towards the ceiling, like this (demo). Please keep your hands in your lap, sit up straight, and try to keep your knee still. Pull up as forcefully as you can. For this trial it is important that you do not push the inside of your foot down. You will hold this until we tell you to stop, about 3 seconds. You will rest for 10 sec, then repeat, for a total of 5 trials. We will now give you a practice trial. Are you ready? OK, Pull! (Stop, rest).

Examiner reviews the 4 individual load cell inputs during this task to ensure the subject is mainly pulling up on the 2 lateral load cells, blue & white traces, negative direction) and not pushing down with medial border of foot (2 medial load cells, red and green traces) which could be caused by using the posterior tibialis vs the peroneus brevis muscles. If necessary, show subject these traces, and guide performance until you are sure subject is mainly performing the task using anterior tibialis plus peroneus brevis muscles.

We will now re-zero the plate, please hold still and keep your foot relaxed. OK, relax. We will now perform the 5 recorded trials. Do you have any questions? Are you ready? OK, Pull! (Stop, rest, repeat).

- Examiner uses timer to control duration of isometric contraction, 3 sec hold, 10 sec rest
- Record and save data for 5 trials
- Setup of next test (Range of Motion Assessment) (software)
- Ensure that binding has not loosened and foot is immobile.

Forms to be completed immediately following completion of Task 1:

- Borg CR-10 scale of Perceived Exertion
- VAS: Isometric Strength Task (Question #1)
Task Two: Force – Controlled Games

1-A. Game A (Board Game – Single Axis): PF/DF, vertical Y axis

Verbal Instructions:

At this time we will again re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax.

For this task you will remain seated with your foot strapped into the device. The foot plate will remain locked in place throughout this task. On the screen you will see a flat board that represents the foot plate. There will be cubes along the Y axis (vertical axis – point to it on screen). The yellow cube represents your current position and can be moved by pushing your toes down or pulling your toes up. Red cubes are targets for you to reach. Pressing down as though you are pressing a gas pedal will move your yellow cube downwards. Pulling up as though you are pulling your toes towards your head will move your yellow cube upwards. If you pull gently, the cube will move slowly, and if you pull quickly the cube will move quickly.

When you move the yellow cube (representing your position) onto the red cube (the target), that cube will turn green indicating that you’ve reached the target. You will need to hold that position for 2 seconds to achieve 1 point. You will hear a “ding” sound if you have successfully captured the target and your point will show up on the score board on the left side of the screen. A new target will then be generated randomly, and you will repeat the process.

You will play the game until you have successfully reached 30 targets. We will also record your time. You may now practice controlling the board and the cube on the screen before the game begins. Do you have any questions?

- Saving data – one block of 30 trials for DF/PF
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile.

1-B. Game A (Board Game – Single Axis): INV-EVR, X Axis, horizontal

Verbal Instructions:

At this time we will again re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax. Now you will play the same game but will work along the X (Horizontal) axis. (Point to axis, move side to side.) You will see the yellow cube (representing your position) and the red cube (representing your target) along the bottom of the screen. Pulling up on the inside of your foot will cause the yellow cube to move to
the right. Pulling up on the outside of your foot will cause the yellow cube to move to the left.

The goal is to reach the red cube and maintain your position for 2 seconds to achieve 1 point on the score board. Once you do so, you will again hear a “ding” sound, and a new target will then be generated randomly.

You will play the game until you have successfully reached 30 targets. You may now practice controlling the board and the cube on the screen before the game begins. Remember, rotating the board toward the right moves the cube to the right, and rotating the board left moves the cube to the left. Do you have any questions?

- Saving data– one block of 30 trials for INV/EVR
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile.

Forms to be completed immediately following completion of Game A:
- Borg CR-10 scale of Perceived Exertion (may rate 1A & 1B separately if desired)
- VAS: Game A – foot not moving (Question #2)

2. Game B (Board Game–Double Axes): DF-PF plus INV-EVR; X and Y axes together

Verbal Instructions:

We will now re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax. For this task, you will play the same game as before. However, this time, to make it more challenging we would like you to try to reach two targets simultaneously.

Now, you will see two red targets, one along the X axis and one along the Y axis. There are also two yellow cubes (representing your current position), one along the X axis and one along the Y axis. You can move both yellow cubes by performing the same actions as in the previous two games. For example, the yellow cube in the Y axis, can be moved downwards by pressing down as though you are pressing a gas pedal. Pulling up as though you are pulling your toes towards your head will move your yellow cube upwards. For the yellow cube in the X axis, pulling up on the inside of your foot will cause the yellow cube to move to the right. Pulling up on the outside of your foot will cause the yellow cube to move to the left.

Pick a single red target, and move the board so that you capture that single targets. When you do so, three green blocks will appear. Now, while maintaining that position attempt to reach the other red target. If you do not maintain your first target position,
the cube will turn red again. The goal is to achieve both red targets simultaneously and maintain that position for 2 seconds. You will hear a “ding” sound if you have successfully captured both targets and your point will show up on the score board on the left side of the screen. Two new target will then be generated randomly.

You will play this game two times. Each game will be played until you have successfully reached 30 targets. You may practice controlling the board and the cubes on the screen now before the game begins. You may find it helpful to use the board as a cue – when it rotates up toward you, the yellow cube moves up, when it rotates down and away from you, the cube moves down. When the board rotates toward the left, the yellow cube moves left; when the board rotates to the right, the cube moves to the right. Do you have any questions?

- Saving data – 2 blocks of 30 trial each (60 reps total recorded)
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile.

Forms to be completed immediately following completion of Game B:

- Borg CR-10 scale of Perceived Exertion
- VAS: Game B – Foot not moving (Question #3)

3. Game C (Star Maze): DF-PF and INV-EVR together, zero at center

At this time we will again re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax.

For this task you will remain seated with your foot strapped into the device. The foot plate will remain locked in place throughout this task. On the screen you will see star shaped maze with 8 rays (arms). There are green cubes within each ray (arm). The purple circle in the center of the star represents your current position and can be moved by pushing your toes down, pulling your toes up, pulling the inside of your foot up, pulling the outside of your foot up, or a combination of these movements. If you pull gently, the purple dot will move slowly, and if you pull quickly the purple dot will move quickly.

The goal of this task is to capture all the green cubes. You can do so by moving your purple dot and touching each green cube. When you reach a green cube, you will hear a “ding” sound indicating that you have successfully reached the cube and the cube will then disappear. Each time you capture a green cube you will receive one point which will show up on the score board on the left side of the screen. Capture all the green
cubes to complete the game. In this game you are also penalized for hitting the ‘walls’ of the maze – you will hear a beep when you do so, and we will also count your errors. So, even though you want to collect the green cubes as fast as you can, if you go too fast and make a lot of errors, you will lose points.

You will play this game two times. Each game will be played until you have successfully reached all green targets. You may now practice controlling the purple dot on the screen before the game begins, until you feel confident you understand the task. Do you have any questions?

- Saving data – 2 blocks of 24 trials each, total 48 trials
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile.

Forms to be completed immediately following completion of Game C:

- Borg’s CR-10 scale of Perceived Exertion
- VAS: Game C – foot not moving – Question # 4

C. Motion Tests

Task One: Range of Motion Assessment

Instructions to Subject:

For this task, the foot plate will become unlocked. You will perform the same four actions as you did in the previous task, but this time the foot plate will move as your foot and ankle move. You do not need to push or pull very forcefully; only a light push or pull will move the foot plate for this task. Move your foot and ankle as far in each direction as you are able to. The apparatus will measure and record your range of motion for each movement. You will perform each motion at two different speeds: your natural speed, and then as fast as you are able. Do you have any questions?

- Apparatus setup for this task
- Software setup for this task
- Step-by-step computer use for this task

Verbal Instructions: DF/PF- self selected speed
For this task you will push gently as though you are pressing down on a gas pedal. Push in this direction as far as your foot and ankle will allow. Then, reverse the direction and pull your foot up as far as it will go. Keep repeating this rhythmic motion (down-up-down-up), at a comfortable pace until we tell you to stop (about 7 repetitions). It is important to go as far as you are able in each direction. Don’t worry about going fast.

At this time we will remove the metal locks and turn on the motors. Your foot might move a little bit, please do not be startled. We will now re-zero the load cells, please hold still and keep your foot relaxed. Ok, relax.

Your foot will now be allowed to move freely. Please practice moving down-up-down-up as far as you can. Good. Do you understand this task? We will now perform the 5 repetitions. Do you have any questions? Are you ready? Begin. (researcher should count out loud the repetitions)

- Saving data – 7 reps for DF/PF - slow (use middle 5 for analysis)
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile on the plate.

Verbal Instructions: **DF/PF- self selected speed**

Now, you will be assisted into neutral by one of the research team members in order to re-zero the load cells, please hold still and keep your foot relaxed. Ok, relax.

We will repeat this same movement (down-up, down-up), but this time going as fast as you can, while still trying to move as far as you can in each direction. Please practice moving down-up-down-up as fast as you can, through your full range of motion. Good. You will now perform the movement for 7 repetitions. Do not stop between movements. You may feel some resistance from the motor if you are able to move faster than our device allows. Do you have any questions? Are you ready? Begin (research member should count out loud the repetitions).

- Saving data – 7 reps for DF/PF- fast (use middle 5 for analysis)
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile.

Verbal Instructions: **INV/EVR- self selected speed**

Now, we will re-zero the load cells, please hold still and keep your foot relaxed. You will be assisted into neutral by one of the research team members to complete this task. Ok, relax.
For this task you will gently roll your ankle outward, as though you are trying to see the arch of your foot. Pull up on the inside of your foot to do so. Pull in this direction as far as your foot and ankle will allow. Then, reverse the movement by trying to lift the outside edge of your foot up towards the ceiling like this (demo). Pull in this direction as far as your foot and ankle will allow. Please keep your hands in your lap, sit up straight, and try to keep your knee still. Try to avoid pushing your toes down toward the floor or pulling your toes up toward the ceiling. Keep repeating this rhythmic movement, in-out-in out, at a comfortable pace, until we tell you to stop (about 7 repetition ). It is more important to move your ankle as far as you can than it is to move fast.

- Saving data– 7 reps for INV/EVR- slow (use middle 5 for analysis)
- Setup for the next movement (software)
- Ensure that binding has not loosened and foot is immobile.

Verbal Instructions: INV/EVR- fast as possible speed

Now, we will re-zero the load cells, please hold still and keep your foot relaxed. You will be assisted into neutral by one of the research team members to complete this task. Ok, relax.

For this task you will repeat the same movement (in-out-in-out, etc), but this time going as fast as you can. Please practice moving in-out-in-out as fast as you can, while still trying to maintain your maximum range of motion. Good. We will now perform the 7 repetitions. Do you have any questions? Are you ready? Begin (research member should count out loud the repetitions)

- Saving data– 7 reps for INV/EVR- fast (use middle 5 for analysis)
- Setup for next movement (software)
- Ensure that binding has not loosened and foot is immobile.

Forms to be completed immediately following completion of ROM Assessment:

- Borg’s CR-10 scale of Perceived Exertion (one for slow, one for fast)
- VAS: Free Ankle Movement Task: self-selected speed, and Free Ankle Movement Task: fast-paced speed (Q’s 5 and 6).
Task Two: Position - Controlled Games

1-A. Game A (Board Game – Single Axis): PF/DF, Y axis, vertical

Verbal Instructions:

Now, we will re-zero the load cells, please hold still and keep your foot relaxed. You will be assisted into neutral by one of the research team members to complete this task. Ok, relax.

For this task, the foot plate will be unlocked. You will control the flat board on the screen by moving the foot plate with your ankle. The direction that you move your ankle will control the direction that the board moves; Pressing down as though you are pressing a gas pedal will tilt the board downwards in that same direction, pulling up as though you are pulling your toes towards your head will tilt the board upwards. If you push or pull gently, the board will tilt slowly, and if you push or pull quickly it will tilt quickly.

There are cubes along the Y (vertical) axis. The yellow cube represents the current position of your ankle and corresponding position of the board on the screen. Red cubes are targets for you to reach by moving your ankle and thus the yellow cube. When you move the yellow cube (representing your current position) onto the red cube (the target), that cube will turn green indicating that you’ve reached the target. You will need to hold that position for 2 seconds to achieve 1 point. You will hear a “ding” sound if you have successfully captured the target and your point will show up on the score board on the left side of the screen. A new target will then be generated randomly. As in prior games, we will also record the time it takes you to complete this task.

You will play the game until you have successfully reached 30 targets. You may now practice controlling the board and the cube on the screen before the game begins. Do you have any questions?

- Device Setup
  - Unlocking footplate
  - Proper foot positioning for zero
  - Check that foot attachment to plate is secure and immobile

- Software Setup
  - Open Flat Plane game in Unity program
  - Under Inspector bar (at right) set the following parameters:
    - X_min: set to patient’s eversion ROM [or some percentage thereof]
    - X_end: set to patient’s inversion ROM [or some percentage]
thereof

- Z_min: set to patient’s dorsiflexion ROM [or some percentage thereof]
- Z_end: set to patient’s plantar flexion ROM [or some percentage thereof]
- Ensure (0,0) set as start position

○ Click Play button at top of Unity window

1-B. Game A (Board Game-Single Axis): INV/EVR, X axis, horizontal

Verbal Instructions:

Now, we will re-zero the load cells, please hold still and keep your foot relaxed. You will be assisted into neutral by one of the research team members to complete this task. Ok, relax.

Now you will play the same game but will work along the X axis. Pulling up on the inside of your foot will cause the board to drop down on the right, and the yellow cube to move to the right. Pulling up on the outside of your foot will cause the board to drop down on the left, and the yellow cube (which represents your current position) to move to the left.

There are cubes along the X axis. Again, the yellow cube represents your current position and the red cube is your target. The goal is to reach the target and maintain your position for 2 seconds to achieve 1 point on the score board. Once you do so, you will again hear a “ding” sound and a new target will then be generated randomly.

You will play the game until you have successfully reached 30 targets. You may now practice controlling the board and the cube on the screen before the game begins. Do you have any questions?

- Device Setup
  ○ Unlocking footplate
  ○ Proper foot positioning for zero set
  ○ Check that foot is secure to footplate – tighten straps if needed

- Software Setup
  ○ Open Flat Plane game in Unity program
  ○ Under Inspector bar (at right) set the following parameters:
    - X_min: set to patient’s eversion ROM [or some percentage thereof]
    - X_end: set to patient’s inversion ROM [or some percentage thereof]
thereof]
▪ Z_min: set to patient’s dorsiflexion ROM [or some percentage thereof]
▪ Z_end: set to patient’s plantar flexion ROM [or some percentage thereof]
▪ Ensure (0,0) set as start position

○ Click Play button at top of Unity window

Forms to be completed immediately following completion of Game A – position controlled:

- Borg’s CR-10 scale of Perceived Exertion (may rate 1A & 1B separately on same form)
- VAS: Game A-foot moving, (Question 7)

2. Game B (Board Game – Double Axis): DF/PF and INV/EVR together

Verbal Instructions:

Now, we will re-zero the load cells, please hold still and keep your foot relaxed. You will be assisted into neutral by one of the research team members to complete this task. Ok, relax.

For this task, you will play the same game as before. However, this time, to make it more challenging we would like you to try to reach two targets simultaneously.

Now, you will see two red targets along the X and Y axes. Yellow cubes represent the current position of your ankle on the two different axes. Moving your ankle to tilt the board in the appropriate direction will allow you to reach the targets. Pick a single red target, and move the board so that you capture that single target. When you do so, three green blocks will appear. Now, while maintaining that position attempt to reach the other red target. If you do not maintain your first target position, the cube will again appear red. The goal is to reach both red targets simultaneously (making them turn green) and maintain those positions for 2 seconds. You will hear a “ding” sound when you have successfully captured both targets and your point will show up on the score board on the left side of the screen. Two new targets will then be generated for your next trial.

You will play this game two times. Each game will be played until you have successfully reached 30 targets. We will also record your time to complete this task. You may now
practice controlling the board and the yellow cube on the screen before the game begins. Do you have any questions?

- **Device Setup**
  - Unlocking footplate
  - Proper foot positioning for zero value
  - Check that foot attachment is secure and immobile on footplate

- **Software Setup**
  - Open Flat Plane game in Unity program
  - Under Inspector bar (at right) set the following parameters:
    - X_min: set to patient’s eversion ROM [or some percentage thereof]
    - X_end: set to patient’s inversion ROM [or some percentage thereof]
    - Z_min: set to patient’s dorsiflexion ROM [or some percentage thereof]
    - Z_end: set to patient’s plantar flexion ROM [or some percentage thereof]
    - Ensure (0,0) set as start position
  - Click Play button at top of Unity window

Forms to be completed immediately following completion of Game B – Position controlled:

- Borg’s CR-10 scale of Perceived Exertion
- VAS: Game B-foot moving (Question 8)

3. **Game C (Star Maze- Double Axis): DF/PF and INV/EVR together**

At this time you will be assisted into neutral by one of the research team members and we will again re-zero the load cells. Please hold still and keep your foot relaxed. Ok, relax.

For this task you will remain seated with your foot strapped into the device. The foot plate will again be un-locked and you are free to move the plate with your ankle. On the screen you will see star shaped maze with 8 rays (arms). There are green cubes within each ray (arm). The purple circle in the center of the star represents your current position and can be moved by pushing your toes down, pulling your toes up, pulling the inside of your foot up, pulling the outside of your foot up, or a combination of these movements. If you pull gently, the purple dot will move slowly, and if you pull quickly the purple dot will move quickly.
The goal of this task is to capture all the green cubes as fast as possible, but without making errors (which happen when you hit the edge of one of the rays). You can capture the green cubes by moving your purple dot and touching each green cube. When you reach a green cube, you will hear a “ding” sound indicating that you have successfully reached the cube and the cube will then disappear. Each time you capture a green cube you will receive one point which will show up on the score board on the left side of the screen. Capture all the green cubes to complete the game. In this game you are also penalized for hitting the ‘walls’ of the maze – you will hear a beep when you hit the edge of a ray, and we will also count your errors. So, even though you want to collect the green cubes as fast as you can, if you go too fast and make a lot of errors, you will lose points.

You will play this game two times (24 trials each). Each game will be played until you have successfully reached all green targets. You may now practice controlling the purple dot on the screen before the game begins. Do you have any questions?

Forms to be completed immediately following completion of Game C – Position controlled:

- Borg’s CR-10 scale of Perceived Exertion
- VAS: Game C-foot moving (Question 9)
- Usability Questionnaire
Abstract:

The ankle joint is critical to upright balance, control, and functional gait patterns. Every year in the US 628,000 people suffer ankle sprains and nearly 795,000 people experience a stroke. Both injuries result in either orthopedic or neurological impairments to the ankle which decreases its functional capacity. Due to varied severity of patient injuries and/or impairments, a need exists for a rehabilitation device that offers assistive and resistive therapy in different stages of recovery. The Virtually-Interfaced Robotic Ankle and Balance Trainer (vi-RABT) was proposed as a rehabilitation system to help such individuals improve their ankle function and balance. The currently developed hardware is composed of a single robotic footplate, an adjustable chair, and three interactive games. The robotic ankle trainer is equipped with mechanisms that allow for torque and angle measurements and two actuators that minimize the interaction force subjects experience with the machine.

In this study, twenty healthy human subjects were recruited and instructed to play three different virtual reality games via the robotic footplate. The games are purposefully designed to assess ankle strength, motion, and control. Subjects were also given subjective scales and questionnaire to rate their perceived performance, fatigue, the
cognitive difficulty of the games, and the overall usability of the interface. The acquired results from the subjective data collection are discussed and represented here.

Introduction:

The ankle is the most common site of sprain injuries in the human body. Approximately one ankle sprain occurs per 30 persons annually worldwide, and an estimated 2,000,000 acute ankle sprains occur annually in the United States\(^1\). Ankle sprain occurs when the ankle is turned unexpectedly beyond what ligaments can bear. Ankle disabilities are also caused by neurological injuries such as traumatic brain injury or stroke, which is the leading cause of permanent disability in the United States\(^2\).

Rehabilitation is a must after ankle sprain as insufficient therapy will considerably compromise ambulation ability and predispose patients to future injury\(^3\). Traditional rehabilitation routines require intensive cooperation and effort of therapists and patients over prolonged sessions. Due to the significance and varied severity of ankle injuries and impairments, a need exists for a well-organized rehabilitation process that meets the needs of therapists and patients. Recent advances in robotics can be utilized to provide more efficient and objective ankle and balance rehabilitation methods. Robotics and automation can provide a transformation of rehabilitation from labor-intensive operations at clinics to technology-assisted interactions at home. The rapid growth in digital electronics and significant progress in computational methods can facilitate the data collection process, provide advanced real-time control systems, deliver more effective diagnosis and offer tailored therapy to the patients.

Vi-RABT is a rehabilitation robotic system that is designed to provide passive, active, assistive or resistive therapy to patients with lower extremity disorders\(^4\). The system has two degrees of freedom (DOF): dorsiflexion / plantarflexion (DFPF) and inversion / eversion (INEV) allowing for complete rehabilitation of all ranges of motion and muscle activation at the ankle joint. Recently virtual reality games were developed for the rehabilitation device and healthy human subjects were evaluated. Three methods of recording subjective data were given to all healthy subjects during data recording (Visual Analog Scale, Borg's Rating of Perceived Exertion Scale\(^5\) and a Usability Questionnaire\(^6\)). The results of the 20 healthy subjects subjective data is reported here.
Methods:

The long term goal for the vi-RABT is to be used for ankle and balance rehabilitation of individuals. In this study, we began working toward this goal by studying human ankle biomechanics. The system was used in static (motors off) and back-drivable mode. Healthy human subjects were recruited to perform isometric (static mode) and isotonic (back-drivable) ankle assessment tests. Our objective was to measure the ankle joint range of motion, strength and motor control, and collect data on healthy subjects perceived fatigue, cognitive effort to complete the tasks, and overall usability of the system. The scales used to measure subjective data and results are reported here.

A: Experimental Procedure:

The experimental protocol was approved by the institutional review board at Northeastern University (NU). Subjects were tested in the Neurorehabilitation Lab of Dr. Holden at NU. They were seated on the adjustable chair, with dominant foot strapped securely into the robotic footplate. To protect subject’s knee joint and to increase measurement accuracy, subjects’ legs were stabilized with pads and straps to minimize hip internal and external rotation. The chair height was adjusted to place the hip and knee in 90 degrees of flexion, and ankle joint in neutral.

Subjects were tested in a series of four different tasks. Task one involved assessing the subjects isometric strength output in dorsiflection (DF), Plantarflexion (PF), Inversion (IN), and Eversion (EV) by having the subject perform 5 maximal contractions of 3 second duration for each of the desired directions. Mean values for strength for each subject were then used to set the game boundaries (80% of maximum strength). Task two required the subjects to play a series of 4 games (Board Game_X, Board Game_Y, Board Game_XY, and Maze Game) that required single or double axis force output from the subjects ankle in order to reach targets and complete the games. After completion of force control (strength) games the subjects maximum ROM was assessed in task three. The subjects performed 7 alternating movements along a sagital and frontal axis at a comfortable pace (DFPF, INEV). During this task, the actuators were turned on and controlled in the back-drivable mode; the footplate showed minimal resistance to movement. Mean values for ROM for each subject were then used to set the game
boundaries (80% of maximum ROM). Subjects then completed task four by playing the same series of games as they did in task two (strength control) however this time controlling the games via movement of the ankle (ROM).

Upon completion of each task during the vi-RABT, the 20 healthy subjects were asked to complete a Borg's Rating of Perceived Exertion scale and a Visual Analog Scale (VAS). The scales can be found in Appendix A and B respectively. At the completion of the vi-RABT testing subjects were also asked to complete a usability questionnaire (Appendix C).

**B: Subjective Data Collection Tools**

The Visual Analog Scale (VAS) requires subjects to rate each task based on difficulty in terms of cognitive understanding and game requirements/complexity of task. The far left side of the VAS indicates very very easy. The far right side of the VAS indicates very difficult. The subject is to make an dash along the continuum of the line as his/her rating of perceived difficulty for that specific task. The purpose of including the VAS in this study was to aid the research team in determining which tasks were perceived to be more challenging to understand, which tasks required more cognitive focus, and ultimately which tasks were easier or harder in comparison to the others.

The Borg's Rating of Perceived Exertion scale is a 0 to 10 scale in which each number along the scale correlates to a level of physical fatigue perceived by the subject. After completion of each task the 20 healthy subjects were asked to circle the number that corresponds to their level of fatigue. Low numbers indicate absent to little fatigue and high numbers on the scale indicate extreme levels of fatigue/exhaustion. Again, inclusion of the Borg's Rating of Perceived Exertion Scale was done as a means to aid the research team in determining which tasks were more or less challenging in terms of fatigue that it caused the subjects.

At the completion of all tasks subjects were then asked to complete a Usability Questionnaire in order to aid the research team in determining if subjects understood the tasks, if the testing took too long or caused excessive fatigue, and how the subjects perceived their performance.
Developing an understanding through subjective interview, scales, and questionnaires is critical to aiding the research team in determining difficulty of the established tasks. Analysis of these subjective ratings can then aid the team in determining proper sequencing of tasks, amount of rest that should be given, and what minimum level of endurance, strength, and cognition may be required in order to successfully complete all the tasks.

**Results:**

After completion of healthy subject data collection (20 healthy subjects), the VAS and Borg's Rating of Perceived Exertion scales were analyzed. The VAS was converted into a measure of distance (cm) by measuring from the beginning marker of the VAS scale to the dash (subjective rating) for each task and for each subject. These measurements for each subject and each task can be found in Table 1. The Borg's Rating of Perceived Exertion data was also collected and can be found in Table 2.

Charts 1, 2, and 4 compare subjects ratings of perceived difficulty of task (VAS Chart 1 and Chart 2) and amount of fatigue for each task (Borg Chart 4). Data is also displayed in such a manner as to compare subjects ratings of strength/force vs. ROM for each of the four games completed in task 2 and task 4 respectively (Chart 3, and 5).

The usability questionnaire was given to subjects to complete as a likert scale (Appendix C). In order to analyze the questionnaire to determine subjects rating of usability the scale was given numerical values. A rating of 1 and 2 was given to the statements in each question which can be perceived as extremely negative/unstatisfactory and negative respectively. A score of 3 was given to indicate neutral responses. A score of 4 and 5 was given to the statements in each question which can be perceived as positive/ satisfactory and extremely positive/satisfactory respectively. Each subjects usability questionnaire was then scored and can be found in Table 3. Appendix D contains each question for the usability questionnaire, the questions mean, median, and mode response (from Table 3), and the associated meaning of these scores. The questionnaire was further broken down into 3 subsections; Cognitive Aspects/ Interface (questions 1-4), Physical Fatigue (questions 5-7), and Subjective Rating of Performance.
Mean values and standard deviations were calculated for these subsections and are presented in Chart 6.

When we look at each individual game it can be determined that overall subjects found single axis games (Board Game_X and Board Game_Y) to be easier to understand and less fatiguing than multiple axis games (Board Game_XY and Maze Game) (chart 3 and chart 5). Overall, through healthy subject testing and subjective ratings of fatigue and difficulty, the Maze game appears to be rated as most difficult and most fatiguing to perform (chart 3 and chart 5).

Review of the usability questionnaire demonstrates that subjects overall found the interface (questions 1-4 and subsection one) to be usable and the majority of the 20 healthy subjects indicated that they “strongly agreed” that they had no trouble understanding what to do in the study (question 3). The majority of subjects rated the length of time of the study from start to finish as “neutral” and did not agree that the study took too long to complete (question 5). The majority of subjects indicated that they disagreed with the statement that their ankle or leg became extremely tired during the study (questions 6 and 7). Questions 9 and 10 asked the subjects to rate on the likert scale how easy it was for them to complete the force control games (question 9) and ROM games (question 10). These two questions are of particular interest to the group as the study aims to discover if a difference in performance and subjective rating of difficulty exists between force control and position control. These two questions on the usability questionnaire can be compared to the subjects rating of perceived exertion (Borg) and VAS for both the strength tasks and ROM tasks. Overall, subjects agreed that when their ankle was free to move (ROM tasks/games) the task was easy (question 10). However, when subjects were asked in question 9, “It was very easy for me to move and hold the dot on the screen when my ankle was held stable”, as in the force control games, subjects had the largest variability in scoring. This question on usability questionnaire yielded the greatest range of given scores (from strongly disagree=1 to strongly agree=5). The overall mean of the scores for question nine was 3.1 which would indicate “neutral”. Further analysis of the data (Table 3) shows that there were three subjects (9,10,12) that stated they strongly disagree with the statement and found it very difficult to move the
dot whereas others agreed that the task was easy. Due to the variety in subject scoring this question yielded the largest standard deviation on the questionnaire.

**Discussion:**

The virtually interfaced robotic ankle and balance trainer (vi-RABT) is described, and subjective scales and questionnaires from 20 healthy subjects are presented. Via review of the subjective data it can be determined that overall subjects found ROM tasks to be easier to understand and perform and to be less fatiguing compared to Strength tasks (Chart 3 (VAS) and Chart 5 (Borg)).

Review of the usability questionnaire indicated that subjects found the interface to be user friendly, the length of the testing session to not be too long or too short, and that extreme fatigue was not experienced in the ankle or leg throughout the conduction of the experiment.

Through healthy subject testing and gathering of both subjective and objective measures the research team can use the information gathered to determine level of difficulty and resultant fatigue from performing the tasks required in the vi-RABT. This information can be used to properly sequence the games so that perhaps the most fatiguing games are performed last as to prevent a decrease in performance on other tasks that require less muscle activation and concentration. The sequencing can also be altered to provide additional periods of rest after the tasks that were rated most fatiguing or difficult to allow ample time of recovery before moving on to another task. All of these elements are critical to analyze and account for before the vi-RABT can begin testing on non-healthy or impaired subjects so to prevent any injuries, excessive fatigue, and the most rewarding sequence of virtual gaming to maximize patient benefits.

Future analysis of subjective rating of fatigue (Borg) and difficulty (VAS) will be compared to subjects objective measures of how they actual performed in the games (force, ROM, and score/time to completion) to see if subjects were able to accurately self reflect and on which tasks they found most difficult compared to which tasks they performed most poorly on.