Position versus Force Control: Using the 2-DOF Robotic Ankle Trainer to Assess Ankle's Motor Control

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***Abstract*—An estimated of 2,000,000 acute ankle sprains occur annually in the United States. Furthermore, ankle disabilities are caused by neurological impairments such as traumatic brain injury, cerebral palsy and stroke. The virtually interfaced robotic ankle and balance trainer (vi-RABT) was introduced as a cost-effective platform-based rehabilitation robot to improve overall ankle/balance strength, mobility and control. The system is equipped with 2 degrees of freedom (2-DOF) controlled actuation along with complete means of angle and torque measurement mechanisms. Vi-RABT was used to assess ankle strength, flexibility and motor control in healthy human subjects, while playing interactive virtual reality games on the screen. The results suggest that in the task with 2-DOF, subjects have better control over ankle's position vs. force.**

I. Introduction

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

Rehabilitation is a must after ankle sprain as insufficient therapy will considerably compromise ambulation ability and predispose patients to future injury [3]. Traditional rehabilitation routines require intensive cooperation and effort of therapists and patients over prolonged sessions. Common ankle and balance rehabilitation systems are built from a simple set of mechanical elements [4], which are not sensorized or networked. Although these systems are very cost-effective and easy-to-use, they are not equipped with basic mechanisms to assess the effectiveness of the ongoing rehabilitation process, nor do they allow semi-independent practice, which can be assessed quantitatively and monitored intermittently by a therapist.

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Due to the significance and varied severities of ankle injuries and impairments, a need exists for a well-organized rehabilitation process that meets the needs of therapists and patients. A number of research prototypes and commercial products have targeted active ankle and balance rehabilitation. The Rutgers ankle rehabilitation system is a 6-DOF Stewart platform for clinical applications. The system is actuated by pneumatic cylinders and monitors the kinetic and kinematic variables. The system is equipped with virtual reality (VR) interface that renders therapeutic games, and has been shown to improve gait in patients with stroke [5].

Vi-RABT is a rehabilitation robotic system that is designed to provide assistive/resistive therapy to patients with lower extremity disorders [6-7]. The system has two degrees of freedom (DOF): dorsiflexion/plantarflexion (DFPF) and inversion/eversion (INEV). The design criteria were portability, small size, lightweight and ease-of-use for the patient and therapist. The system was designed to provide enough counteracting torque to the patient's weight (in standing posture) while still affording the desired range of motion. The axis of rotation is aligned with the ankle joint. The robotic footplate is instrumented with angle and force measurement units.

In this study, we have used the vi-RABT as a diagnostic tool to analyze the force and position control in human ankle joint. This paradigm can be useful in robot assisted therapy where there is a question for the most effective biological marker to trigger/control an external manipulandum. There is variety of applications in exoskeletons, active arm supports and electrical wheelchairs that are controlled by human intention. Force-based control interfaces are used in rehabilitation robots where patients practice to regain control, mobility and strength [8]. Position-based control using joystick was studied to control an upper extremity orthoses [9]. [10] compared electromyography (EMG), force and position control in a 1-DOF upper extremity control task. Healthy human subjects were instructed to track a 1-D goal on the screen by producing the arm EMG, generating force and moving a joystick at hand. Looking into the tracking error, the EMG control was better than the force control which was better than position control.

We have used the vi-RABT to characterize the ankle motor control. Using a single robotic force-plate, the ankle position control is compared with force control and early results are provided. Linear controllers were developed to drive the system in back-drivable mode [7]; two virtual reality games were designed; and healthy human subjects were tested to compare the two biomechanical variables.

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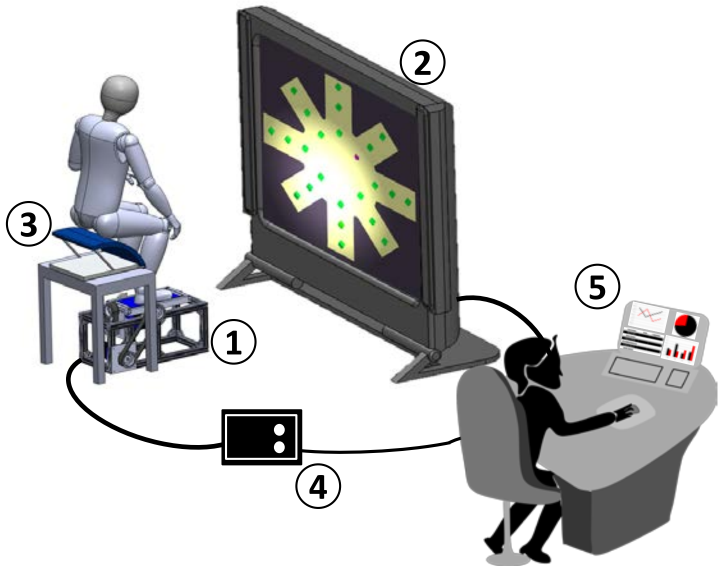

Figure 1. The compoenents of vi-RABT. Subject is seated on an adjustable chair (3); His foot is strapped into the the robotic ankle trainer (1); The real-time machine (4) controls the 2-DOF robotic footplate (1); The 3-D display is used to project the virtual reality game (2); The subject is instructed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

II. Methods

The components of the robotic ankle trainer system are shown in Fig. 1. The system is composed of a robotic footplate, an adjustable chair, a real-time operating machine, the therapist's station, and the large 3-D screen. Subjects will be seated on the chair, foot strapped and secured to the robotic footplate. They face the large screen and are encouraged to engage in goal-oriented VR games, to improve their ankle function. Footplate outputs are interfaced to the VR game; subjects control the footplate by moving their foot. The therapist monitors the progress.

A. System Hardware

The most essential part of the system is the robotic footplate that provides 2-DOF controlled actuation to the subject's foot. The footplate is actuated by rotary electrical motors along dorsiflexion/plantarflexion (DFPF) and inversion/eversion (INEV) axes of the ankle joint. The INEV axis is housed by the surrounding frame that is driven by the DFPF motor. The power from both motors is transmitted through a pulley-timing belt mechanism to the robotic footplate. Four load cells are placed in the corners of the footplate to create a "robotic force-plate". The associated torque values along both axes can be calculated from load cell measurements. The force-plate not only measures the compression force but also the tensile forces applied to the foot strap by the subject.

Each axis of rotation is equipped with an optical encoder. Two encoders are used to measure the instantaneous angles along each axis. To increase the accuracy of measurements, encoders are installed in the closest proximity to the footplate, i.e. the robot's end-effector. Appropriate housing and mechanical attachments are designed to secure the encoders and ensure the accurate reading.

Two computers are used in this setup: 1) the precise real-time machine is programmed to control the footplate; 2) the host computer is used for monitoring and data logging purposes. Computers are networked via direct Ethernet connection. Two projectors are used to create a 3-D experience. The wide projection screen (3×2 m) can increase the chance of patient engagement in the rehabilitation procedure. Speakers are utilized to augment the entertaining experience. This component provides facilitation of the motor learning through a wide variety of mechanisms.

Due to the variability in human sizes and proportions of the legs, we used a chair with incremental height adjustments, shown in Fig. 1. Future versions will allow training of the ankle while positioned in a range of angled seated positions. It should also be noted that the system is measuring the footplate angle, not the ankle angle. Our bench tests showed highly significant correlation between the ankle and footplate angle [9, 10]. To reduce error due to foot-footplate interface, we have stabilized the ankle with a heel/calf support and stabilized the knee and hip with straps and pads to minimize rotation.

B. Control Software

Part of the current experimental design, as explained in the next section, was to assess ankle's range of motion (ROM) and control. Accordingly subjects were required to freely move the footplate along both DOFs, i.e. DFPF and INEV. However this was not possible due to the involved transmission mechanism, which causes a significant amount of internal resistance along each axis of rotation. The control objective was to use the electrical motors to compensate for the system's internal resistance. The system needs to work in back-drivable mode, so that the subject feels minimum interaction force while moving the footplate.

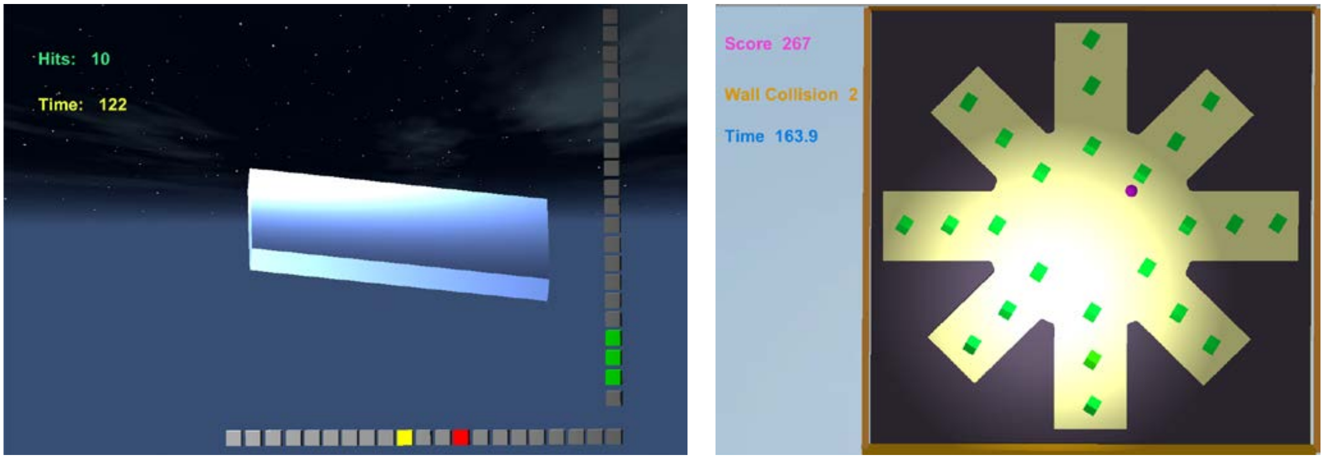

Figure 2. The virtual reality games, from subjects perpective. Left: the Board Game, subejct has reached to the taget along the DFPF axis (y-axis) and he needs to stay there for about 1.1 seconds; Right: the Maze Game, subject is controlling and moving the pink avatar to acquire the green cubic goals.

The most crucial control objectives for this rehabilitation task were focused on no overshoot and the fastest transient behavior. Using system identification techniques two proportional-integral-derivative (PID) torque controllers were designed for each actuator [7]. The controller was developed in LabVIEW 2013 real-time module (National Instrument, Austin, TX) and programmed into the real-time machine. The control loop was executed at 1 KHz.

C. Therapist Interface

The system is equipped with a host station for the therapist. Therapist interface is a graphical medium (developed in LabVIEW 2013) that receives the data from the real-time machine at 50 Hz. This is a lower-priority operation, compared to the real-time controller. The therapist can monitor the ongoing training session and provide objective recommendations to increase the efficacy of the therapy. He/she can also change the parameters and alter the regimen during the training session. The data are collected and stored in this computer.

D. Game Interface

Fig. 2 shows the virtual reality games that were used in the current study. The board game is composed of three main components: 1) The blue board (plate), which represents the actual footplate under subject's foot; 2) Horizontal and vertical box sets which demonstrate a guideline to the subject; and 3) the yellow and red box indicators to represent the current and desired position of the subject, respectively. The goal of the game is to move the yellow target along the guidelines and stay next to the red target for about 1.1 sec continuously. As shown in Fig. 2, at the instant of reaching to the target, the three boxes in the target neighborhood turn into green. If the subject can keep his position for a short period (around 1.1 sec) in that area, then the next target will turn red. This game was utilized in three different scenarios: playing solely along the y-axis (DFPF); along x-axis (INEV) and along both DOFs. In each case there is the total number of 30 goals along each axis to achieve.

Using a similar concept, in the maze game, subjects are instructed to move the avatar (purple ball) within a start shape maze plane to pick up all green cubes. Additionally they are instructed to avoid the walls. Hitting the ball to the wall is considered as a collision and accompanied by an unpleasant high-pitch audio signal. There is the total number of 25 cubic goals to achieve in this game.

The game boundaries are specified based on the subjects' maximum ROM and strength, which are measured at the beginning of the test session. Subjects are encouraged to collect the targets in the minimum amount of time; and with the least number of collisions in the maze game. A pleasant low-pitch audio signal is accompanied after acquiring each target. The elapsed time, number of hits and collisions are shown on the screen to the subject, shown in Fig. 2.

E. Experimental Procedure

The long term goal for the vi-RABT is to be used for ankle and balance rehabilitation of individuals. In this study, we began working toward this goal by studying ankle motor control. The system was used in static (motors off) and back-drivable mode (motors on). Healthy human subjects were recruited to perform isometric (static mode) and isotonic (back-drivable) ankle assessment tests. Our objective was to measure the ankle joint range of motion, strength and motor control. Results of the first five subjects are reported here.

The experimental protocol was approved by the institutional review board at Northeastern University (NU). Subjects were seated on the adjustable chair, with right foot strapped securely into the robotic force-plate. To protect subject's knee joint and to increase measurement accuracy, subjects' legs were stabilized with pads and straps to minimize hip internal and external rotation (Fig. 1, right). The chair height was adjusted to place the hip and knee in 90 degrees flexion, and ankle joint in neutral.

At the start of each session, subject's strength was assessed isometrically, with the footplate locked mechanically and the actuators turned off. The ankle was in neutral position, the tibia perpendicular to the footplate. Subjects performed 5 maximal contractions of 3 sec duration each for each of the 4 directions (DFPF and INEV). In the next set of trials maximum ROM was assessed by performing 7 alternating movements along each axis at a comfortable pace. During this task, the actuators were turned on and controlled in the back-drivable mode; the footplate showed minimal resistance to movement. Mean values for strength and ROM for each subject were then used to set the game boundaries (80% of maximum).

After in initial assessment trials, every subject played four different games, each twice, in the isometric and isotonic conditions (4*2*2 = 16 games/subject). Subjects first played the 1-DOF Board game along DFPF axis, and then the Board game along INEV. Next they performed 2 blocks of the 2-DOF Board game; followed by 2 blocks of the maze game.

III. Results

Subjects' maximum range of motion and strength are reported in Table I.

TABLE I. Results from Five Human Subjects.

Axis	Ankle Characteristics	
	Strength (Nm)	***ROM (Deg)***
Dorsiflexion	19.54 ± 9.09	17.77 ± 5.20
Plantarflexion	-33.11 ± 4.30	-27.05 ± 7.39
Inversion	10.61 ± 1.49	17.67 ± 6.59
Eversion	-7.85 ± 2.95	-12.54 ± 4.73

The PID controller has placed the footplate into back-drivable mode. The experienced RMS torque values by the subjects were 1.3 ± 0.26 Nm along DFPF and 0.7 ± 0.12 Nm along INEV axis. Accordingly the task was not perfectly isotonic as subjects experienced variable load on the ankle. The game completion time and number of collisions in the maze game were recorded. The mean number of collisions in the isometric tests across subjects was 8.5 ± 6.43; and in the isotonic tests was 4.37 ± 3.6. Fig. 3 represents mean values of the game completion time across subjects for each game. Subjects did not show a significant difference in the position vs. force control in the 1-DOF game. However the position control was better than force control in both 2-DOF games.

IV. Discussion and Conclusion

The virtually interfaced robotic ankle and balance trainer (vi-RABT) is described, and early test results from five subjects are presented. The system is actuated along 2-DOF and is instrumented with angle and torque measurement mechanism. Two virtual reality games were used to assess ankle strength, range of motion and motor control.

According to Fig. 3 and in the 2-DOF games, subjects showed better control over ankle position versus force. This result is also consistent with the number of undesired collisions in the maze game. In contrast to the reported cases in upper extremities, this results support the application of ankle position as a more refined control variable to trigger/control the presumable exoskeleton. Similar effect prevailed in the next 15 subjects to be reported in future.

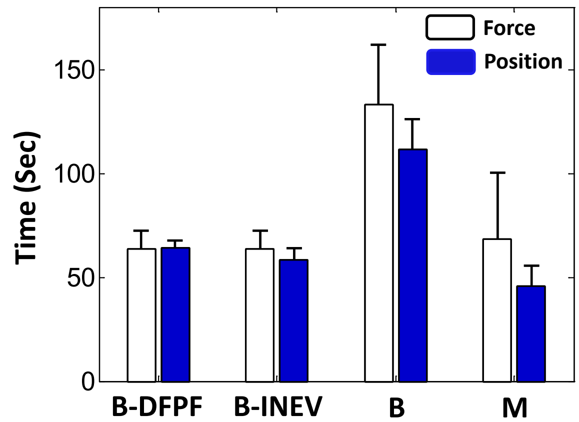

Figure 3. Results from virtual reality games. "B" represents Board Game and "M" represents Maze Game. The first two blocks were along single axis: dorsiflexion/plntarflexion(DFPF) and inversion/eversion (INEV).

However, this difference might be due to experimental design as the force games were played first. Subjects might have learned the cognitive aspect of the game in force games and used that knowledge in the position games. Further randomized experiments are required to confirm this result. This was the first step in using the vi-RABT for ankle assessment. After finishing the current experiment, our next step will be to develop assistive/resistive ankle rehabilitation protocols. The vi-RABT has the potential to be used for variety of ankle and balance disorders.

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