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vi-RABT: Virtually Interfaced Robotic Ankle and Balance Trainer

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Abstract— **Each year in the US, 628,000 people suffer an ankle sprain, and 795,000 suffer a new or recurrent stroke. Due to improved survival rates after stroke, significant increases in stroke population are projected by 2030. So far, there is no cost-effective robotic ankle/balance trainer in the market. In this paper, we present the Virtually-Interfaced Robotic Ankle and Balance Trainer (vi-RABT), a low-cost robotic system that will improve overall ankle / balance strength, mobility and control. The system is equipped with 2 degrees of freedom (DOF) controlled actuation along with complete means of force and angular measurements. The preliminary results on a single robotic footplate confirm the system design. The system will be used for measurement of ankle kinematics, ankle kinetics and balance function, as well as for retraining motor control and strength of the ankle during plantarflexion / dorsiflexion (PF/DF), ankle inversion / eversion (IN/EV) and circumduction motions.**

I. Introduction

The ankle joint plays a vital role in our simplest everyday activities such as standing, walking, running, and maintaining stable posture. This joint is usually under the stress of the entire body weight, and accordingly is highly subject to physical trauma [1]. Neurological problems such as stroke, cerebral palsy and traumatic brain injury cause motor control impairments in the ankle joint. In contrast, orthopedic injuries such as ankle sprains damage the joint and ligaments, and produce secondary muscle weakness, but leave motor control mechanisms intact. Due to varied severities of patient injuries or impairments, a need exists for a rehabilitation device that offers assistive and resistive therapeutic mechanisms in different stages of rehabilitation.

Conventional ankle and balance rehabilitation systems are built from a simple set of rigid and elastic mechanical elements. These systems are very cost-efficient and easy-to-use for the physical therapist. The Complete Ankle Rehabilitation Device (CARD) was designed by practitioners to aid in faster rehabilitation at clinic or home [2]. Utilizing a combination of elastic bands the device can provide resistance to ankle motion in multiple degrees of freedom. The axes of motion are in line with those of the ankle joint and the patient uses the system in the seated posture. Based on similar principles, other passive mechanical systems provide ankle training in the upright position for balance rehabilitation, e.g. the wobble board [3], Bosu ball [4], balance pads [5] and DynaDisc [6]. In spite of the lower cost and usability of these systems, they are not able to provide the motor control training, needed in neuro-rehabilitation, and active assistive / resistive options for orthopedic problems. Nor can they quantitatively monitor patients' performance and progress to objectively assess rehabilitation procedures.

Utilizing the recent advances in robotics and automation, a number of research prototypes and commercial products have targeted active ankle and balance rehabilitation. These systems can be categorized as wearable exoskeletons for over ground walking and stationary systems that can be used in hospital or home settings. The AnkleBOT is a wearable 2-DOF exoskeleton that provides assistive / resistive rehabilitation for plantarflexion / dorsiflexion (PF/DF) and inversion / eversion (IN/EV) of the ankle joint [7]. The AnkleBOT is sensorized with kinetic and kinematic measurments and utilizes an interactive video interface to instruct the specified training protocols. The system has a total weight of 3.6 Kg, which is potentially a barrier for patients with serious impairments. Further testing is needed to study the long-term effect of device on human subjects in more demanding applications such as over-ground walking. Furthermore there is no balance training mechanism implemented in this device.

A 2 DOF orthosis, developed by the University of Delaware, is made of lightweight aluminum and telescopic plastic elements, and provides independent control of dorsiflexion / plantarflexion and supination / pronation axes during gait [8]. The Robotic Gait Trainer of the Arizona State University (RGTASU) is a 2-DOF exoskeleton that is developed using the new Spring Inside Muscle (SIM) actuator [9]. The SIM actuator is a bi-directional pneumatic actuator that combines an air muscle and a compression spring, to provide opposing flexion and extension movement across the ankle joint. The Powered Ankle-Foot Orthosis (PAFO) is a 2-DOF air muscle actuator that is controlled using the subjects muscle activation patterns [10]. The electromyography (EMG) reading from Soleus and Tibialis anterior muscles triggers the PF/DF actuation of the air muscle actuator. The system is made of lightweight carbon fibers and polypropylene, metal hinge joint, and two artificial pneumatic muscles.

The Rutgers ankle rehabilitation system is a 6-DOF Stewart platform for clinical applications. The system is actuated by pneumatic cylinders and monitored by kinetic

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and kinematic sensors. The system is equipped with virtual reality (VR) interface that renders therapeutic games, and has been shown to improve gait in patients with stroke [11].

The Ankle Dorsiflexion Plantarflexion Exercise Device (ADPED) is another clinic-based rehabilitation system that specifically targets patients with complicated ankle problems such as joint contracture deformity [12]. The system design provides an adjustable footplate that rotates around the inversion / eversion axes to adapt to the patient's foot angle to reduce the pain and increase the efficiency for variety of individuals. The system applies smooth continuous passive motion (CPM) exercise to the ankle joint in sitting position.

The Lower Limb Exerciser with Intelligent Alloys (LEIA) was designed based on the novel shape memory alloy (SMA) actuators [13]. SMA actuators are lightweight, solid-state alternative to conventional hydraulic, pneumatic, and electrical actuators. It provides a system with good repeatability and precision. This is a 1-DOF ankle rehabilitation system that can be controlled by EMG signal from the Tibialis anterior muscle.

In 2008, our team developed the Northeastern University Virtual Ankle and Balance Trainer (NUVABAT) for ankle and balance rehabilitation [14]. This was a 2-DOF (PF/DF and IN/EV) movable footplate that was instrumented with force and angle sensors, and embedded within a standing platform. The system design allowed for use in stable (footplate locked) or dynamic (footplate movable) mode, in either sitting or standing position. Magneto-Rheological Fluid (MRF) brakes could provide variable resistance along both axes. Later, using center of pressure (COP) measurements augmented by game interface, a series of pre-gait, weight shifting and balance control tests were conducted [15]. These games are unique as the COP is derived unilaterally (vs. bilaterally for other balance training systems), a feature particularly useful for patients with stroke. The absence of actuators in the design of NUVABAT was an inhibiting factor in exploring the dynamic exercise for active assistive and resistive therapy, and led to the design of our current device, the vi-RABT.

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

The vi-RABT is a 2-DOF rehabilitation system that provides actuated assistive and resistive therapy to patients with lower extremity disorders. The system is equipped with angle sensors in addition to the means for force and torque measurements. Using a simple control algorithm, preliminary testing was conducted on a human subject. The system has a promising potential to be effectively used in physical therapy of ankle deficits, balance disorders and variety of mobility impairments, such as stroke.

II. Design Requirements

A. *Ankle Anatomy and Pathologies*

The ankle region is where the bones from the foot and leg meet. The tibia and fibula of the lower leg and the talus of the foot form the Talocrural joint, where plantarflexion / dorsiflexion (DF/PF) occur. The 5 tarsal bones, the calcaneous bone, and the 5 metatarsal bones interface with each other to form several other ankle joints, including the Subtalar, Transverse Tarsal and Tarsometatarsal joints. The foot movement of Inversion / Eversion (IN/EV) is a complex combination of motion at several of these joints. Inversion is a combination of supination, adduction and plantarflexion, while eversion combines pronation, abduction and dorsiflexion. These multi-joint motions are a key to the ability of the foot to adapt to different support surface conditions and maintain upright balance. Ligaments, the strong elastic bands that connect the bones to one another, are also an important contributor to the flexible stability characteristic of ankle function. Finally, the muscles, connected to the bones via tendons, act as the actuators. The central nervous system (CNS) recruits the muscle fibers to do the desired work using a servo mechanism.

Neurological injuries such as stroke affect primarily the control of the muscles via the CNS, but can secondarily produce changes such as joint / ligament stiffness or laxity. Conversely, orthopedic injuries such as sprains or fractures are primarily mechanical, but can produce secondarily motor control problems such as slowing of motor responses due to mechanical changes in injured soft tissues. There are immense variety of injuries and diseases that include ankle strengthening, motor control or balance training as part of the required rehabilitation plan.

B. *System Specifications*

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

TABLE I. System Design Requirements.

Metric	**Design Specification**	
Torque (N-m)	PF/DF	200
	IN/EV	50
Speed (RPM)	PF/DF	20
	IN/EV	25
Range of Motion (°)	Dorsiflexion	25
	Plantarflexion	60
	Eversion	30
	Inversion	40
Maximum user weight (Kg)	150	
Footplate size (shoe size)	Women 6 - Men 14	

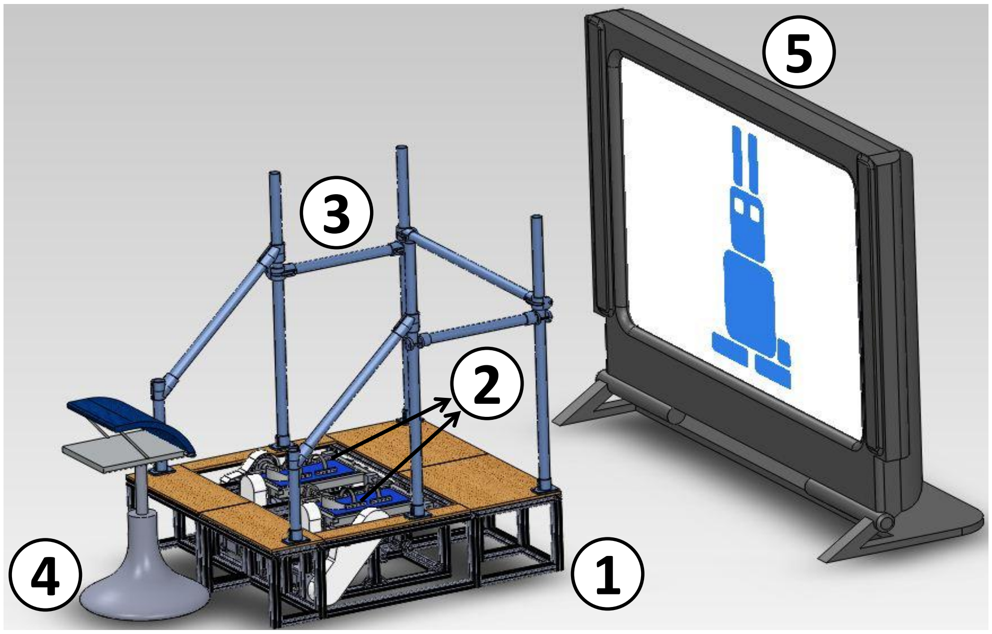

Figure 1. vi-RABT schematic. Subjects feet will be strapped on the robotic force-plates (2); Patinets will be instructed to play the VR game as shown on the screen (5); The system can be used in stading or sitting posture using the adjustable chair (4); The surrounding rails (3) provides safety features to the patinets during practice.

III. Design & Implementation

A. System Description

The building components of vi-RABT are shown in Fig. 1. The system is composed of an electromechanical hardware in contact with the patient and a video screen to present the interactive games. The vi-RABT can be used for ankle and balance training of individuals. The system is equipped with force/angle sensors as well as actuators to apply 2-DOF rehabilitation exercises to each foot. Patients can use the system in a seated or standing posture. They face the large screen and are encouraged to engage in goal-oriented VR games, to improve their ankle function.

As shown in Fig. 1, the final system will be composed of 1) a stationary platform; 2) two robotic force-plates; 3) an adjustable seat; 4) the wide 3D projection screen and safety features as elaborated below. At this stage of our research, we are focused on a single robotic platform.

B. Stationary Platform

This subsystem serves as the housing for the robotic force-plates and the safety rails. The stationary platform provides additional space around the robotic force-plates for the patients to step on. This might be needed based on the specific training protocol. The overall area of the platform is 110 (L) x 100 (W) cm×cm and the surface is at the same height as the robotic force-plates.

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

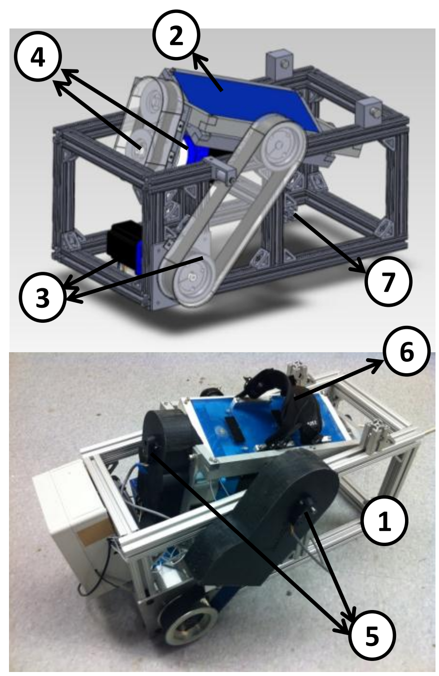

Figure 2. The robotic force-plate with 2-DOF actuation (TOP: CAD drawing; BOTTOM: Experimental Prototype). The cubic support frame (1); internal and external layers of the footplate (2); the PF/DF motor and transmission system (3); the IN/EV motor and transmission system (4); the encoders (5); the foot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

C. Robotic Force-plates

The essential contribution of this system is to provide 2-DOF controlled actuation that will deliver assistive / resistive rehabilitation to the lower extremities. The vi-RABT is composed of two robotic footplates (currently only one is implemented with actuators) to provide objective manipulation to the human legs bilaterally. In the static mode (the motors off), the system can be used as a force-plate for monitoring COP, either unilaterally (presently implemented) or bilaterally. The unilateral COP monitoring is a unique feature useful for pre-gait, weight shifting and balance activity training in patients with stroke. These features were tested in our previous system, the NUVABAT [14-15].

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

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

C.1 Actuation and Transmission Mechanism

The robotic force-plate is actuated by electrical motors along 2-DOF. The primary design criterion of the robotic platform was the ability to provide enough counteracting torque to the patient's weight (in standing posture) while still affording the desired range of motion. Other crucial criteria were portability, low size, lightweight and ease-of-use.

Two motors were selected based on the required torque / speed, as specified in Table I, and response time in this application. Accordingly the 660 W brushless DC motor (BLY-344S-48V-3200 from Anaheim Automation, Anaheim, CA) was connected to the gearbox (GBPH-0902-NP-100) with a 100:1 ratio to gain the mechanical advantage and provide the required characteristics along the PF/DF axis. Similarly the 220 W brushless DC motor (BLY-342S-160V-3000) was connected to the gearbox (GBPH-0902-NP-100) to actuate the IN/EV axis. The motors have 300% maximum producible torque (rated torque) which is a secure enough margin for this application. Both motors were electrically driven by power controllers (PF/DF: XSL-230-40, IN/EV: XSJ-230-10 from Copley Controls, Canton, MA). In order to control the motors, a custom-made computer software was developed in LabVIEW (National Instrument Corp., Austin, TX). The software was developed on a desktop computer and connected to the power controllers via a portable USB data acquisition board (NI-USB 6216, National Instrument Corp.).

The power from both motors was transmitted by a pulley (with 1:1 ratio in both axes) and timing belt. The belt and pulley were selected to match the required torque and RPM. The IN/EV motor is connected to the bottom of the external layer via an aluminum plate (Fig. 2). The power from this motor is transmitted through a pulley (8MX-45S-36) and poly chain timing belt (8MGT-1120-36, from Gates, Denver, CO) to the internal acrylic plate. As shown in Fig. 2, the PF/DF motor is located in the bottom corner of the support frame. Similarly the power from PF/DF motor is transmitted through a pulley (8MX-45S-36) and poly chain timing belt (8MGT-1120-36, from Gates, Denver, CO) to the robotic footplate. This setup allows for maximum efficiency and minimal backlash as well as enough flexibility to deal with misalignment issues.

C.2 Sensing Mechanisms

The robotic footplate is instrumented with angle and force measurement sensing units. In order to measure the force, the internal layer is built of five different components: an acrylic plate, an aluminum plate, load cells, metal crossbars and aluminum beams as shown in Fig. 3. The patient's foot is strapped on the acrylic plate. Acrylic was chosen because it is significantly lighter than aluminum and provides a relatively high rigidity. The aluminum plate was attached to the acrylic plate to support and strengthen the footplate and ensure minimal deflection. Four load cells (53CR from Honeywell Inc., Morristown, NJ) were inserted symmetrically in the four corners of the footplate, in between the aluminum plate and the two metal crossbars. The metal crossbars are connected to the surrounding aluminum beams.

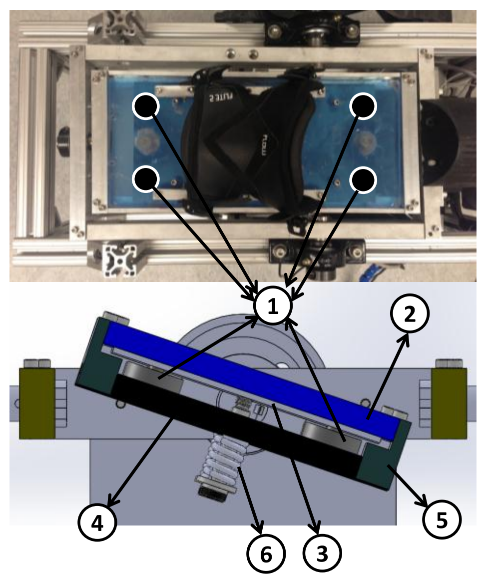

Figure 3. The robotic force-plate, load cells and sensing mechanism (TOP: experimental prototype; BOTTOM: CAD drawing). The load cells (1); acrylic plate (2); aluminum plate (3); metal crossbar (4); aluminum beams (5); the linear spring to create a preload (6).

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

Another important variable for control is the position or angular displacement. Two optical encoders (ENC-A5DI-1250-394-H-G, from Anaheim Automation, Anaheim, CA) were used to measure the instantaneous angle of rotation along each axis. The encoders were placed in the closest proximity to the footplate, i.e. the robot's end effector, for accurate measurement (see Fig. 2). For that purpose an appropriate housing was designed and 3D-printed for the pulleys so that the encoders can be connected to the pulleys on the footplate.

C.3 Foot Straps

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

D. Chair

Due to the severity and complexity of injuries, many patients (e.g., patients with stroke) may need to begin training in the seated posture. For those patients, an adjustable seat that allows training in incremental positions between sitting and standing is ideal. Accordingly we utilized a chair system with adjustable height. The chair allows training of the ankle while positioned in a range of angular seated positions thus allowing hip and knee to move from flexion (seated) to extension (standing). Our current prototype allows only regular seated posture.

E. Virtual Reality Interface

Another unique feature of the vi-RABT is the interactive gaming interface, which allows augmented feedback based on both kinematic and haptic features of the subject performance, and thus facilitation of the motor learning through a wide variety of mechanisms. Two projectors (Hitachi's CP-SX1350) were used to create a 3D interface. The wide projection screen (3×2 m) was used to increase the patient engagement in the rehabilitation procedure. Speakers will be utilized to augment the experience. A large screen display will be a compelling and motivating input for subjects who may have difficulty feeling or seeing small movements in their ankle while practicing their exercises, especially in the presence of sensory impairments. So far we have implemented different weight shifting, range of motion and stepping games similar to the NUVABAT [15].

F. Safety Features

We anticipate that the majority of the patients who use this device will have impaired ankle strength and/or balance control. Therefore, rigorous hardware and software safety features were considered in the design phase. These features prevent excessive footplate rotation and extreme torque values. The hardware features include the foot straps; safety handlebars, a harness (when standing), and mechanical stops.

Algorithms targeting safety were implemented in the system control software. These features specifically provide limit thresholds for both angular displacement and maximum applied torque. For example in the reported experiment (see next section), the maximum threshold was set to 25° for DF and -60° for PF. So when the footplate reached the threshold, it automatically stopped the rotation. This value can be adjusted according to severity of patients' deficits.

In order to further assure patient's safety in the system, hardware mechanical safety features were considered separately. So in order to avoid excessive rotation, a mechanical stop was considered for the IN/EV axis. As shown in Fig. 2, this is implemented underneath the footplate and acts as a limiter to mechanically prevent excessive rotation (> 45°) of the footplate along the IN/EV axis.

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

In the future balance tests, in order to increase the patient's security and also counteract part of his weight, a safety harness will be added to this system. The harness serves to protect the patient if they were to lose their balance. It can also be used to bear some of the patient's weight depending on the ongoing rehabilitation paradigm. The harness will be mounted directly onto the system and should be easily attached or removed.

IV. CONCLUSION

At this stage of our research, only one robotic footplate is fully instrumented. In order to investigate the integrity and feasibility of the completed robotic force-plate, a preliminary control software was developed (LabVIEW, National Instrument Corp., Austin, TX). The software was used to read the angular displacements from the encoders, along 2-DOF, and control the motors. A joystick pad was considered as a user interface. By pressing the four directional arrows on the joystick, the user could move the robotic footplate in four different directions. The range of motion was limited by the software. The video demonstration of this experiment is submitted for more tangible visualization.

A healthy male subject (one of the experimenters) was recruited to stand on robotic footplates, having his right foot on the single motorized footplate. His left leg was free on the left static footplate. He was instructed to follow the motions applied by the robotic footplate, and to distribute his weight between the two plates at his comfort and confidence.

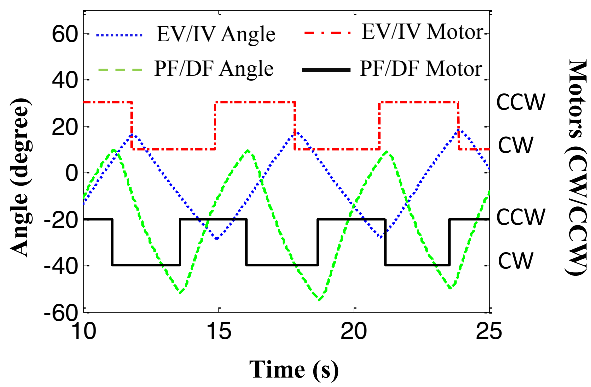

Figure 4. Preliminary results: Subject standing on the robotic force-plate and controlling the footplate via joystick. Plate angles (triangular shape): IN/EV (dots), PF/DF (dashed); and the alternating commands to the motors (pulse signals): IN/EV motor (dot-dash), PF/DF motor (solid). The DF and IN angles are toward positive direction. Motors turned clock-wise (CW) / counter-clock-wise (CCW) with a pulse voltage on the rising / falling edge.

As shown in Fig. 4, the experimenter was pressing the arrow keys on the joystick to control the force-plate along four directions. The presented curvature (closer to the peaks) on the triangular shape PF/DF plot is due to the subject's resisting weight on the footplate.

V. CONCLUSIONS

This paper described a novel 2-DOF robotic ankle and balance trainer called the virtually-interfaced robotic ankle and balance trainer (vi-RABT). Vi-RABT can be used for measurement of ankle kinematics, kinetics and balance function, as well as for retraining standing balance, motor control and strength of the ankle during plantarflexion / dorsiflexion (PF/DF), ankle inversion / eversion (IN/EV) and circumduction motions. Furthermore, the vi-RABT was designed for use in either a sitting or standing position to accommodate early and late phases of rehabilitation training. The system is composed of A) a robotic force-plate to apply desired force profiles and motion trajectories to the human lower extremities; B) the surrounding platform to host the robotic force-plates and supply safety hand grips for the patients; C) the harness to increase the safety and selectively compensate the patient's weight as needed by the therapeutic regimen; D) the chair to provide the possibility of following the exercise regimen in the seated posture; and E) a 3-D wide screen to project virtual reality games and create an entertaining, immersive therapy experience for the patient.

Single robotic footplate was recruited. The robotic force-plate is instrumented with force and angular displacement sensors to provide full control, monitoring and diagnostic capabilities. Beyond effectiveness, other major specifications for the final product were the ease-of-use, portability, small size and lightweight. Considering the amount of delivered power, these specifications were fairly achieved by the presented mechanical design, gear-motors and power transmission mechanism. The strong electrical motors are able to counteract the patient's weight and provide the desired assistive/resistive therapy. The vi-RABT is equipped with software and hardware safety features to assure effective human-machine interaction.

Preliminary results, using one robotic footplate, confirm the system design and promising potentials. More objective rehabilitation exercises with more human subjects will be performed in the near future. Accordingly the desired therapeutic protocol will be implemented using a more advanced control method. We will test the system on healthy subjects and extend the paradigm to patients.

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