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DESIGN AND TEST OF NORTHEASTERN UNIVERSITY VIRTUAL ANKLE AND BALANCE TRAINER (NUVABAT)

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Mechanics and Design

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ABSTRACT

The ability to control the ankle muscles and produce adequate range of motion in the ankle joints are key components of gait and balance function. Patients who suffer from neurological impairments, such as stroke or traumatic brain injury, frequently lose gait and balance function due in part to loss of ankle control. Described in this thesis is a unique two degree of freedom (DOF) mechatronic device with a virtual reality interface that has been developed to meet the needs of such patients for ankle and balance rehabilitation. The Northeastern University Virtual Ankle and Balance Trainer (NUVABAT) rehabilitation system has five components: i) a patient-actuated device; ii) control software; iii) a practitioner graphical interface; iv) virtual reality software; and v) training software. The system can be used for measurement of ankle kinematics and balance function as well as for retraining motor control of the ankle, and can be used in either a sitting or standing position to accommodate early and late phases of rehabilitation training. We report here the details of the various design features and initial testing of the device.
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Also, I would like to thank my physical therapy group students, Andrew, Kirsten, and Naoto. It is nice to have you to work with me on the training protocols. Without you, all those nice games, rules and tests cannot be made. I am so happy to have you.

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1 INTRODUCTION

Impaired control of gait and dynamic balance are frequent problems in patients with stroke [1-3]. Such deficits interfere with overall functional independence and can place these patients at an increased risk for falls [4, 5]. In a recent study of 972 patients with stroke receiving inpatient rehabilitation in 6 facilities in the US, the most common treatment activity was gait-related activity, and >50% of these sessions involved work on balance and postural awareness. Pre-functional activities were the next most common treatment, and >50% of these sessions involved strength training [6]. The importance of balance control to gait function was shown in a recent prospective longitudinal study of 101 patients with stroke [7]. These authors found that improvements in balance control were more important in improving walking ability than were improvements in leg strength or muscle synergy control. Other authors have shown that deficits in mobility, muscle strength and motor control about the ankle joint are key factors that contribute to gait and balance deficits in patients with stroke [8-10]. Many treatments to improve gait and balance function in patients with stroke are aimed at control of the ankle or include ankle exercises as a component of treatment [11, 12]. These studies describe the use of balance activities, ankle strengthening exercises and functional neuromuscular stimulation (FNS) of ankle muscles in treatments aimed at improving gait balance control. In another example, researchers found that passive dynamic stretching about the ankle joint in a standing position produced significant short-term increases in walking speed and cadence, and decreases in ankle spasticity [8].
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. Examples of currently available devices used for ankle rehabilitation include Wobble Boards (lowcost) [13], Thera-Band (lowcost) [14], Wii Balance Board [15], Ankle Foot Orthosis at University of Delaware (AFOUD) [16], Robotic Gait Trainer (RGT) [17], Powered Ankle-foot Orthosis (PAFO) [18], Ankle Dorsiflexion Plantarflexion Exercise Device (ADPED) [19] and the Rutgers Ankle (RA) [20].

Wobble Boards are low cost wooden or plastic platforms with a rubber semi-sphere attached to the bottom of the board [13]. Patients stand on the board and attempt to balance on it. While these devices can be useful for balance training in athletes or patients with orthopaedic injuries, they are often too difficult for patients with stroke to use safely. In addition they do not provide any quantitative measurement outputs that could be used to adjust exercise difficulty and to measure progress over time. The Thera-Band professional resistance bands are elastic bands which can be used for stretching or resistive exercise. Proper use of these bands for resistive exercise can elicit both concentric or eccentric contractions from the muscles, thus contribution to improvements in strength, range of motion and coordination [14]. The Wii Balance Board is shaped like a household body scale, and it has multiple pressure sensors that are used to measure the user’s balance (the location of the intersection between an imaginary line drawn vertically through the center of mass and the surface of the balance board) and weight [15].
The AFOUD is a two DOF ankle device which is composed of three links connected by two revolute joints corresponding to the three segments [16]. This orthosis can be used as a stand alone measurement device to measure the joint forces and moments applied by the human at ankle joint. The RGT is a tripod mechanism, consisting of a flat plate and two bi-directional actuators. The patient’s leg acts as the fixed link. [17]. It uses a Matlab and Simulink platform to control the pneumatic actuator which provides assistance to muscle contraction during gait training. The PAFO consists of a carbon fiber and polypropylene shell wrapping around the leg, a steel hinge joint connecting footplate and the shell, and two artificial pneumatic muscles which are controlled by proportional myoelectric control. This robotic exoskeleton device can provide planter flexion torque at the ankle, but lacks of inversion/eversion movement control [18]. The ADPED is a passive motion exercise device, which enables passive movement of ankle inversion/eversion during plantarflexion / dorsflexion (PF/DF) [19]. Patients are only allowed to practice with this device in a seated position. The RGT, PAFO, and ADPED are useful devices to assist patients, but are geared towards passive robotic assistance, vs. active movement control by the patient. In addition, they do not address the balance component of training, or comprehensive training of ankle motion and strength control in all planes of movement. Furthermore, they do not offer an interactive virtual-reality based interface.

The Rutgers Ankle (RA) incorporates a Stewart platform, which utilizes six pneumatic pistons working in parallel to create a 6 DOFs platform [20]. When in use, the RA is interfaced with a virtual reality software which guides the patient’s movements and controls the force feedback of the platform. This is an excellent device for ankle
rehabilitation, but presently can only operate in a seated position and does not offer balance control training. In addition, it is not commercially available, and would likely be expensive to produce due to its use of expensive sensors and actuators.

The NUVABAT system described in this thesis has been designed to have the following capabilities: i) provide variable torque resistance in both PF/DF and inversion/eversion direction, ii) ability to measure the forces applied to the footplate and the center of the pressure those forces, iii) Allow patients to be trained in both seated and standing positions, iv) have a virtual reality interface and software programs to facilitate ankle and balance training, v) could be used as an ankle kinematic measurement device vi) be a low cost device to fabricate. The specifications of this device are discussed in section 3.2 of this thesis.
2 BACKGROUND

2.1 Anatomy of the Human Ankle

Before discussing the design of an ankle rehabilitation device, it is important to first describe the anatomy and physiology of the human ankle. The ankle (talocrural) joint is a hinge joint. It is formed by the articulation of the talus with the malleoli of the tibia and the fibula [21].

The ankle is capable of allowing the foot to move in three degrees-of-freedom-dorsiflexion/plantarflexion, eversion/inversion, and abduction/adduction. Dorsiflexion is an upward movement of the foot in the sagittal plane, so that the dorsal surface of the foot approaches the anterior surface of the leg, and plantarflexion is a downward movement of the foot, where the dorsal surface of the foot moves away from the anterior surface of the leg [21]. Eversion is the movement turning the ankle and foot outward; Inversion is the movement turning the ankle and foot inward with respect to the leg. Abduction is the movement of the foot away from the midline of the body; weight is on the medial edge of the foot, and adduction is the movement of the foot toward to the midline of the body; weight is on the lateral edge of the foot. Pronation is a combination of ankle eversion and abduction, while supination is a combination of inversion and adduction [22]. A visual representation of these ankle movements is depicted below in Figure 1.

Each of these motions has a range that is deemed healthy for an average individual. These ranges are represented below in Table 1 as the maximum angle of flexion relative to the foot's neutral position [22].
The asymmetries between the various ranges of motion are indicative of the complex nature of ankle motion. In order to understand these complexities, one must first become familiar with the bones, muscles, and ligaments of which the ankle is comprised. The following sections will take a close look at the anatomy of the human ankle.

**Table 1: Range of Motion of the Ankle [23]**

<table>
<thead>
<tr>
<th>Range of motion</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorsiflexion</td>
<td>26°</td>
</tr>
<tr>
<td>Plantar Flexion</td>
<td>48°</td>
</tr>
<tr>
<td>Inversion</td>
<td>22°</td>
</tr>
<tr>
<td>Eversion</td>
<td>12°</td>
</tr>
<tr>
<td>Adduction</td>
<td>33°</td>
</tr>
<tr>
<td>Abduction</td>
<td>38°</td>
</tr>
</tbody>
</table>
2.1.1 Bones and Joints of the Ankle

The term ankle refers primarily to the talocrural joint, but also includes two related articulations: the proximal and distal tibiofibular joints. The term foot refers to all the structures distal to the tibia and fibula. The major joints of the ankle and foot are the talocrural, subtalar, and transverse tarsal joints. The talus is mechanically involved with all three of these joints. The multiple articulations made by the talus help to explain the bone’s complex shape, with nearly 70% of its surface covered with articular cartilage. [23].

Figure 2 depicts an overview of the terminology that describes the regions of the ankle and foot. The terms anterior and posterior have their conventional meanings when referring to the tibia and fibula. Within the foot are three regions, each consisting of a set of bones and one or more joints. The rear-foot consists of the talus, calcaneus, and subtalar joint; the mid-foot consists of the remaining tarsal bones, including the transverse tarsal joint and the smaller distal intertarsal joints; and the forefoot consists of the metatarsals and phalanges, including all joints distal to and including the tarsometatarsal joints [23].

The talus is the most proximal tarsal bone. Its dorsal or trochlear surface is a rounded dome, convex anterior-posteriorly and slightly concave medial-laterally (see Figure 3). Cartilage covers the trochlear surface and its adjacent sides, providing smooth articular surfaces for the talocrural joint. The prominent head of the talus projects forward and slightly medial toward the navicular [23].
The long and thin fibula is located lateral and parallel to the tibia. The fibular head can be palpated just lateral to the lateral condyle of the tibia. The slender shaft of the fibula transfers a small fraction of the load through the leg, most of it being transferred through the thicker tibia. The shaft of the fibula continues distally to form the sharp and easily palpable lateral malleolus. The lateral malleolus functions as a pulley for the tendons of the peroneus longus and brevis. The alteral malleolus also forms the lateral wall of the ankle joint [23].

The distal end of the tibia expands in size to accommodate loads transferred across the ankle. On the media side of the distal shaft of the tibia is the prominent media malleolus. On the lateral side is the fibular notch, a triangular concavity that accepts the distal end of the fibula at the distal tibiofibular joint [23].

The talocrural joint is formed by the articulation of the trochlear surface and the sides of the talus, with the rectangular cavity formed by the distal end of the tibia and both malleoli. The concave shape of the proximal side of the ankle mortise is maintained by connective tissues that bind the tibia with the fibula [23].

The subtalar joint is the set of articulations formed by the posterior, middle, and anterior facets of the calcaneus and the talus (see Figure 4). To appreciate the extent of subtalar joint motion, one can firmly grasp the unloaded calcaneus and twist it in a side-to-side and rotary fashion. During this motion, the talus remains nearly fixed within the talocrural joint. Pronation and supination during non-weight-bearing activities occur as the calcaneus moves relative to the fixed talus. Mobility at the subtalar joint allows the foot to assume positions that are independent of the orientation of the superimposed ankle.
and leg. This function is essential with feet held wide apart, and keeping one’s balance on a rocking boat [23].

The transverse tarsal joint has a strong functional relationship to the subtalar joint. As subsequently described, these two major joints function cooperatively to control most of the pronation and supination posturing of the entire foot. The transverse tarsal joint, also known as the mid-tarsal or Chopart’s joint, consists of two articulations: the talonavicular joint and the calcaneocuboid joint. Although functionally related, each joint is anatomically distinct. The talonavicular joint is the articulation between the convex head of the talus and the continuous concavity formed by the proximal side of the navicular bone and the dorsal surface of the plantar calcaneonavicular ligament (see Figure 4). The calcaneocuboid joint is the lateral component of the transverse tarsal joint, formed by the junction of the anterior surface of the calcaneus and the proximal surface of the cuboid.

---

**Figure 2 : The Essential Terminology Used to Describe the Regions of the Foot and Ankle [23]**
Each articular surface has a slight concave and convex curvature that, when articulated, forms an interlocking wedge that resists sliding. The joint is therefore relatively inflexible, providing an element of rigidity to the lateral column of the foot [23].

Figure 3: A Medial View of the Bones of the Right Ankle and Foot [23]

Figure 4: A Superior View of the Talus Flipped Laterally to Reveal Its Plantar Side and the Dorsal Side of the Calcaneus [23]
2.1.2 Ligaments and Tendons of the Ankle

A ligament is defined as a thick band of cartilage that attaches bone to bone and is responsible for the stabilization of a joint. Only able to stretch by 6% of its original length, ligaments can be susceptible to snapping if put under large abnormal loads [24].

The medial side of the ankle joint is protected by five strong ligamentous bands (see Figure 5), four of them connecting the medial malleolus of the tibia with the posterior tarsal bones, the calcaneus, talus, and navicular. These four ligaments are known collectively as the deltoid ligament. The fifth band (plantar calcaneonavicular) provides a horizontal connection between the navicular bone and the sustentaculum tali projection on the medial aspect of the calcaneus. It is also known as the spring ligament [21].

The lateral side of the ankle is reinforced by three ligaments collectively called the lateral collateral ligament. It connects the lateral malleolus with the upper lateral aspect of the calcaneus and with anterior and posterior portions of the talus. The components of the lateral collateral ligament are named the calcaneofibular, anterior and posterior talofibular ligaments [21].

The medial and lateral ligaments allow for stability during dorsiflexion and plantarflexion of the ankle. The ligaments of the ankle are used for structural stability and fluidity of ankle movement [24].

The largest ligament of the foot is the plantar fascia which runs along the bottom of the foot [24]. Forming the arch of the foot, the plantar fascia can stretch and contract to allow the body to balance on the foot [25].
Tendons are the thick band-like tissues that attach muscles to bone. The Achilles tendon is the largest and strongest tendon of the foot and is located on the back of the heel. [26] The Achilles tendon attaches the calf muscles that plantarflex the foot to the calcaneous. Integrity of the Achilles tendon is critical to activities such as standing on the toes, running, jumping, and climbing stairs [25].
2.1.3 Muscles of the Ankle

There are two types of muscle groups in the foot: intrinsic and extrinsic. Intrinsic muscles are muscles that are located in the foot/ankle and are used for stability of the foot and arches, as well as toe movement. Eleven of the twenty-two muscles of the ankle and foot are intrinsic, that is, they are located entirely within the foot. The other eleven muscles are extrinsic; they have distal tendon attachments on the foot but are otherwise located outside it (shown in Table 2) [21].

<table>
<thead>
<tr>
<th>Extrinsic Muscles</th>
<th>Intrinsic Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Anterior Aspect of Leg</em></td>
<td></td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td></td>
</tr>
<tr>
<td>Extensor digitorum longus</td>
<td></td>
</tr>
<tr>
<td>Extensor hallucis longus</td>
<td></td>
</tr>
<tr>
<td>Peroneus tertius</td>
<td></td>
</tr>
<tr>
<td><em>Lateral Aspect of Leg</em></td>
<td></td>
</tr>
<tr>
<td>Peroneus longus</td>
<td></td>
</tr>
<tr>
<td>Peroneus brevis</td>
<td></td>
</tr>
<tr>
<td><em>Posterior Aspect of Leg</em></td>
<td></td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td></td>
</tr>
<tr>
<td>Soleus</td>
<td></td>
</tr>
<tr>
<td>Tibialis posterior</td>
<td></td>
</tr>
<tr>
<td>Flexor digitorum longus</td>
<td></td>
</tr>
<tr>
<td>Flexor hallucis longus</td>
<td></td>
</tr>
</tbody>
</table>

Intrinsic muscles include the short flexors and extensors of the toes, and the abductors and adductors of the toes. Extrinsic muscles are responsible for moving the ankle/foot and are located farther up the leg in the calf.. This muscle group includes the large gastrocnemius-soleus muscle (commonly referred to as the calf muscle) [27]. For dorsiflexion, the tibialis anterior, peroneus tertius, peroneus brevis, extensor digitorum longus, and extensor hallucis longus are responsible for it. And gastrocnemius, soleus, and peroneus longus, tibialis posterior, , flexor digitorum longus, and flexor hallucis longus perform the movement of plantar flexion. Supination(Inversion and Adduction) is performed by the tibialis posterior, flexor digitorum longus, flexor hallucis longus, and peroneus longus . Pronation (Eversion and Abduction) is performed by the peroneus
longus, brevis and tertius, with possible help from the extensor digitorum longus [21] (see Figure 6 and Figure 7).

The extensors and flexors are responsible for toe movement; the long toe extensors assist in ankledorsiflexion during the action of stepping forward, while the long toe flexors stabilize the toes on the ground [25]. The gastrocnemius and soleus are responsible for plantarflexion and are the major muscles used in walking once the individual’s center of gravity is passed over the foot.

Figure 6: Front View of the Foot Muscles
2.1.4 Common Ailments for Ankle

In order to develop an ankle rehabilitation device, it is important to understand the overall physical condition of the ankle and the reasons of rehabilitation training behind it. Lots of the stroke patients have troubles on their motor control of their ankle, and lose their balance function for they cannot perform a normal function on their ankle muscle. Peripheral nerve disorders can cause paralysis of the dorsiflexor muscles and result in a ‘dropped’ foot. Common orthopedic ailments include ankle sprains, strains, fracture, torn ligaments, and Achilles tendinitis. It is common to get your ankle injured in the daily activities, where can cause further damage by applying a relatively low force to the extent. So it is vital to have a rehabilitation device that can safely train the ankle and get the patients recovered from all kinds of situations.
Ankle sprains and ankle strains are two of the most common ankle ailments. Strains affect the tendons and muscles, and can result from a pull, twist, or acute tear. This is commonly a result of overstretching or over-contraction of the affected muscle. Ankle sprains are injuries to ligaments caused by misalignment or hyperextension of a joint due to external trauma, such as a fall [26]. Ankle sprains account for 10% of injuries treated in emergency rooms as well as 15% of all sports-related injuries [28]. Rehabilitation for sprains, as well as most ankle conditions should be started within the first 72 hours of the injury. [29]. Severe sprains, if left untreated or not cared for properly can lead to degenerative joint disease as well as osteochondritis dissecans, stress fracture of the cuboid, and avascular necrosis of the talus [28].

Plantar fasciitis is a common condition where the plantar fascia, the connective tissue that runs along the bottom of the foot from heel to toe, shortens due to overuse and can develop micro tears, and become inflamed and painful. Recommendations for recovery include various ankle strengthening exercises, passive joint mobilization, active joint range of motion exercises, increased arch support, and applying cold to the affected area [30]. Heel spurs, most commonly caused by chronic or untreated plantar fasciitis, are bone growths that occur on the bottom of the heel where tissues attach [31].

Stress fractures are a type of bone fracture caused by abnormally high loads being carried by the bone due to localized muscle fatigue. Since the fatigued muscles are no longer able to carry their normal loads, the loads are instead applied to the bone, resulting in stress fractures. Treatment includes a combination of rest and rehabilitation; improper care and repeat injury can result in chronic foot problems as well as the fracture not being able to heal properly [32].
All of these disorders could potentially benefit from treatment using the ankle device described in this thesis.

2.2 Patent Search

There are some patents related to the ankle rehabilitation devices which help to establish what has already been done as well as where the advantages are of the device. Those devices could give us better ideas on how to develop our devices. The following sections will go into each related patents.

2.2.1 Patent: Ankle Rehabilitation Device (#5368536)

This device (see Figure 8) is a portable ankle rehabilitation device. The foot plate is supported by a post which can be adjusted to separate exercises in either plantar flexion or dorsiflexion or inversion or eversion movements. The resistance of the exercises comes from the mechanism which includes two bars linkage coupled with a spring. Similar to the linkage, the spring has different attachment points which to adjust different resistance to the exercise. For this mechanism, this ankle rehabilitation device only allows one direction of training at one time [33].

Figure 8: Ankle Rehabilitation Device, Patent 5,368,536
2.2.2 Patent: Exercise Device for Foot, Ankle and/or Shin (#7364534)

This ankle rehabilitation device claims a specific design in which the ankle can travel through its full range of motion. The range of motion and resistance is provided through two axes for PF/DF and Abduction/Adduction that intersect underneath the platform. This device helps to exercise the muscles around the ankle by providing variable resistance. And this adjustable resistance is provided by a configuration that operates through friction where an adjustment can be made to the normal force on the two surfaces in contact with each other (see Figure 9) [34].

![Figure 9: Exercise Device for Foot, Ankle and/or Shin, Patent 7,364,534](image)

2.2.3 Patent: Ankle Rehabilitation Device (#6277057)

This patent claims a design of an ankle rehabilitation device. The device is setup as a support arm extending upward from the base. A foot platform is located on the support arm and can rotate through plantar flexion, inversion, internal rotation, dorsiflexion, eversion and external rotation. Resistance is provided with respect to the base and the connection from the support arm to the base is a ball and socket type joint. The ball and
socket joint is supported by hydraulic arms that are used for both movement and resistance. This is the focus of the claims of the patents. There are no claims in regards to portability, programmability, feedback or VR (see Figure 10) [35].

![Figure 10: Ankle Rehabilitation Device, Patent 6,277,057](image)

### 2.2.4 Patent: Ankle Rehabilitation Device (#5215508)

This device claims to be able to isolate the ankle and subtalar joint complex and exercise those muscles directly responsible for inversion and eversion of the subtalar joint as well as those responsible for dorsal and plantar flexion of the ankle joint. This device claims the setup of using two hydraulic pistons to actuate the movement as well as a means for attaching the device to the leg. The pistons provide the movement of the ankle in range of motion exercises but can also be used as resistance in strengthening exercises. The operation of the device as well as the design to use two hydraulic pistons in this arrangement is the focus of this patent (see Figure 11) [36].
2.2.5 Patent: Range of Motion Exercise Device (#7322914)

This patent claims using elastic members extended between the frame portion and the foot support to supply tension to resist motion of the body contact member relative to the frame portion. This resistance of the members provides the resistance to the range of motion exercises. An adjustable pivot member, shown as 74, provides an adjustable point to base the range of motions around. The moving pivot point as well as the elastic resistance provides the movement and resistance required for an ankle workout (see Figure 12) [37].

Figure 11: Ankle Rehabilitation Device, Patent 5,215,508
2.2.6 Patent: Ankle Rehabilitation and Conditioning Device(#5722919)

This patent describes a device for attaching weights to the sole of a person’s foot or shoe. With the leg properly supported, the device can provide resistance in all degrees of freedom. To adjust the amount of resistance, weights can be removed or added and their position on the mounting platform can be changed. The patent also takes into account the possibility of adding isolation features to limit the movement of the device when in use, allowing for better control of the exercises. This patent claims using removable weights in a cantilever arrangement to provide the resistance. To adjust the resistance weights can be either added or removed or slid to a different location on the foot (see Figure 13) [38].
2.2.7 Patent: Ankle Exercise Device (#6821235 B1)

This device claims that it is an easily transported device which could be assembled and disassembled in a very convenient way. There is a foot-engaging element that can move in a spherical pattern and has resistance to movement generated by elastic straps. And those straps can be added, changed or removed to adjust the resistance to the exact pattern required to achieve maximum benefit for the user (See Figure 14) [39].

Figure 13: Ankle Rehabilitation and Conditioning Device, Patent 5,722,919
2.2.8 Patent: Electromechanical Exercise Apparatus (USD542,867 S)

This device, the Ijoy Board, is a balance trainer. Users stand on the non-slip balance trainer platform, select the program and speed using the infrared wireless remote control, and experience the excitement and exercise benefits of a realistic board ride. It is an interactive way to train the users’ leg and core muscles right at home [40].
2.2.9 Patent: Ankle Rehabilitation System (#6162189)

This system is designed for rehabilitating an ankle in which a mobile platform receives a patient's foot. The mobile platform can be moved in six degrees of freedom, and the position and orientation of the mobile platform is measured. The force exerted by the foot against the mobile platform is also measured in six degree of freedom. And all those signals are forwarded to an electronic interface and fed to a programmable computer. The programmable computer determines desired force feedback to be applied by the controller interface to the mobile platform. The desired feedback signal moves the mobile platform to a desired position or applies a desired force or torque to the mobile platform. The whole system can include simulation of virtual objects which can be moved by the user to simulate an exercise. (see Figure 16) [41].

Figure 16: Ankle Rehabilitation System, Patent: 6,162,189
## 2.2.10 Patent Summary

The following table, Table 3, summarizes the key points from the patent above in relation to the design needs.

<table>
<thead>
<tr>
<th>Patent</th>
<th>Relevant Claims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle Rehabilitation Device (#5,368,536)</td>
<td>Using a two bar linkage coupled to a spring to provide resistance to a portable ankle rehabilitation device</td>
</tr>
<tr>
<td>Exercise Device for Foot, Ankle, and/or Shin (#7,364,534)</td>
<td>A portable ankle device where two axes intersect to provide the range of motion</td>
</tr>
<tr>
<td>Ankle Rehabilitation Device (#6,277,057)</td>
<td>An ankle rehabilitation device in which the foot platform is connected to the base by a ball and socket joint and maneuvered by three hydraulic pistons</td>
</tr>
<tr>
<td>Ankle Rehabilitation Device (#5,215,508)</td>
<td>The design of a inversion and eversion based rehabilitation device using two pistons</td>
</tr>
<tr>
<td>Range of Motion Exercise Devices (#7,322,914)</td>
<td>An ankle rehabilitation device in which the foot platform is supported by elastic members and pivots about an adjustable balance point</td>
</tr>
<tr>
<td>Ankle Rehabilitation and Conditioning Device (#5,722,919)</td>
<td>An ankle rehabilitation device that uses removable weights in a cantilever arrangement to provide adjustable resistance to the ankle’s range of motion</td>
</tr>
<tr>
<td>Ankle Exercise Device (#4,337,939)</td>
<td>An adjustable resistance ankle rehabilitation device that can be assembled and disassembled easily.</td>
</tr>
<tr>
<td>Electromechanical Exercise Apparatus (USD542,867 S)</td>
<td>An Interactive Balance Trainer</td>
</tr>
<tr>
<td>Ankle Rehabilitation System (#5,429,140)</td>
<td>An integrated virtual reality system that is incorporated with a force, position feedback ankle mobile platform for rehabilitation</td>
</tr>
</tbody>
</table>
2.3 Current State of Art Orthotic Products and Prototypes

2.3.1 Wobble Board

The wobble board, also known as a balance board, is a wooden or plastic platform with a semi sphere, usually made from rubber, attached to the bottom of the board (see Figure 17). The board is used extensively for balance exercises to help prevent ankle injury and to increase range of motion and strength in the ankle after an injury. When in use, the patient stands on the platform and attempts to balance on it. Slight shifts in the patient’s center of gravity will cause the board to shift, forcing the patient to compensate in order to maintain balance. From these exercises, the patients hone their ankle reflexes, which is critical for proper function and prevention of injury [13].

![Wobble Board Image](image_url)
2.3.2 UC Santa Barbara Device

This device consists of a platform with a post in each corner and a ring suspended at the center by eight elastic bands (see Figure 18). It can provide resistance in three degree-of-freedom. And compared to the commonly used elastic band, it can provide more resistance. The device is constructed from aluminum and elastic polymers, it is lightweight and inexpensive to manufacture. Also, the design itself allows for ease of portability.

The design does not have sensors, so it is impossible for the therapist to make a quantitative assessment of the patient’s progress [42].

2.3.3 Ankle Foot Orthosis at University of Delaware (AFOUND)

This ankle foot orthosis is developed by University of Delaware. As shown in Figure 19: Ankle Foot Orthosis at University of Delaware Figure 19, the AFOUND is a two DOF ankle device which is composed of three links connected by two revolute joints corresponding to the three segments. The object of this device is to measure the forces and torques applied by the human during Dorsiflexion/Plantarflexion and
Pronation/Supination motion. They used Newton-Euler analysis to convert the raw force-torque sensor and encoder data into joint forces and torques. Thus, this orthosis can be used as a standalone measurement device to measure the joint forces and moments applied by the human at both ankle joints [16].

Figure 19: Ankle Foot Orthosis at University of Delaware

2.3.4 Robotic Gait Trainer at Arizona State University (RGTASU)

Bharadwaj et al. at Arizona State University developed a robotic gait trainer for rehabilitation of an injured ankle. The goal was to create a lightweight robotic device that could be worn for safe retraining an ankle that was paralyzed as a result of a stroke. The
device uses a tripod design, with two actuators serving as two of the tripod legs and the patient's leg as the third.

The RGT is a tripod mechanism, where the patient’s leg is the fixed link, consisting of a flat plate and two bi-directional actuators. It is controlled by a Matlab and Simulink platform. The actuators provide variable resistance based on user inputs. This design is also referred to as “spring-over-foot” and is shown below in Figure 20.

The main drawback of this device is that it only allows movement in the dorsiflexion/plantar-flexion. And the weight and bulkiness seem to be a problem when the stroke patients wear it.
2.3.5 Powered Ankle-foot Orthosis at University of Michigan (PAFO)

The goal of this device is intended as a tool for studying gait biomechanics and rehabilitation after neurological injury, and it is the improved prototype of their previous powered ankle-foot orthosis (see Figure 21).

![PAFO Diagram]

**Figure 21**: Powered Ankle-foot Orthosis at University of Michigan

This PAFO consists of a carbon fiber and polypropylene shell wrapping around the leg, a steel hinge joint connecting footplate and the shell. It has two artificial pneumatic muscles to provide dorsiflexor and plantar flexor torques about the ankle. Due to the pneumatic actuators, this device is effective in producing high external torques. The two
artificial pneumatic muscles are controlled by proportional myoelectric control. This robotic exoskeleton device could provide planter flexion torque at the ankle, but lacks of inversion/eversion movement control [18].

2.3.6 Ankle Dorsiflexion Plantarflexion Exercise Device (ADPED)

This device is a passive motion exercise device for ankle dorsiflexion/plantarflexion. The ADPED is expected to relieve pain during motion exercise as well as increase the contact area between the footplate and the patient’s sole, and the exert force becomes more efficient. All the trainings on this device would be conducted in a sitting position. Three the prototypes are developed as shown in Figure 22, from the left to the right is the first, second, and third prototype.

![Ankle Dorsiflexion Plantarflexion Exercise Device](image)

Figure 22: Ankle Dorsiflexion Plantarflexion Exercise Device

2.3.7 Rutgers Ankle (RA)

This device is the most famous ankle device in the rehabilitation area. It is developed for allowing remote monitoring by therapists. The system allows patients to perform various of exercises with a virtual environment. Patients can develop strength, flexibility, and coordination with this device.
As shown in Figure 23, the Rutgers Ankle incorporates a Stewart platform, which utilizes six pneumatic pistons working in parallel to create a 6 DOFs platform. When in use, the RA is interfaced with a virtual reality software which guides the patient’s movements and controls the force feedback of the platform.

This is an excellent device for ankle rehabilitation, but presently can only operate in a seated position and does not offer balance control training. In addition, it is not commercially available, and would likely be expensive to produce due to its use of expensive sensors and actuators [20].

2.3.8 Balance Master

The Balance Master is developed by provides objective assessment and retraining of the sensory and voluntary motor control of balance with visual biofeedback. The System utilizes a fixed 18” x 60” dual force plate to measure the vertical forces exerted by the patient's feet.
The interactive technology and clinically proven protocols allow the clinician to objectively and systematically assess sensory and voluntary motor components of balance control. The objective data helps the clinician accurately identify underlying impairments for more effective treatment planning [43].

![Balance Master](image)

**Figure 24: Balance Master**

### 2.3.9 Dynamometer Based Rehabilitation System

The Biodex System 4 is a device that is currently in production and commercially available as shown in Figure 25. It features five different modes of operation to facilitate different rehabilitation requirements depending on the injury and the plan for treatment. For use, the patient places his or her foot in the sleeve on the device and performs circular motions with his or her foot. Kits are also available for knee, hip, elbow, wrist and shoulder rehabilitation.
The device’s passive mode is used primarily for range of motion exercises. In this setting, the device uses a torque limit to control the maximum amount of torque applied to the patient’s joint and only allows movement if the applied torque is below the limit set. This mode also uses speed controls, with lower speeds being useful for extending the range of motion in the joint. The major drawback of the device is its size. The Biodex System 4 requires sixty four square feet of floor space [44].

2.4 Conclusion

From the previous sections it is seen that a variety of devices with the different technologies and concepts have been developed for ankle rehabilitation purposes. Each of these device and technologies has their advantages and disadvantages. For example, The RGT, PAFO, and ADPED are useful devices to assist patients during actual walking. However, they do not address the balance component of training, or comprehensive
training of ankle motion and strength control in all planes of movement. Furthermore, they do not offer an interactive virtual-reality based interface. And the Rutgers ankle device presently can only operate in a seated position and does not offer balance control training. In addition, it is not commercially available, and would likely be expensive to produce due to its use of expensive sensors and actuators.

Therefore it is concluded that there lies an opportunity in terms of technology as well as from a commercial point of view to develop a new breed of low cost ankle rehabilitative device.
3 CONCEPT AND PROTOTYPE DEVELOPMENT

3.1 Design Needs

Preliminary concepts for an ankle rehabilitation device which helps patients who are suffering from neurological disorders such as a stroke or Multiple Sclerosis have been defined. The proposed design will be able to help patients regain their function, ankle strength, full range of motion and motor control in their ankle. The device should also be able to track the ankle motion in sitting and standing positions, measure torque produced in DF/PF and Inversion/Enversion, and assess balance via COP measurements. A virtual reality visual feedback system for the device is also planned.

3.1.1 Balance Training Exercise

The primary function of this device is to help neurological patients train their balance function by practicing shifts in their center of pressure (COP) with feet in different configurations. When feet are fixed, such shifts are primarily controlled by the muscles around the ankle. One feature of the device is that there are four load cells to measure the force and position of center of the pressure. By trying to shift the weight on to one of their feet, patients train their motor control and sense of balance.

Some weight shifting training games and certain training protocol would be applied into the training process, and all the data including time, force, position would be recorded while in the training.
3.1.2 Range of Motion Exercise

The second main function of this device is to help neurological patients regain full range of motion in their ankle. One feature of the device is that it will be designed in a way that will allow for motion in plantar flexion, dorsiflexion, inversion and eversion. Means will also be devised to limit motion in some of these directions. For example, motion in inversion can be limited when working with a patient who has difficulty performing dorsiflexion with eversion. Since neurological patients tend to have their foot default to an inversion and plantar flexion position, dorsiflexion and eversion will be the main focus.

There are a number of simple devices available that could be adapted for use with a neurological patient. The device should have a means of keeping the foot attached to the surface of the device, which could be accomplished in a number of ways. The exercises for regaining range of motion in the ankle are well known and this design will be able to perform them.

3.1.3 Motion Tracking

For the virtual reality function, there will be a set of sensors on the device to accurately track motion of the device in all degrees of freedom. Fortunately there are a number of sensors that can be adapted to do this. The release of the Nintendo Wii demonstrates that motion-tracking technology can be successfully used for a virtual reality system.

Accurate sensors will be necessary so that the device can detect even very small movements. This will allow patients whose range of motion is very limited at the beginning of rehabilitation to effectively use the device.


### 3.2 Design Specifications

The design specifications have been generated with a device that is to be used by a sitting patient for range of motion exercises. These parameters are covered in Table 4: Design Specifications.

#### Table 4: Design Specifications

<table>
<thead>
<tr>
<th>Design Specification</th>
<th>Corresponding Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees of Freedom</td>
<td>2 (Plantar/Dorsiflexion and Eversion/Inversion)</td>
</tr>
<tr>
<td>Functions</td>
<td></td>
</tr>
<tr>
<td>• Dorsiflexion</td>
<td>Motion Sensing and Angle.</td>
</tr>
<tr>
<td>• Plantarflexion</td>
<td>Motion Sensing and Angle.</td>
</tr>
<tr>
<td>• Inversion</td>
<td>Motion Sensing and Angle.</td>
</tr>
<tr>
<td>• Eversion</td>
<td>Motion Sensing and Angle.</td>
</tr>
<tr>
<td>Range of Motion</td>
<td></td>
</tr>
<tr>
<td>• Dorsiflexion</td>
<td>0–45°</td>
</tr>
<tr>
<td>• Plantarflexion</td>
<td>0–45°</td>
</tr>
<tr>
<td>• Inversion</td>
<td>0–13°</td>
</tr>
<tr>
<td>• Eversion</td>
<td>0–13°</td>
</tr>
<tr>
<td>Measurement System – Motion</td>
<td></td>
</tr>
<tr>
<td>• Accuracy</td>
<td>Able to track motion in real time</td>
</tr>
<tr>
<td>Measurement System - Position</td>
<td></td>
</tr>
<tr>
<td>• Range</td>
<td>360°</td>
</tr>
<tr>
<td>• Resolution</td>
<td>1024/revolution</td>
</tr>
<tr>
<td>Virtual Reality</td>
<td></td>
</tr>
<tr>
<td>• Computer Interface</td>
<td>USB</td>
</tr>
<tr>
<td>• Feedback</td>
<td>Graphic interface</td>
</tr>
<tr>
<td>• Data Logging</td>
<td>Yes</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>Must prevent falls.</td>
</tr>
<tr>
<td>Force</td>
<td></td>
</tr>
<tr>
<td>• Max Weight Supported</td>
<td>300lb</td>
</tr>
<tr>
<td>Torque</td>
<td></td>
</tr>
<tr>
<td>• Dorsi/Plantarflexion</td>
<td>0 – 15 Nm</td>
</tr>
<tr>
<td>• Inversion/Eversion</td>
<td>0 – 5 Nm</td>
</tr>
<tr>
<td>Research</td>
<td></td>
</tr>
<tr>
<td>• Polhemus</td>
<td>Device must be minimally ferrous</td>
</tr>
<tr>
<td>• Force sensing</td>
<td></td>
</tr>
</tbody>
</table>
The parameters of the device were determined through research of ankle anatomy and mechanics. Existing devices were also reviewed, as were patents for mechanisms that were already used. An interview with Professor Holden provided a need for a rehabilitation device for those who have suffered brain damage or neurological ailments, such as a stroke. For these patients, regaining range of motion and flexibility in the joint is the one focus of their rehabilitation and this device needs to facilitate that. Other important needs are strengthening muscles, and improving motor control, especially to increase the speed of reciprocal motions and to regain the ability to rapidly generate torque.

Since range of motion is a relevant parameter of the device, the device needs to be able to allow motions of up to full plantarflexion to full dorsiflexion and full inversion to full eversion. The range of motion is along two axes, the first being plantar and dorsiflexion while the second is inversion and eversion. Many neurological patients have problems with active dorsiflexion and eversion control. Their resting ankle position maybe plantarflexion-inversion. Since strength building is a goal of this device, resistance to movement should be adjustable and the device should be able to rest in the patient’s current ‘neutral’ position. Adjustable mechanical stops are also needed to allow the therapist to restrict certain movements during practice. The device needs to have a means of determining its position relative to a default position. This can either be 0° for both axis, which is the position of the ankle for a healthy individual with the plane of the foot perpendicular to the leg, or from a position set as default at the beginning of the exercise session. The position must also be taken continuously and accurately for the device to perform its function. To measure the position, the angles of the foot along the two axes
relative to neutral must be known. Thus, the sensor system must either directly measure the angle or measure the parameters needed to calculate those angles. Presently, the device can be interfaced with a Polhemus motion tracker sensor for this purpose. This sensor, attached to the bottom side of the foot plate, will yield 6DOF motion information, corresponding to DF/PF and inversion/eversion of the foot.

Virtual reality will be a major function of this device. To accomplish this, the device will need to interface with a computer for data recording and visual feedback. Presently, this could be done by an existing VR system by using a polemus motion tracker system [45]. To do this, a USB connection will be required as well. Also, a graphic interface will need to be developed that will allow the parameters of the exercises to be entered and any games that are developed for use with this device to be easily accessed. Another function for consideration would be having the software upload the data collected during the exercise session to a server where the patient’s doctor or physical therapist can review the results and monitor progress remotely.

The device needs to be able to support the full weight of a 300lbs person with a factor of safety of two. It must also accommodate the increased forces that would be generated by a 300 lb person moving quickly to avoid a fall. Also, the device needs to have means to prevent the patient from falling. Stroke patients may have impaired balance. To help keep them upright, the device should have a support platform with support rails for the patient to hold on to. For weaker patients, a safety harness may be added as well.
3.3 Design Concept

Four different design concepts were developed with the design specification and design needs in mind. While brainstorming it was determined that the project could go in two directions; the device could be a wearable device or it could be an external device. The following sections go into further detail and explain each concept.

3.3.1 Current Ankle Device Design Concept

The following are showing the current ankle device design concepts. Including wearable ankle rehabilitation device and training platform ankle rehabilitation device.

3.3.1.1 Wearable Ankle Rehabilitation Device

Wearable rehabilitation devices are those which could be worn on patients, like exoskeleton, it is used in training or assisting activities in daily life. Usually, support structure, actuators, and sensors would be added in this device in order to realize the required function. Figure 26 is showing a simple idea of this design concept.
3.3.1.2 Training Platform Ankle Rehabilitation Device

The design of training platform would be operated by tilting the platform from its neutral position by moving a weight away from the apex of the foot platform. Similar to the childhood game “Tilt Maze” the second platform has two frames which can move independently of each other; one frame moving the foot in plantar and dorsiflexion while the other moves the foot in eversion and inversion (see Figure 27). By allowing the patient to stand on a platform that is equidistant from the ground as the platform that is working the ankle, the patient is able to maintain the neutral position and therefore targeting the affected areas instead of putting added stress on the leg not being used in the exercise. For added stability a bar, which is attached to the base of the device, allows the patient to hold on.

Figure 27: Training Platform
3.4 Northeastern University Virtual Ankle and Balance Trainer (NUVABAT)

Based on those concepts and specifications as discussed in the former sections, the final prototype of the device has the following specifications:

Table 5 : NUVABAT Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Resistance Torque on PF/DF</td>
<td>0.25-15Nm</td>
</tr>
<tr>
<td>Passive Resistance Torque on Inversion/Eversion</td>
<td>0.25-6Nm</td>
</tr>
<tr>
<td>Range of Motion on Plantarflexion</td>
<td>0-45°</td>
</tr>
<tr>
<td>Range of Motion on Dorsiflexion</td>
<td>0-45°</td>
</tr>
<tr>
<td>Range of Motion on Inversion</td>
<td>0-13°</td>
</tr>
<tr>
<td>Range of Motion on Eversion</td>
<td>0-13°</td>
</tr>
<tr>
<td>Overall Length</td>
<td>24.3”</td>
</tr>
<tr>
<td>Overall Width</td>
<td>16.6”</td>
</tr>
<tr>
<td>Overall Height</td>
<td>14.6”</td>
</tr>
</tbody>
</table>

3.4.1 NUVBAT Assembly

Due to the complexity of the design, it will helpful to explain the overall assembly first and then followed by the descriptions of each of the individual components in the sections to follow. The final design of NUVABAT is as shown in Figure 28.

The NUVABAT system consists of a small 2 DOF moveable platform housed within a larger stable platform. The inner smaller platform can move about a med-lat axis, while the outer platform moves about an anterior-posterior axis, thus accommodating all possible ankle motions, PF/DF, and inversion/eversion. With the anterior-posterior and medial-lateral moving at once, the patients could also perform circumduction. Adjustable mechanical stops allow the practitioner to change the range of motion of the device to suit the needs of the patient. Magneto-Rheological Fluid (MRF) brakes allow for variable resistance to be set in either or both axes, to accommodate the strength capabilities of the
patient. These components are used for ankle mobility and strength training. Motions of the platform (and thus the ankle) can be monitored in 3D using a Polhemus electromagnetic tracker (capable of 6 DOF tracking) attached to the bottom of the foot plate box. This will allow the NUVABAT device to be interfaced with a virtual reality (VR) display [45]. Various VR scenes can make the exercise more fun and interesting, thus increasing motivation of the patient to perform the rehabilitation movements. Practitioners will be able to adjust the exercise difficulty and quantitatively measure the patient’s performance.

Figure 28 : NUVABAT Assembly
Four load cells are incorporated into the platform. These sensors are used to calculate the center of the pressure of the applied forces that are normal to the platform. With the footplate locked in a flat position (parallel to the floor) the device can be used for balance and weight shift training in the standing position (See Figure 30). For advanced balance training, the footplate can be unlocked, and the patient can practice controlled ankle movements, with or without resistance, in the standing position. This function will require the addition of actuators to safely control ankle movement while standing on platform.

For ankle range of motion training, a patient would place his/her foot on the footplate (see Figure 29) in either a standing position or a seated position. Depending on the requirements of the VR game interface that has been selected, the patient would try to reach different position targets set by the game. Resistance on anterior-posterior and medial-lateral axes would only be used in the sitting position unless the patient is highly advanced in skill. For balance training, patients would stand on the platform, and then apply force to the footplate, attempting to shift their weight to different locations in the standing position.
The passive resistance torque on PF / DF and inversion / eversion can be adjusted by changing the input voltage of MRF damper in control interface according to the patient’s abilities, and the feedback signals of the forces and footplate position and orientation are sent to the host computer, recorded in the patient’s database, and used to implement the VR displays.

Also, a support platform was built for the safety factor of the patient. It’s a aluminum structure platform which the support rails are built from PVC bars (see Figure 30). This platform allows patents to work on standing balance training as shifting or stepping.
In summary, the NUVABAT device, shown in Figure 28 & Figure 29, consists of the haptic interface, sensors, MRF brakes, MRF brake controllers, torque amplifying mechanism, the host computer, support structural and the standing platform.

The Table 6 below is the list of the bill of materials for NUVABAT of the very first design.
<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Supplier</th>
<th>Qty</th>
<th>Price</th>
<th>Total Price</th>
</tr>
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<tr>
<td>Platform top</td>
<td>6x13 1/4&quot; Lexan</td>
<td>Ace Glass Company</td>
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<td>10</td>
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<tr>
<td>Platform Insert</td>
<td>Plywood</td>
<td>JT</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Platform Bottom</td>
<td>Hard Maple 1X5X6</td>
<td>Wightman Specialty Woods</td>
<td>1</td>
<td>9.36</td>
<td>18.72</td>
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<tr>
<td>Long Lip</td>
<td>Cherry</td>
<td>JT</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Short Lip</td>
<td>Cherry</td>
<td>JT</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Felt Lining for Lips</td>
<td>Felt strips</td>
<td>Ace Hardware</td>
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<td>3.79</td>
<td>7.58</td>
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<td>Dorsi Shaft</td>
<td>1&quot;D by 1’ L Aluminum shaft 88615K441</td>
<td>Mcmaster</td>
<td>1</td>
<td>18.35</td>
<td>3.67</td>
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<td>Straps</td>
<td>Velcro Straps</td>
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<td>2</td>
<td>0</td>
<td>0</td>
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<td>Flanged Shaft Mount</td>
<td>62645K43 for 1&quot; shaft</td>
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<td>3</td>
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<td>7.34</td>
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<tr>
<td>Plantar Dorsi Bearings</td>
<td>IGUS KSTI-16 Pillow Blocks</td>
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<td>0.99</td>
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<td>Frame Right</td>
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<td>Copper Counter Weight</td>
<td>Copper Cylander</td>
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<td>0</td>
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<td>Copper Wire</td>
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<td>0</td>
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<td>Lowes</td>
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<td>0</td>
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<td>500lb force sensor</td>
<td>Honeywell</td>
<td>4</td>
<td>400</td>
<td>1600</td>
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<tr>
<td>Brake rod</td>
<td>.5&quot;D by 3'L Aluminum Shaft 88615K27</td>
<td>Mcmaster</td>
<td>2</td>
<td>32.62</td>
<td>43.38</td>
</tr>
<tr>
<td>Rubber Stops</td>
<td>.5&quot; ID Rubber Tube 9697K237</td>
<td>Mcmaster</td>
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<td>11.33</td>
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Table 6 continues to page 50
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<tr>
<th>Item</th>
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<td>Rotational Damper</td>
<td>Lord MRF Damper</td>
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<td>Damper Controller</td>
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<td>0.23</td>
<td>48.82</td>
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<td>1.95</td>
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<td>80/20</td>
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<td>3059 1/4-20 button head socket cap screws 3/8 L</td>
<td>80/20</td>
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<td>3061 1/4-20 button head socket cap screws 1/2L</td>
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<tr>
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<td>16.61</td>
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<td>Connecting Plate</td>
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<td>16.61</td>
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<td>0</td>
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<td>Thread inserts</td>
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49
<table>
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<tr>
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<td>Lowes</td>
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<td>0</td>
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<td>Washers</td>
<td>M4 Washers</td>
<td>JT</td>
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<td>0</td>
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### 3.4.2 Cable Drive Torque Amplify Mechanism Design

Because the muscles on the patient's anterior leg which control PF/DF movement produce much higher torque than the muscles which control inversion / eversion movements, the MRF damper cannot be used to directly drive the foot plate on PF/DF. The device needs a torque amplify mechanism on the PF/DF for the MRF damper (See Figure 31).

With comparing several concepts of this torque amplify mechanism including gearbox, timing belt, cable drive, we finally decided on doing the cable drive, for the building price and the compact factor.
To achieve a compact design, an amplification mechanism consisting of two round gears, steel pulley, steel wire and support structure is placed on the bottom of device. Three sections of steel wire, which wrap around the two round gears and the steel pulley, are fixed by set screws on the gears. The turning buckles between them are used for tightening the steel wire to provide enough friction to drive the big gear that rotates with the MRF damper. Due to the tightness of the steel wire, there is no backlash on the anterior-posterior movements. The steel wire transmits the force from the MRF damper to the big gear. The ratio of the gear on the brake shaft to the gear on the PF / DF shaft is 1:2.5. Thus, the resistance torque is amplified by 2.5 times, and the range of the torque of the PF / DF would be from 0.25-15Nm.

For the detailed design, most components are bought from McMaster website, and the components sheet is listed below (Table 7).

![Figure 31: Cable Drive Torque Amplify Mechanism](image-url)
For the detailed design, most components are bought from McMaster website, and the components sheet is listed below (Table 7).

Table 7: Bill of Materials for Torque Amplifier Parts

<table>
<thead>
<tr>
<th>Component</th>
<th>Part Number</th>
<th>Material</th>
<th>Supplier</th>
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</tr>
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<td>aluminum</td>
<td>McMaster</td>
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<td>90494A029</td>
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<td>McMaster</td>
<td>$1.08</td>
<td>1</td>
<td>$1.08</td>
</tr>
<tr>
<td>Plastic sheet</td>
<td>8739K55</td>
<td>delrin</td>
<td>McMaster</td>
<td>$55.72</td>
<td>2</td>
<td>$111.44</td>
</tr>
<tr>
<td>Precision Ball Pulley</td>
<td>3434T24</td>
<td></td>
<td>McMaster</td>
<td>$6.36</td>
<td>1</td>
<td>$6.36</td>
</tr>
<tr>
<td>Shims 0.01&quot;</td>
<td>93574A711</td>
<td>steel</td>
<td>McMaster</td>
<td>$8.59</td>
<td>1</td>
<td>$8.59</td>
</tr>
<tr>
<td>Shims 0.3mm</td>
<td>98055A221</td>
<td>steel</td>
<td>McMaster</td>
<td>$6.45</td>
<td>1</td>
<td>$6.45</td>
</tr>
<tr>
<td>Shoulder Screw</td>
<td>91259A632</td>
<td>steel</td>
<td>McMaster</td>
<td>$1.69</td>
<td>1</td>
<td>$1.69</td>
</tr>
<tr>
<td>Socket Cap Screw</td>
<td>90128A607</td>
<td>steel</td>
<td>McMaster</td>
<td>$6.49</td>
<td>1</td>
<td>$6.49</td>
</tr>
<tr>
<td>Socket Cap Screw</td>
<td>90128A254</td>
<td>steel</td>
<td>McMaster</td>
<td>$4.46</td>
<td>1</td>
<td>$4.46</td>
</tr>
<tr>
<td>Socket Cap Screws</td>
<td>92196A242</td>
<td>steel</td>
<td>McMaster</td>
<td>$6.52</td>
<td>1</td>
<td>$6.52</td>
</tr>
<tr>
<td>Socket Cap Screws</td>
<td>90128A226</td>
<td>steel</td>
<td>McMaster</td>
<td>$6.56</td>
<td>1</td>
<td>$6.56</td>
</tr>
<tr>
<td>Socket Cap Screws</td>
<td>92220A187</td>
<td>steel</td>
<td>McMaster</td>
<td>$12.64</td>
<td>1</td>
<td>$12.64</td>
</tr>
<tr>
<td>Socket Cap Screws</td>
<td>90128A586</td>
<td>steel</td>
<td>McMaster</td>
<td>$7.07</td>
<td>1</td>
<td>$7.07</td>
</tr>
<tr>
<td>Socket Cap Screws</td>
<td>92196A309</td>
<td>steel</td>
<td>McMaster</td>
<td>$3.29</td>
<td>1</td>
<td>$3.29</td>
</tr>
<tr>
<td>Steel wire</td>
<td>3461T63</td>
<td>steel</td>
<td>McMaster</td>
<td>$1.69</td>
<td>10</td>
<td>$16.90</td>
</tr>
<tr>
<td>Washer</td>
<td>91090A110</td>
<td>steel</td>
<td>McMaster</td>
<td>$3.65</td>
<td>1</td>
<td>$3.65</td>
</tr>
<tr>
<td>Washer</td>
<td>98032A466</td>
<td>steel</td>
<td>McMaster</td>
<td>$1.99</td>
<td>1</td>
<td>$1.99</td>
</tr>
<tr>
<td>Washer</td>
<td>94744A233</td>
<td>steel</td>
<td>McMaster</td>
<td>$4.09</td>
<td>1</td>
<td>$4.09</td>
</tr>
<tr>
<td>Washer</td>
<td>91090A112</td>
<td>steel</td>
<td>McMaster</td>
<td>$5.10</td>
<td>1</td>
<td>$5.10</td>
</tr>
<tr>
<td>Washer</td>
<td>91083A029</td>
<td>steel</td>
<td>McMaster</td>
<td>$3.73</td>
<td>1</td>
<td>$3.73</td>
</tr>
<tr>
<td><strong>Total Price</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$818.01</strong></td>
</tr>
</tbody>
</table>
3.4.3 Foot Plate Design

In order to measure the force and the center of pressure on the foot plate, four load cells are placed on the corners. To locate those load cells, a thin plastic position sheet was built. Thus, the load cells are steadily hold in place and the wires could go through those channels on the sheet (see Figure 32).

Since the load cell’s measuring range is from 5 lbs to 500 lbs, the preload is needed to keep the precision of the measuring. So two disc springs are added between each set of the washer and nut to keep the foot plate from loosen. Due to the two disc springs, the preload can be up to 30 lbs on each load cell by strengthening the screws.

Figure 32 : Foot Plate Design
The outer frame of the wooden box is designed and machined by undergraduate students of capstone team. It is constructed out of American maple. Figure 33 shows the foot plate which was plunge-routed out of a single piece of wood.

![Wooden Foot Plate Fabrication](image)

**Figure 33 : Wooden Foot Plate Fabrication**

Below the Table 8 is the plus bill materials for the foot plate.

**Table 8 : Bill of Materials for the Foot Plate**

<table>
<thead>
<tr>
<th>Component</th>
<th>Part Number</th>
<th>Material</th>
<th>Supplier</th>
<th>Price</th>
<th>Units</th>
<th>Qty</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>8702K69</td>
<td>Polyethylene</td>
<td>McMaster</td>
<td>$5.92</td>
<td>1</td>
<td>2</td>
<td>$11.84</td>
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<tr>
<td>Aluminum</td>
<td>8975K373</td>
<td>Aluminum</td>
<td>McMaster</td>
<td>$43.19</td>
<td>1</td>
<td>1</td>
<td>$43.19</td>
</tr>
<tr>
<td>Washer</td>
<td>91083A029</td>
<td>Steel</td>
<td>McMaster</td>
<td>$3.73</td>
<td>222</td>
<td>1</td>
<td>$3.73</td>
</tr>
<tr>
<td>Disc Springs</td>
<td>9713K61</td>
<td>Stainless Steel</td>
<td>McMaster</td>
<td>$4.35</td>
<td>12</td>
<td>1</td>
<td>$4.35</td>
</tr>
<tr>
<td>Socket Cap Screw</td>
<td>92196A245</td>
<td>Stainless Steel</td>
<td>McMaster</td>
<td>$7.94</td>
<td>100</td>
<td>1</td>
<td>$7.94</td>
</tr>
<tr>
<td>Socket Cap Screw</td>
<td>92210A113</td>
<td>Stainless Steel</td>
<td>McMaster</td>
<td>$5.94</td>
<td>100</td>
<td>1</td>
<td>$5.94</td>
</tr>
<tr>
<td>Socket Cap Screw</td>
<td>92196A543</td>
<td>Stainless Steel</td>
<td>McMaster</td>
<td>$6.40</td>
<td>25</td>
<td>1</td>
<td>$6.40</td>
</tr>
<tr>
<td>Socket Cap Screw</td>
<td>90128A226</td>
<td>Steel</td>
<td>McMaster</td>
<td>$6.56</td>
<td>25</td>
<td>1</td>
<td>$6.56</td>
</tr>
<tr>
<td><strong>Total Price</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$89.95</strong></td>
</tr>
</tbody>
</table>
3.4.4 Foot Binding Suit

The footplate is an aluminum plate with 14.00” length, 7.00” width and 0.375” thickness. There are tapped holes on both sides of the heel cup and the aluminum pieces that fix the positions of the foot binding cover and the toe binding strap. The heel cup guarantees the patients to start practice from the same position each time. The foot binding helps the patients to get better training of their tibialis anterior when they are doing dorsiflexion movement. Adjustable locations of those bindings make it fit for different sizes of foot. The foot binding cover and toe binding strap are off-the-shelf products. The heel cup is built from rapid-prototyping material. Due to the safety concerns, the foot-binding would only be used in seated position training while the weight shift balance training and the standing range of motion training would not require the patient to wear them.

3.4.4.1 Toe Binding

From the test by comparing testers’ feelings on doing dorsiflexion movements on the NUVABAT with a toe strap or without a toe strap, it proved that the muscles work better on doing dorsiflexion movement when the testers strap the toe area. Modify the off-shelf products (Figure 34) or build similar kit is the best way to build up a toe strap on our device.
Finally, for the easy adjustability, a toe binding design shown in Figure 35 was developed. A long strap and two custom machined connecting parts are the whole toe binding kit. It is easy to adjust the position and can be very tight for the toe.

3.4.4.2 Foot Binding

Off-shelf product “Flow” snow foot binding kit was directly used in our device this time, with two more custom machined connecting parts (see Figure 36).
3.4.4.3 Heel Cup

In order to get a suitable shoe heel curve, several different sizes of shoes are measured and marked seven points on each curves (Table 9), so we would know what kind of curves could fit for the shoes. Drew a vertical center line, drew three horizontal lines on the points of 0.4 inch, 0.8 inch and 1.2 inch to the bottom of the curve. Measure the length of the horizontal lines.

<table>
<thead>
<tr>
<th>Shoe Size</th>
<th>center</th>
<th>0.4&quot;</th>
<th>0.8&quot;</th>
<th>1.2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0&quot;</td>
<td>1.74&quot;</td>
<td>2.34&quot;</td>
<td>2.66&quot;</td>
</tr>
<tr>
<td>9</td>
<td>0&quot;</td>
<td>2.1&quot;</td>
<td>2.75&quot;</td>
<td>3.01&quot;</td>
</tr>
<tr>
<td>10</td>
<td>0&quot;</td>
<td>2.1&quot;</td>
<td>2.77&quot;</td>
<td>3.14&quot;</td>
</tr>
<tr>
<td>11</td>
<td>0&quot;</td>
<td>2.34&quot;</td>
<td>3.04&quot;</td>
<td>3.4&quot;</td>
</tr>
<tr>
<td>13</td>
<td>0&quot;</td>
<td>2.34&quot;</td>
<td>3.07&quot;</td>
<td>3.52&quot;</td>
</tr>
</tbody>
</table>

Based on those data, a nice curved heel cup was designed in solidworks.
3.4.5 Mechanical Stop

Adjustable mechanical stops for both DOFs were designed. On inversion / eversion two aluminium bars are set in two curved slots. Rotating the plastic knob to tighten the plastic pad on two ends of the aluminium bar would lock its position by friction forces. (See Figure 38)
For the mechanical stop on PF/DF direction, a lead screw is used to move the whole assembly up and down. The U-channel aluminum piece is the supporting structure to hold the foot box. Thrust bearings and sleeve bears are used to reduce the friction. The key part is the fast prototype machine part which connects the position nut and the holding block (See Figure 39).

To adjust it, we can rotate the knobs on the side to move u-channel aluminium pieces upwards or downwards. These adjustable mechanical stops allow the practitioner to limit the range of motion to prevent overstretching for patients.

3.4.6 Support Platform

Patients need a platform so that both feet are supported at the same time and that they are at the same height when executing an exercise in the standing training modes (Figure 30).
The platform consists a 41” by 29” by 12.58” frame with an open top and a 21” by 29” lid, both of which are made by 80/20 aluminium extrusion. This lid could be fixed on either side of the frame in order to satisfy the requirements of switching the side of the device to train either the right or left foot. Handle bars are set on the side, clamped on the platform. Their height is also adjustable to fit for different height of patients. The real platform structure picture is shown in Figure 40.

Figure 40 : Aluminum Support Platform Structure
PVC bars are used as the support rails. Several set of holes are on the PVC bars to make the support rails adjustable. All the whole support PVC bars are fixed on the aluminum platform by eight c-clamps.

### 3.4.7 Load Cells

The four Honeywell Model-53-CR, low cost, load cells with a 5-500lb range have a very good linearity. They are placed at each one of the four corners the foot plate. Their readings are use in conjunction of the principle of moments to calculate the position of the COP which is used in the VR game. (See Figure 41)

![Honeywell Load Cell](image)

**Figure 41**: Honeywell Load Cell

### 3.4.8 Wire Sensor

Wire sensor is used to measuring the angle position of the foot plate. Four sensors were selected for this DOF (See Table 10). Based on the price and dimensions, we chose the sensor wps-50mk30 from Micro-Epsilon Company for our application.
A pulley was built by fast prototype machine to transfer the rotation into linear motion for the sensor (See Figure 42). The range of motion for Inversion/Eversion is from -13° to 13° and the diameter of the pulley is 2.6 inch, so the converting factor is 0.578 mm/°. And the resolution of the wire sensor we choose is 0.1mm, so the resolution for the angle can reach to 0.2 °. It’s much safer to keep the edge of the pulley under the edge of the foot plate, so we did not build a larger pulley to get a higher resolution for it.

Table 10: Wire Sensors

<table>
<thead>
<tr>
<th>Name</th>
<th>Price($)</th>
<th>Range</th>
<th>Resolution</th>
<th>Output</th>
<th>Company</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPS-50 MK30</td>
<td>165</td>
<td>50mm</td>
<td>0.1mm</td>
<td>Analog Voltage</td>
<td>Micro-Epsilon</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>SP1-4</td>
<td>154</td>
<td>120mm</td>
<td>1%</td>
<td>Analog Voltage</td>
<td>Celesco</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>MTA 3L-5KC</td>
<td>395</td>
<td>76mm</td>
<td>0.40%</td>
<td>Analog Voltage</td>
<td>Celesco</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>LX-PA-2-P10K-L2M-K</td>
<td>228.5</td>
<td>50mm</td>
<td>1%</td>
<td>Analog Voltage</td>
<td>UniMeasure</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>
3.4.9 Accelerometer

A DE-ACCM3D Buffered ±3g Tri-axis Accelerometer, which has up to 360mv/g sensitivity, was chosen for the plantar flexion and dorsiflexion measurement (Figure 43). Since this sensor has been used in lots of applications in our lab, it is directly chosen for the measurement on PF/DF.
The sensor needs to be vertically attached to the PF/DF shaft so as to directly measure the angle. A fast-prototype housing was designed for wrapping the sensor and attach it to the shaft (Figure 44).

![Figure 44: Accelerometer](image)

The wrap is composed of three parts. The dimension of the wrap is 1.5”x1.4”x0.85”. Two set screws will go through the three parts to hold them together.

![Figure 45: Accelerometer Wrap Exploded View](image)
3.4.9.1 Accelerometer Wrap Part A

It is the front cover of the accelerometer. In order to fix on the shaft, I made a cut in between, so it could be used as a shaft collar by tightening the screw. The rotating would not create a big torque for the wrap, so this clamp could generate enough friction to hold the wrap and sensor from sliding on the shaft.

![Figure 46: Accelerometer Wrap Part A](image)

The dimension of the square groove on the back is a little smaller than the dimension of accelerometer. With a gap left between accelerometer wrap part A and accelerometer, when tightening the set screws, the accelerometer would be well clamped in between.

![Figure 47: Section View of the Accelerometer Wrap](image)
3.4.9.2 Accelerometer Wrap Part B

Part B is a thin layer in the middle. No rotating play on the accelerometer is very important to the measurement, and two screw clearance whole is not enough precise to hold the layer from tiny play, so a position block was designed for this layer.

![Figure 48: Accelerometer Wrap Part B](image)

3.4.9.3 Accelerometer Wrap Part C

Part C is designed for the cover of the wires. The wire would be sticked on the inside wall of the cover and go through from the hole down there, so the long term rotating movements would not do any damage to the solder points to the accelerometer.

![Figure 49: Accelerometer Wrap Part C](image)
3.4.10 **Pohelmus Sensor**

Pohelmus sensor is a 3d motion tracker. By computing the position and orientation of a small sensor as it moves through space, it provides dynamic, real-time measurements of position (X, Y, and Z Cartesian coordinates) and orientation (azimuth, elevation, and roll).

The pohelmus sensor is attached at the bottom of the foot plate to get the dynamic measurement in real time. In order to protect the sensor, another fast prototype housing was design which is shown in Figure 50. As shown in figure, two parts wrap the sensor and the assembly can be put into the frontal box which is screwed into the foot plate. This allows a practioner to take the sensor out to use it into other rehabilitation application as a whole motion tracking system.

![Figure 50: Polhemus Sensor with Housing](image)
3.4.11 Damper

Since resistances are needed on both PF/DF and inversion/eversion for the training purpose, two brakes are needed on those two degree of freedoms. Several brakes were selected for this application (See Table 11). Due to the compatibility with the polhemus sensor and the lead time for the damper, we finally decide to use the MRF fluid from the LORD Company.

Adjustable resistance acting on the PF/DF and inversion/eversion is generated by two MRF brakes. An MRF brake controls its torque output by adjusting the magnetic field to change the characteristics of its magneto-rheological fluid. The adjustable magnetic field is controlled by the input current. In our device, we use LabVIEW to send a voltage signal to a digital servo amplifier which can proportionally convert the voltage signal to DC current. The output torque of the MRF brake ranges from 0.25-6Nm on inversion / eversion, which is a proper resistance range for stroke patients. However, the strength of the muscles on the patient's anterior leg which controls inversion / eversion is weaker than the one for PF / DF movements. Therefore, the resistance torque needs to be amplified on the anterior-posterior movements. To achieve a compact design, an amplification mechanism consisting of two round gears, steel pulley, steel wire and support structure is placed on the bottom of device. Three sections of steel wire, which wrap around the two round gears and the steel pulley, are fixed by set screws on the gears. The turning buckles between them are used for tightening the steel wire to provide enough friction to drive the big gear that rotates with the MRF damper. Due to the tightness of the steel wire, there is no backlash on the anterior-posterior movements. The steel wire transmits the force from the MRF damper to the big gear. The ratio of the gear
on the brake shaft to the gear on the PF / DF shaft is 1:2.5. Thus, the resistance torque is amplified by 2.5 times, and the range of the torque of the PF / DF would be from 0.25-15Nm.

Table 11 : Damper Selections

<table>
<thead>
<tr>
<th>Name</th>
<th>Torque</th>
<th>Dia</th>
<th>Thickness</th>
<th>V</th>
<th>Price</th>
<th>Leadtime</th>
<th>Company</th>
<th>Pics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange-Mounted, Electric Brakes 2.5</td>
<td>22Nm</td>
<td>125mm</td>
<td>53mm</td>
<td>24V</td>
<td>$360</td>
<td>in stock</td>
<td>New Torque Inc</td>
<td></td>
</tr>
<tr>
<td>RNB 1.6ZG</td>
<td>16Nm</td>
<td>117mm</td>
<td>45.3mm</td>
<td>24V</td>
<td>$344</td>
<td>10-12 weeks</td>
<td>Ogura</td>
<td></td>
</tr>
<tr>
<td>RNB-1.6G</td>
<td>16.3Nm</td>
<td>117mm</td>
<td>41mm</td>
<td>24V</td>
<td>$281</td>
<td>Delivery from Japan</td>
<td>Ogura</td>
<td></td>
</tr>
<tr>
<td>VCSH 2.5</td>
<td>30Nm</td>
<td>113mm</td>
<td>47.9mm</td>
<td>24V</td>
<td>$393</td>
<td>8-10 weeks</td>
<td>Ogura</td>
<td></td>
</tr>
<tr>
<td>VBSH 2.5P</td>
<td>30Nm</td>
<td>108mm</td>
<td>47.9mm</td>
<td>24V</td>
<td>$435</td>
<td>8-10 weeks</td>
<td>Ogura</td>
<td></td>
</tr>
<tr>
<td>Model FB42</td>
<td>28Nm</td>
<td>108mm</td>
<td>56.6mm</td>
<td>24V</td>
<td>$350</td>
<td>5 weeks</td>
<td>Inertia Dynamics</td>
<td></td>
</tr>
<tr>
<td>Rotary MRFBrake</td>
<td>5Nm</td>
<td>92mm</td>
<td>36.5mm</td>
<td>24V</td>
<td>$470</td>
<td>in stock</td>
<td>Lord</td>
<td></td>
</tr>
</tbody>
</table>
3.4.12 **Wire Packaging**

Since there are too many wires, it is so messy to connect those sensors directly to the data collecting box. Second, the thin wires and the amplifiers need a stable box to hold them to prevent them from breaking them by accidently dragging or pulling. Third, it becomes more convenient to disconnect the human interface part with the hardware part.

For the three reasons above, I decided to build this package box. The wires terminal is a 15slots VGA head which is ordered from L-Com. So a high quality VGA cable is used as the connecting cable between this box and the other box beside the computer (the right picture in Figure 51). The Figure 51 shows those two boxes without the top cover.

![Wire Packaging Boxes](image)

*Figure 51 : Wire Packaging Boxes*
4 SOFTWARE DESIGN

4.1 Introduction

The main training and control software for the ankle device is written in LabVIEW and 3D Panda. LabVIEW is short for Laboratory Virtual Instrumentation Engineering Workbench, and it is a platform and development environment for a visual programming language from National Instruments[46]. 3D Panda is a open source game engine, a framework for 3D rendering and game development for Python and C++ programs [47].

For the NUVABAT system, two training modes have been developed in the software: 1) Stable Mode – the platform is fixed in a stable horizontal position and the patient is standing with the involved foot on the platform. COP measures are used as inputs to a game interface for weight shifting and balance exercises; this game can be displayed on a regular computer monitor or larger VR display; 2) Dynamic Mode – in this mode, the ankle moves freely about either or both axes, and with or without resistance, as determined by the MRF damper settings. The VR software includes a virtual teacher which the patient can use to guide the movement, a variety of visual and auditory feedback features and scoring system to help gauge and measure progress and enhance patient motivation during therapy.

The following is the LabVIEW interface for the whole program is shown below in Figure 52: LabVIEW Interface for NUVABATFigure 52.
4.2 Weight Shifting Training Mode

4.2.1 Limits of Stability

The first training program is the “Limits of Stability” (See Figure 53). This test is performed with the subject standing with a comfortable base of support stance with equal amounts of weight on each leg, one foot on the foot plate, another foot on the platform. When the subject is ready, practice of the test will begin, allowing the subject to more fully understand how the device works. The subject will be able to see his center of pressure (COP) moving on the screen in front of him. A center position will be found first by asking the subject stand in a relaxed standing posture. Then, the subject shifts his weight straight forward (towards 12 o’clock) as far as possible without lifting his heel or bending his knee. When the subject is at his limit, the examiner will press the record
button that allows the computer to record the location and magnitude of COP in 10Hz. So the maximum weight shifting location and magnitude will be the average value of those data in that direction. Limits are measured in forward, backward, lateral, and diagonal planes (8 directions) with clock positions described to the subject. The subject’s results will be recorded and saved. And later, the results will be used in the Dot Game and Bar Game as the reference of the targets. The subject will step off the platform to fill out a visual analog scale (VAS) regarding his ability to balance during the test.

Figure 53: Weight Shifting Training Mode – Limits of Stability
4.2.2 Dot Game

In this game, patients stand within involved leg on the stable level foot plate, non-involved Leg on the platform (see Figure 54), and shift their weight forward, backward, diagonally, and side to side, try to follow the targets. Those targets are based on the tests results of the limits of stability, for difficult level we directly use the COP test result as the targets, and for easy level we use 80% of the LOS test result as the targets.

![Dot Game Standing Position](image)

Figure 54: Dot Game Standing Position

LabVIEW reads the signals from the load cells and gets the force magnitude and then calculates the COP position. A computer screen then displays a white frame with the same proportion as the real foot plate. A small black dot represents the COP of the patient’s involved leg. (Figure 55). The first four coloured bars on the right bottom show the force reading of the four load cells, and the yellow bar shows the total force applied.
on the foot plate. A red circle represents the target which patients would try to keep the black dot inside, under a set amount of force, during a required time period before the limit time runs out. If the black dot goes out during the time-counting period or the total force drops below the setting force, the counter would start to time. The blue bar beneath the white frame is the time which the patient has kept the black dot under the requirements, and the green bar shows how much time is left for this trial. If patients successfully keep the black dot in the target under those conditions, then the system will encourage the patients with a sign of “Good Job!” shown at the center of the frame. Then, the red dot continues to appears at the next spot. Otherwise, if the limit time runs out, a sign of “You missed it, Keep trying!” would be shown and the next target would appear at the next location.

There are two routing modes to choose in this game---predictable or random. Normally, the patients use the predictable mode to practice, so the target would appear in a sequential set of locations in a clockwise direction. In random mode, the target would appear in any spot inside the area lined up by those LOS points. All sides and corners would be tested and the finish time for each spot would be recorded by the system. The practitioner could also adjust the radius of the black dot, red target, required force magnitude, and keeping time by changing the parameters in the text boxes on the top left. A score would be given after patients finish the game. For now, the score is based on the finish time for now, and the formula of the score system needs to be adjusted and finalized when more tests have been done. If the patients get a score more than which the practitioner set, then they would go into the next level, which means bigger amount of force requirements. During these exercises, the practitioner could know from the result
which spot is the weak part for the patients and which they are not able to steady act force on. Thus, the practitioner could find out which muscle needs to be strengthened by other exercises.

![Figure 55: Weight Shifting Training Mode – Dot Game](image)

### 4.2.3 Bar Game

There are two activities within this game, forward stepping and back stepping. Both involve weight shifting in a stepping pattern.

The first test is forward stepping. This test is conducted with the foot on the foot plate in the forward position and the foot on the platform in the back ward position. The forward stepping test promotes the loading response of gait, with the foot on the foot plate being loaded. The target to reach with the cursor is a bar that extends across the screen (See Figure 5). The subject will shift his weight alternately back and forth between the two bars. More force is required to be put through the foot plate on the forward bar compared
to the backward bar. This will promote normal gait in which the leg coming into stance will need increased weight-bearing as the subject moves forward.

The second test for the Bar Game is back stepping. In this test, the foot on the foot plate is back while the foot on the platform is forward in a stepping pattern. This pattern will promote terminal stance, off-weighting the foot that is on the foot plate. The subject will again shift his weight alternately back and forth between the two bars. Since we are trying to get weight off the foot as the subject shifts forward, the force requirements for this test are reversed from the previous test, with less weight wanted for the forward bar.

![Figure 56: Weight Shifting Training Mode - Bar Game](image)

**4.3 Range of Motion**

When the footplate is free to move, the 3D motions of the foot are captured using a 6 DOF Polhemus sensor mounted on the base of the plate. These data are then used in a VR display to provide feedback to the patient about their performance. The software has
a graphics editor which allows the user to create different training scenes to accomplish different movement goals. A virtual ‘teacher’ is first recorded by having a healthy subject perform the desired movement at the desired pace while in the device. This trajectory is then mapped onto a virtual object and displayed as an animated loop for the patient to observe and copy. As the patient practices the movement in the VR, a second animation, representing the patient’s movement, is also displayed. The mismatch between the teacher and patient displays acts as a powerful visual feedback to enhance error correction by the patient. Following each movement a score is displayed. The score is calculated based on a quantitative 3D trajectory match between patient and teacher trajectory. If preferred, the score may be hidden or summary feedback based on several trials can be displayed. One current scene for ankle range of motion (ROM) training is shown in Figure 57. The virtual teacher is displayed as a white wire frame disc which rotates in 3D in a forward-backward direction for PF / DF. The patient’s ankle movement is displayed as a solid green disc. Additional scenes show the disc moving side to side for inversion / eversion, or in a clockwise or counter-clockwise circle for circumduction in either direction. (See Figure 57)
The 2-DOF robotic interface provides feedback between the virtual environment and the user. Figure 58 is a screen capture from the game that has been developed using the Panda3D game engine. The patient travels in a two dimensional maze using motion output signal from the NUVABAT; where the motions of the ankle correspond to the movement in two axes in the VR. The position of the patient’s avatar on the screen is controlled indirectly by velocity modulation, whereas, the position of the footplate defines the velocity vector of the user avatar. Both degrees of freedom of the device can be used simultaneously in coordinated movements by the patient to navigate the diagonal
maze pathways, like up-down in maze game corresponds to DF/PF motion of foot, and left-right in maze game corresponds to inversion/eversion motion of the foot.

![Maze Game Image](image.png)

**Figure 58**: Dynamic Mode – Screen Capture of a 2D Display of Sample Maze Created in Panda3D Game Engine

The purpose of the game is to collect the green objects in the maze while avoiding the red ones. You would win 50 points for collecting each green dot, and lose 100 points for collecting each red dot. This goal of object collection presents visual motor integration tasks to the patients, challenging them with cognitive and problem solving tasks. The difficulty of the mazes and the level of force interaction associated with movements through the maze can be fully adjusted to suit the needs of the user.

Communication between LabVIEW and the Panda 3D engine is handled by User Datagram Protocol (UDP). The information is passed over the network (either on the
same computer or different computers) and then translated in Panda 3D to the movements the patient sees as visual feedback.

### 4.5 Strengthening Mode

Either range of motion mode or motor control and coordination mode can be used. Different resistance controlled by MRF damper could be added on as the strengthening mode.
5 EVALUATION AND TESTING

5.1 Foot Plate Force Measuring Testing

Two weights (52.0N and 92.9N) were used to test the COP measurement on the foot plate. On the plate we have drawn vertical and horizontal lines and circles which mark the weight’s position. For each location where two lines cross (see Figure 59), the theoretical force and position are recorded and compared to the test COP and force measurement using the load cells. The COP position and force errors are shown in Figure 60 and Figure 61. The position errors represent the distance from the load cell measured coordinate position to the actually applied position in the virtual scale unit (pixel) [\(\)]. So 10-15 pixels which is the average error in the COP measurement means that the measured position is \(0.23''-0.33''\) away from the actual location, which is a relatively small error. The force error is seen in Figure 60 and Figure 61 is around 5% which is acceptable for this application.

Figure 59: Foot Plate Force Measuring Test Setting
Figure 60: Position and Force Error in COP for 52.08Nm

Figure 61: Position and Force Error in COP for 92.90Nm
5.2 Pohelmus Sensor Compatibility Testing

As we know the pohelmus sensor uses magnetic field to work, so its compatibility with MRF damper needs to be tested.

The experiment was set as shown in Figure 62. The MRF damper is turned on and sitting at a set distance with the pohelmus sensor, the motion of polhemus is recorded by the software. So by moving the polhemus sensor in a straight line with different distances, the tracks in the software could be compared to show from where the MRF damper begin to affect the performance of the polhemus sensor.

![Figure 62: Pohelmus Sensor Compatibility Test Setting](image)

Figure 63 shows the result. From the result, we could easily see the MRF damper would not affect the performance of the polhemus sensor when it is 5 inch or farther away from
it. So when patients take the test, the polhemus sensor cannot be affected, for it is more than 6 inch space between the MRF damper and the polhemus sensor.

Figure 63: Polhemus Sensor Compatibility Test Result

5.3 Weight Shifting Game Testing

5.3.1 Limits of Stability (LOS)

The test protocol is as follows. This test is performed with the subject standing with a comfortable base of support stance with equal amounts of weight on each leg, one foot on the foot plate, the other foot on the platform. When the subject is ready, practice of the
test will begin, allowing the subject to more fully understand how the device works and moves. The subject will be able to see his center of pressure (COP) moving on the screen in front of him. A center position will be found first. Then, the subject shifts his weight straight forward (towards 12 o’clock) as far as possible without lifting his heel or bending his knee. When the subject is at his limit, the examiner will press a button that allows the computer to record the maximum weight shift in that direction. Limits are measured in forward, backward, lateral, and diagonal planes (8 directions) with clock positions described to the subject (See Figure 64). The subject’s results will be recorded and saved. The subject will step off the platform to fill out a visual analog scale (VAS) regarding his ability to balance during the test. See Appendix D: AnalogBalanceScale.

Four healthy subjects took part in the test with foot size shown in Table 12, 8 directions of their COP limits were recorded as shown in Figure 64. In Figure 64, it can be seen that the healthy subjects have different limits of stability area. The size of foot is not the decisive factor on their capability to shift their center of pressure forward or backward. Even two of them have the same foot size, but they can have very different limit of stability area. Especially subject 3, his foot is smaller than subject1, but he has the largest limits of stability area, since his interests of surfing which helps a lot. So setting the targets in Dot Game and Bar Game is necessary to base on results of limits of stability tests.

<table>
<thead>
<tr>
<th>Subject1(Male)</th>
<th>Subject2(Female)</th>
<th>Subject3(Male)</th>
<th>Subject4(Female)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>7</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 12 : Foot Size of the Subjects
5.3.2 Dot Game

The “Dot Game,” involves the subject shifting his COP into a target in white panel on the left side of the screen (See Figure 55). The subject’s body weight will be entered into the computer, along with which side of the body is on the foot plate. There are easy and difficult levels of this game. The subject will perform both levels, but the level that the subject performs first will be randomly chosen.
The easy level parameters are found in Table 13. Before the test begins, the subject will stand with one foot on the foot plate and one foot on the platform, a comfortable base of support, and equal amounts of weight in each leg. Once the subject is standing naturally on the device, the examiner sets the origin. The origin represents the “center,” where the subject has equally distributed weight between the right and left legs.

Table 13: Easy Level Parameters for Dot Game

<table>
<thead>
<tr>
<th>Target Radius (pixels)</th>
<th>Holding Time (seconds)</th>
<th>Time per Trial (seconds)</th>
<th>Force Requirement (%)</th>
<th>Predictability</th>
<th>Center Target</th>
<th>Coordinate Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1</td>
<td>10</td>
<td>30</td>
<td>Routing</td>
<td>Yes</td>
<td>At limits of stability</td>
</tr>
</tbody>
</table>

The target radius of 20 pixels allows for a large circular target at which to aim. The subject has to shift his weight so that his cursor (representing his COP on that side) enters the target. In order to complete that trial, the subject must keep the cursor inside the target for 1 second. The subject has 10 seconds to complete a trial. If the subject is able to complete the trial, the computer records how long it took for that trial to be completed. If the subject does not get the cursor inside the target for 1 second during that trial, it is recorded by the computer and the test moves on to the next trial. There is a force requirement in order to make the cursor move. For this level, the subject needs to put 30% of his total body weight into the side being tested to move the cursor towards the target. The easy level has “Routing Predictability,” meaning that each consecutive target that is away from center will go in counterclockwise order to the next target. The target positions are based on that subject’s limits of stability previously conducted. The position at which the subject was able to maximally shift his weight will become the position of...
the target. After one peripheral target trial is performed, the target returns to the center. The targets will alternate between center and peripheral. The subject will complete three rounds of twelve targets (completing three counterclockwise rotations around the origin, which will add up to 36 trials).

The difficult level protocol parameters are in Table 14. As before, an origin of the subject’s quiet standing on the foot plate will be found.

<table>
<thead>
<tr>
<th>Table 14: Difficult Level Parameters for Dot Game</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Radius (pixels)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

The difficult level has a smaller target radius and longer holding time, requiring more control in the subject’s weight shifting. Each trial will continue to be 10 seconds and success/fail will be recorded by the computer as before. This level requires more force to be put through the foot plate in order to make the cursor move. Instead of going in a counterclockwise trend, the targets will go in random order as to not allow the subject to predict where the target will be next. The target will not return to center between peripheral targets. The coordinates of the targets will no longer be pre-determined, but rather variable within that subject’s LOS. The subject will complete a total of 36 trials.

Following the completion of both levels, the subject will fill out a VAS for each of the levels regarding his ability to balance during these tests.
Three healthy subjects (see Table 15) took part in the preliminary tests; two routings were tested— with center and without center. The time for the training are shown in Figure 65.

Table 15: Healthy Subjects for Dot Game Tests

<table>
<thead>
<tr>
<th></th>
<th>Subject1</th>
<th>Subject2</th>
<th>Subject3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Female</td>
<td>Female</td>
<td>Male</td>
</tr>
<tr>
<td>Age</td>
<td>50</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

Figure 65: Dot Game Test Result a) Easy Level b) Hard Level; x Axis is the Target Number, y Axis is the Finishing Time
These preliminary tests are only to verify the complexity and distinctions of the Dot Game training protocols. In Figure 65, the x axis in both charts shows the trail number from 1 to 12, and y axis shows the finishing time. It can be seen from Figure 65 that testing subjects are capable of finishing the required task in both level, but the average time of chart b (hard level) is much greater than chart a (easy level), which means, the two settings are reasonable and can distinguish the complexity of the training.

### 5.3.3 Bar Game

There are two tests within this game, forward stepping and back stepping. Both involve weight shifting in a stepping pattern.

The first test is forward stepping. This test is conducted with the foot on the foot plate forward and the foot on the platform back. The forward stepping test promotes the loading response of gait, with the foot on the foot plate being loaded. The target to reach with the cursor is a bar that extends across the screen (See Figure 56). The subject will shift his weight alternately back and forth between the two bars. More force is required to be put through the foot plate on the forward bar compared to the backward bar. This will promote normal gait in which the leg coming into stance will need increased weight-bearing as the subject moves forward.

The second test for the Bar Game is back stepping. In this test, the foot on the foot plate is back while the foot on the platform is forward in a stepping pattern. This pattern will promote terminal stance, off-weighting the foot that is on the foot plate. The subject will again shift his weight alternately back and forth between the two bars. Since we are
trying to get weight off the foot as the subject shifts forward, the force requirements for this test are reversed from the previous test, with less weight wanted for the forward bar.

Both of these tests also have two levels, which will be randomized as to which level the subject performs first. Table 16 shows the parameters for the easy and difficult levels that will be used for both the forward stepping and back stepping tests. The difficult level’s bar width is smaller and holding time is longer to again require more control in the subject’s weight shifting. The distance between the bars is further for the difficult level to force the subject to keep control with more translation. The distance will be based off of that subject’s LOS. The subject will perform 36 trials at each level. The VAS will be filled out for each level between the forward stepping and back stepping tests.

<table>
<thead>
<tr>
<th>Table 16: Bar Game Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
</tr>
<tr>
<td>Easy</td>
</tr>
<tr>
<td>Difficult</td>
</tr>
</tbody>
</table>

Four Healthy Subjects (see Table 17) took the preliminary tests of the bar game for both easy and hard level for the left foot. Their forces, time for trials, and the COP tracks were also recorded. Figure 66, Figure 67, Figure 68, Figure 69 shows the time result for the tests. And Figure 70 shows the COP track of subject1 stepping forward test for easy model as an example.

<table>
<thead>
<tr>
<th>Table 17: Healthy Subjects for Bar Game</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Age</td>
</tr>
</tbody>
</table>
Figure 66: Time of Stepping Forward Test for Easy Level

Figure 67: Time of Stepping Back Test for Easy Level

Figure 68: Time of Stepping Forward Test for Difficult Level
As the Dot Game test, the Bar Game test shown above is also preliminary tests to verify the complexity and distinctions of this training protocol. In Figure 68 and Figure 69, the x axis in the charts shows the trial number from 1 to 36, and y axis shows the finishing time.

From the finishing time of the test, it can be seen that there are not much difference on the results of those four healthy subjects on trying the easy level tests; they can easily finish their tasks for this level. There are no fails in the easy test (10s means fail). For the hard model, it can be seen the average time and standard deviation are much higher than the easy level’s (See Table 18 and Table 19). They even have lots of fails on those trails. So it can be informed that two settings can distinguish the training level quite well, but the difficult level needs to be adjusted a little bit easier.

Table 18: Average Finishing Time for the Bar Game Trials

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Forward-Easy</th>
<th>Back-Easy</th>
<th>Forward-Difficult</th>
<th>Forward-Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject1</td>
<td>1.027</td>
<td>1.003</td>
<td></td>
<td>4.117</td>
<td>4.221</td>
</tr>
<tr>
<td>Subject2</td>
<td>1.614</td>
<td>1.341</td>
<td></td>
<td>4.621</td>
<td>3.701</td>
</tr>
<tr>
<td>Subject3</td>
<td>1.070</td>
<td>1.318</td>
<td></td>
<td>4.907</td>
<td>6.148</td>
</tr>
<tr>
<td>Subject4</td>
<td>1.417</td>
<td>1.426</td>
<td></td>
<td>5.620</td>
<td>4.191</td>
</tr>
</tbody>
</table>
Table 19: Standard Deviation of the Finishing Time for the Bar Game Trials

<table>
<thead>
<tr>
<th>SD</th>
<th>Forward-Easy</th>
<th>Back-Easy</th>
<th>Forward-Difficult</th>
<th>Forward-Difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject1</td>
<td>0.119</td>
<td>0.094</td>
<td>0.888</td>
<td>0.632</td>
</tr>
<tr>
<td>Subject2</td>
<td>0.765</td>
<td>0.422</td>
<td>1.747</td>
<td>0.790</td>
</tr>
<tr>
<td>Subject3</td>
<td>0.215</td>
<td>0.841</td>
<td>2.377</td>
<td>2.535</td>
</tr>
<tr>
<td>Subject4</td>
<td>0.580</td>
<td>0.552</td>
<td>2.627</td>
<td>1.043</td>
</tr>
</tbody>
</table>

Figure 70: Subject1 Stepping Forward Test for Easy Model
Figure 70 shows one training track of COP in one of the tests, which shows the software function of recording training track. The plot area represents the foot plate, the light pink bar represents the target bar in bar game, and the colorful polylines represent the tracks of the COP. The polylines are consisted of a trail of points, which are recorded in a 10Hz rate while the subject is doing the training. So from this chart, a more direct view of the performance of subjects could be seen, which will help the physical therapist get a more direct sense of their balance function.

In total, physical therapist could analysis their ability on balance function from those training games and result information, muscle disease or part of the motor control function losing could be seen through the numbers in the future. But further analysis of the testing should be conducted.
6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

We developed and tested a novel robotic device for virtual reality based ankle rehabilitation and balance training of patients recovering from various neurological ailments such as stroke or traumatic brain injury. The ability to control the ankle muscles and produce adequate range of motion in the ankle joints are key components of gait and balance function. Patients who suffer from neurological impairments frequently lose gait and balance function due in part to loss of ankle control. Our two degree of freedom (DOF) robotic device with a virtual reality interface can meet the needs of such patients for ankle and balance rehabilitation.

6.2 Future Work--- Robotic Ankle and Balance Trainer (RABT)

In the future, tests for range of motion, motor control and coordination, and strength mode with present prototype need to be conducted. Those tests would be conducted with healthy subjects, then with patients.

Also, a new prototype of Robotic Ankle and Balance Trainer would be built, which is also a two degree of freedom robotic platform, but it will be actuated by two novel hydraulic actuators. A closed-loop computer control system and virtual reality interface would be developed with a set of sensors for measuring angular position, velocity and torques relevant to ankle motion. The concept design of the device is shown in Figure 71.
Figure 71: Robotic Ankle and Balance Trainer

The RAB-Trainer is actually the second prototype of NUVABAT, so most of the designs would be based on the NUVABAT, just some of the dimensions would be changed to accommodate the new design. The advanced part is the ERF actuator (see Figure 72). We changed the MRF damper to ERF actuator, so this ankle device becomes a robotic device instead of patient-actuated balance trainer. Also, the RAB-Trainer can be used in either sitting or standing position with a harness or without a harness (See Figure 73).
Figure 72: ERF Actuator

Figure 73: RAB-Trainer with Support Platform
The RAB Trainer in Dynamic Mode will be under closed loop control so that it will be able to fast and accurately generate the position or torque trajectories prescribed by the medical practitioner. The controller will also ensure a safe and smooth force and position interface between the patient’s foot and the robotic platform. The control hardware of the system will consist of two PCs: a host computer, and a real-time target. The host computer will run LabVIEW that will be used to generate the practitioner’s Graphical User Interface (GUI) and the Virtual Reality (VR) game engine that will generate the VR displays to the patient. The practitioner will be able modify the exercise parameters through their GUI, and another monitor will display the virtual environment for the patient. The real-time target will be the dedicated controller of the system that will run all the time critical tasks such as data acquisition and controls using LabVIEW Real-Time Operating System. To achieve accurate force/torque and position control, a non-linear impedance controller will be developed. This controller will be based on our previous work where we have developed and successfully implemented various impedance control schemes for rehabilitation robotic devices.
Appendix A: LabVIEW Software Code

Figure 74: Labview Code Overview; 1) Parameters Initialization 2) Signals Collecting and Units Changing 3) Data Organizing 4) Training Rules Function 5) LOS Function 6) Dot Game Routing Generating 7) Graphic Function 8) Time Counting Function
Figure 75: Signal Collecting; Collecting Signals from Load Cells and Motion Sensors
Figure 76: Data Organizing; Organize the Processed Data and Put Them into Arrays
Figure 77: Training Rules Realization; Realize the Required Training Mode
Figure 78: LOS Function; Limit of Stability Mode Code
Figure 79: Dot Game Routing Generating; Base on the LOS Data and the Selected Mode, It Generated the Routing for the Dot Game
Figure 80: Graphic Function
Figure 81: Time Counting Function; All the Time Counting Used in the Training are Programmed Here
Figure 82: Output Excel Format Pattern---Dot Game & Bar Game

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>151.827</td>
<td>334.795</td>
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<tr>
<td>155.9</td>
<td>181.3</td>
</tr>
<tr>
<td>177.778</td>
<td>217</td>
</tr>
<tr>
<td>184</td>
<td>322.8</td>
</tr>
<tr>
<td>179.222</td>
<td>431.889</td>
</tr>
<tr>
<td>158.2</td>
<td>459.2</td>
</tr>
<tr>
<td>128</td>
<td>430.111</td>
</tr>
<tr>
<td>108.4</td>
<td>318.6</td>
</tr>
<tr>
<td>107.2</td>
<td>209.9</td>
</tr>
</tbody>
</table>

Natural Standing Position

Up Position
Up Right Position
Right Position
Down Right Position
Down Position
Down Left Position
Left Position
Up-Left Position

Figure 83: Output Excel Format Pattern---Limit of Stability
Appendix B: NUVABAT Study Screening

Questionnaire

NUVABAT Study
Screening Questionnaire

Name:  
Age:  
Gender:  
Height:  
Weight:  
Contact Info:  
  Primary Phone Number:  
  Secondary Phone Number:  
  E-mail Address:  
  Mailing Address:  

Subject #:  
Date:  

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

2. Do you have any implanted electronic devices? (e.g. pacemaker, automatic defibrillator, medication pumps)  Yes / No
   If yes, please explain:

   Note: Question #2 is only pertinent for tests that utilize Polhemus motion tracker. The balance test does not use the Polhemus. The question was retained to save re-screening subjects who may want to return in the future when we test other parts of the NUVABAT system.

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

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

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

6. Do you have any balance problems, or had an injury affecting your balance in the past 3 months? Yes / No
7. Have you fallen in the past 6 months? Yes / No
   If yes, please explain:

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

9. Have you ever played a sport where you kick a ball? Yes / No
   If yes, please list sports:

10. While standing on 1 leg, can you go up and down on your toes 10 times? Yes / No
Appendix C: Borg’s CR-10 Scale of Perceived Exertion

Borg’s CR-10 scale of Perceived Exertion

Subject #_________________ Date:_________________

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.

0 Nothing at all

0.5 Extremely weak (just noticeable)

1 Very weak

2 Weak (light)

3 Moderate

4

5 Strong (heavy)

6

7 Very strong

8

9

10 Extremely strong (almost max)

• Maximal

---

Appendix D: AnalogBalanceScale

Subject #_________________________ Date:_________________________

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

Limits of Stability Task:

<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>

2. Dot Moving 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>

3. Dot Moving Task B:

<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>

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>
<td>Very very easy</td>
<td>Almost impossible</td>
</tr>
<tr>
<td>to balance</td>
<td>to balance</td>
</tr>
</tbody>
</table>
Appendix E: Usability Questionnaire

Usability Questionnaire

Subject #_____________  Date:________________

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>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td></td>
<td></td>
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</tr>
</tbody>
</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>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8. I made many errors.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</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>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</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>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly Disagree</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix F: Subject Protocol- Stable Mode

**Equipment Needed:**
- NUVABAT device and platform with rails
- Computer and NUVABAT software
- Screwdriver
- Chair
- Tape for heel location
- Tape Measure
- Paper for shoe tracing
- Pencils

**Forms:**
- Informed Consent
- Completed Screening Questionnaire
- Borg Scale
- VAS
- Usability Questionnaire

**Explanation of Stable Mode:**
“We are going to have you stand on this device with your Right/Left leg on the foot plate and your Left/Right leg on the wooden platform. The foot plate under your Right/Left foot will be stable and not move during these tests. The handlebars are there for you if you lose your balance, but we prefer for you not to use them.”

**Limits of Stability**
Examiner clicks “Reset Load Cell”
“You can now stand on the device with your feet at a comfortable distance apart, with your Right/Left heel against the heel cup. You want to have your weight evenly distributed between your feet and hold still.”
“I want you to watch the white screen in front of you. You can just ignore the dials on the rest of the screen. Now shift your weight around to see how the black dot moves on the screen.”
“Do you feel like you understand how to make the black dot move?”
Once the subject is standing correctly on the device, Click “Origin”:
“We’re going to measure how far you are able to shift your weight in 8 different directions. We will describe the directions by referencing numbers on a clock. Without bending your knee, or lifting your heel or toes shift your weight through your foot as far as you can and hold it until I say to come back to the dot in the center. We’ll start by having you shift towards 12 o’clock.”
Once the subject is shifted forward maximally, the examiner clicks “OK”
After 1 second, a dot will appear on the screen. “Back to the center.” Switch Dial to Position 2. “Now shift to in between 1 and 2 o’clock.”
Once shifted, the examiner clicks “OK.” Once dot appears:
“Back to the center.” Switch Dial to Position 3. “Now shift to 3 o’clock.”

Once shifted, the examiner clicks “OK.” Once dot appears:
“Back to the center.” Switch Dial to Position 4. “Now shift to in between 4 and 5 o’clock.”

Once shifted, the examiner clicks “OK.” Once dot appears:
“Back to the center.” Switch Dial to Position 5. “Now shift to 6 o’clock.”

Once shifted, the examiner clicks “OK.” Once dot appears:
“Back to the center.” Switch Dial to Position 6. “Now shift to in between 7 and 8 o’clock.”

Once shifted, the examiner clicks “OK.” Once dot appears:
“Back to the center.” Switch Dial to Position 7. “Now shift to 9 o’clock.”

Once shifted, the examiner clicks “OK.” Once dot appears:
“Back to the center.” Switch Dial to Position 8. “Now shift to in between 10 and 11 o’clock.”

Once shifted, the examiner clicks “OK.” “We are done with that test, you can step off.”

Examiner saves data
Subject fills out VAS

---

**Dot Game**

**Easy Level**

**Before standing on foot plate:**

- Target Radius= 20
- Holding Time= 1
- Enter Body Weight of Subject
- Game Level=3
- Set to side (Right vs. Left)
- Set to Routing
- Set to With Center
- Set to Predicted
- Set Percentage to 70
- Press “Routing Generating”

“Now you will play a game. As you know from the testing we just did, the black dot shows where your weight is on the foot plate. You will see this same black dot, but there will also be a larger red target. When you see the target, you want to shift your weight so that the black dot goes inside the target and you want to hold it there for 1 second. You have 10 seconds to get the black dot inside the target. The target will start in the center. Once that is completed, the target will move to the outside so you have to shift your weight to get the black dot inside the target. Each time, the target will return to the center. The target will eventually make a full circle around your foot. There will be 2 bars underneath the screen. The top bar is blue and shows how long your black dot has been inside the red target. The bottom bar is green and shows how much of your 10 seconds has elapsed. If you keep the black dot inside the target for 1 second, the screen
will say ‘Good Job’ and the next target will appear. If you do not get the black dot within the target for 1 second during the 10 seconds you are allotted, the screen will say ‘You Missed One Keep Trying!’ At this level, you need to have 30% of your body weight pushing into the foot plate in order to make the black dot move. The yellow bar on the side of the screen shows how much weight you are bearing. (Examiner-point to 30%) You will complete 3 consecutive rounds of 12 targets. Do you have any questions?”

If yes, answer the questions
If no, Click Reset Load Cell

“You can now stand on the platform. I want you to stand naturally, with an even amount of weight on each leg and your heel against the heel cup. (Give them time to adjust) We will let you practice now until you feel comfortable with the game. Let me know when you have a good idea of what you’re doing.”

Click Game Start and allow practice.

“Tell me when you want to start”

Then:
• Click “Game Start”
• Subject performs COG weight shifting for 3 rounds of 12 targets

Subject steps off platform.
Allow subject to sit.

Difficult Level

Before standing on platform:
• Target Radius=12
• Holding Time= 3
• Enter Body Weight of Subject (should not have changed from Easy Level)
• Game Level= 6
• Set to side (Right vs. Left)
• Set to Random
• Set to Unpredictable
• Set Percentage to 90

“This time, the target will be a different size and its placement on the screen is unpredictable. You need to do the same as before in which you shift your weight to put the black dot inside the red target. You again have 10 seconds to complete this, but you have to hold it inside the target for 3 seconds this time. The blue bar below the screen will again show how long your black dot has been inside the target and the green bar below that will again show how much of your 10 seconds of allotted time has elapsed. At this level, you need to put 60% of your weight into the platform to make the black dot move. (Examiner-point to 60%) Again, the yellow bar on the side of the screen shows how much weight you are bearing. The green box lights up when you have enough weight. You will complete a total of 36 targets. Do you have any questions?”

If yes, answer the questions
If no, click Reset Load Cell

“You can now stand on the platform. I want you to stand naturally, with an even amount of weight on each leg and your heel against the heel cup. (Give them time to
We will let you practice now until you feel comfortable with the game. Let me know when you have a good idea of what you’re doing.”

Click “Game Start” for practice “Tell me when you want to start.”

Then:
- Click “Game Start”
- Subject performs COG weight shifting for total of 36 targets

Subject steps off platform.
Allow subject to sit. Administer VAS form about balance at this time.

**Bar Game**

**Stepping Forward-Easy Level**

Before standing on foot plate:
- Bar Width= 50
- Holding Time= 1 sec
- Force Requirement-Up= 5
- Force Requirement-Down= 1

“Now we will play a game in which you have your feet in a stepping pattern, with your Right/Left foot forward and your Left/Right foot back. I want you put your Right/Left foot on the foot plate with your heel against the heel cup and stand with your opposite leg on the platform as if you were taking a step forward onto your Right/Left leg.”

Subject stands on device.
Measure the subject’s step length using the L square. Put tape where heel is

Once the subject is positioned correctly:
“Tell me when you want to start.”

Examiner sets the “Down” Bar to the position at which the subject’s weight is shifted.

“Now shift your weight as far forward as you can.”

Move the “Up Bar” to that position. Look at position on Y-axis. Move the “Up” Bar 2 cm closer to the “Down” Bar.

“During this game, you are going to be shifting your weight back and forth between the 2 bars on the screen. When you shift, don’t let your heel or toes of the Right/Left foot come off the foot plate, and don’t let your Right/Left knee bend. The heel of the Left/Right foot can come off the platform as you are shifting forward onto the Right/Left foot. You must alternate between the forward bar and backward bar, otherwise the attempt won’t count as completed. You will have 10 seconds to shift your weight into the bar and you must hold it inside for 1 second. The blue bar under the screen will show how long you've been in the correct location and the green bar shows how much of the 10 seconds has gone by. You’re required to have at least 50% of your weight in your Right/Left Foot when you shift forward and 10% when you shift backward, so keep this in mind if your attempt doesn't seem to be counted. The green box comes on when you have enough weight. If the trial is successful, the screen will say “Good Job!” If you are unable to complete the trial in 10 seconds, the screen will say ‘You Missed One, Keep Trying!” If
you miss one, keep alternating to the other bar. You will shift your weight a total of 36 times, 18 forward and 18 backward. Do you have any questions?

If yes, answer the questions.
If no, “We will let you practice now until you feel comfortable with the game. Let me know when you have a good idea of what you’re doing.”
Click “Game Start”
Subject practices.
“Tell me when you want to start.”
Click “Game Start”
Subject performs test

Allow subject to sit.

Stepping Forward-Difficult Level
Before standing on the foot plate:
- Bar Width= 30
- Holding Time= 3 sec
- Force Requirement-Up= 5
- Force Requirement-Down= 1

“Now we're going to play the same game, but this time the size of the bar will be different and you have to hold your weight for 3 seconds inside the bar, which will be shown again by the blue bar. You still have 10 seconds to complete each trial, which will be represented by the green bar under the screen. The amount of weight for each bar stays the same as the last game, with at least 50% of your weight in your Right/Left leg when you shift forward and 10% when you shift back. You will shift your weight a total of 36 times, 18 forward and 18 backward. Do you have any questions?”
If yes, answer the questions.
Examiner sets the “Up” bar 2 cm forward from its current location (where the original maximum forward weight shift was).
If no, “We will let you practice now until you feel comfortable with the game. Let me know when you have a good idea of what you’re doing.”
Click “Game Start”
Subject practices
“Tell me when you want to start.”
Click “Game Start”
Subject performs test.

Allow subject to sit. Administer VAS form about balance at this time.

Back Stepping-Easy Level
Before standing on the foot plate:
- Bar Width= 50
- Holding Time= 1 sec
- Force Requirement-Up= 1
- Force Requirement-Down= 5
“Next we will play a game similar to the last, but this time your feet will be placed as if you were stepping forward onto your Left/Right leg. So your Right/Left foot will be on the foot plate and your Left/Right foot will be placed in a comfortable step position forward on the platform. As before, I would like you to place your Right/Left foot on the foot plate with your heel against the heel cup.”

**Subject stands on the platform.** Measure the subject’s step length using the L square. Put tape at heel.

Once positioned correctly:

“I want you to shift your weight forward towards your toes without lifting your heel or bending your knee. Most of your weight should be in your Left/Right leg.”

Examiner sets the “Up” Bar to the position at which the subject's weight is shifted.

“Now shift back into your heels as far as you can go.”

Examiner sets “Down” bar 2 cm closer than maximum weight shift.

“Just like the game you just played, you will be shifting your weight forward and backward between 2 bars. As before, you have to alternate between the bars in order for them to count as completed attempts. You will still have 10 seconds to complete each attempt, shown by the green bar, and you have to hold your weight in the correct location, shown by the blue bar. For this game, you will need to have at least 10% of your weight in your Right/Left leg when you shift forward and 50% when you shift backward. When you shift, don’t let your Right/Left heel or toes come off the foot plate and don’t let your knee bend. You will shift your weight a total of 36 times, 18 forward and 18 backward. Do you have any questions?”

If yes, answer questions.

If no, “We will let you practice now until you feel comfortable with the game. Let me know when you have a good idea of what you’re doing.”

Click “Game Start”

Subject practices.

“Tell me when you want to start.”

Subject performs test.

Allow subject to sit.

**Back Stepping-Difficult Level**

**Before standing on the device:**

- Bar Width=30
- Holding Time= 3 sec
- Force Requirement-Up= 1
- Force Requirement-Down= 5

“Now we’ll play the same game with some changes. The size of the bar will be different, and you will need to hold your weight in the bar for 3 seconds, shown by the blue bar. You will still have 10 seconds to complete the attempt, shown by the green bar. You will shift your weight 36 times again. Do you have any questions?”

If yes, answer the questions.

If no, have subject stand on the device and get set.
Examiner sets the “Down” bar 2 cm further from current position. “We will let you practice now until you feel comfortable with the game. Let me know when you have a good idea of what you’re doing.”
Click “Game Start”
Subject practices.
“Tell me when you want to start.”
Subject performs test.

Subject steps off platform.
Allow subject to sit. Administer VAS form about balance at this time.

Follow up with Usability Questionnaire and Modified Borg Scale.
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[43] (2010, Balance Master. Available: 