CAPTURING ANKLE BENCHMARK KINEMATICS USING AN INTERACTIVE SENSORY WOBBLE BOARD

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ABSTRACT

The current state-of-the-art sensory devices have enabled a reliable tracking of the human's movements. This had a positive impact on the medical field in general and on the physical rehabilitation domain in particular since it created new possibilities to the patients to train from their homes. Home-based rehabilitation systems have emerged as promising assistive tools for effective training and diagnosis. In order to provide a productive training experience, these systems should provide good assessment reports for both the patient and the clinician. The objective of this work is to form a metric to evaluate the ankle motion for rehabilitation applications. For this purpose, we use our sensory-mounted wobble board as an input interface to play a specially developed computer game that offers an intuitive and entertaining training experience. We invite 15 healthy subjects to test our system. The data collected during the play are used to derive a set of benchmarks for a number of parameters, namely the angular velocity and jerkiness.

***Index Terms*—** Home-based rehabilitation, wobble board, inertial measurement unit, medical devices and applications.

1. INTRODUCTION

Ankle injury is a very common type of foot impairments that affect people from different walk of lives. Among those people are post-stroke patients, athletes, and physically demanding factory workers. For instance, stroke which is a leading cause of death in the world and of disability in the developed nations [1], leaves about 20% of stroke survivors with neuromuscular disorders which can cause alterations to their gait cycles. On the other hand, athletes are frequently encountered with ankle sprains at some point of their lives [2]. Statistics have revealed that ankle sprains account for up to 21% of sports-related injuries [3]. As was reported in [4], these injuries result quite often in the following muscle strengths: a) Dorsiflexion: the act of turning the foot upward, b) Plantarflexion: the act of bending the foot downwards toward the sole, c) Eversion: the act of turning the foot outward at the ankle, d) Inversion: the act of turning the foot inward, inside out. Figure 1 illustrates the different motions of the ankle.

Overcoming these deficiencies is normally achieved through a rehabilitation regimen. The outcome of such a process is to improve the quality of life of the patient and to reintegrate her or him as much as possible into society [5]. This is normally done by focusing on training that helps the patient to develop strength, flexibility and proprioception in the injured body segments. Unfortunately, respecting the guidelines of a long-term rehabilitation process is a tedious task for many people. For example, patients living in rural areas have limited access to therapy clinics that are mostly located in major cities. Consequently, these patients have to travel frequently to the cities, the issue that might be very cumbersome for many. On the other hand, lacking an adequate insurance plan by many patients might lead them to drop a number of therapy sessions, and therefore yield to an extended healing period.

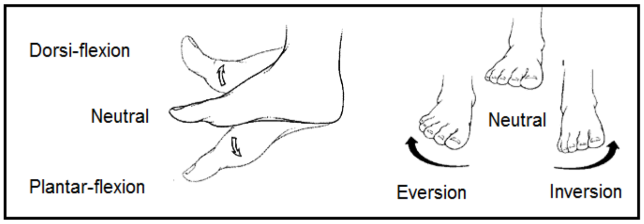


Fig.1. The different motions of the ankle

Therapists recommend a complementary home training using some of the prevalent passive cheap devices such as foam rollers, elastic bands and wobble/balance boards. Despite the usefulness of such devices in therapy, patients normally get bored of the exercise due to its static nature. On the other hand, such tools do not offer clinicians the means to monitor the progress of their patients because they cannot store training related information. Fortunately, the tremendous development in the field of sensory technologies has created the opportunity of tracking human's motion in a precise and robust manner. This has drawn new boundaries for medical applications, particularly for monitoring the health condition of patients while at home. Home-based rehabilitation has evolved in recent

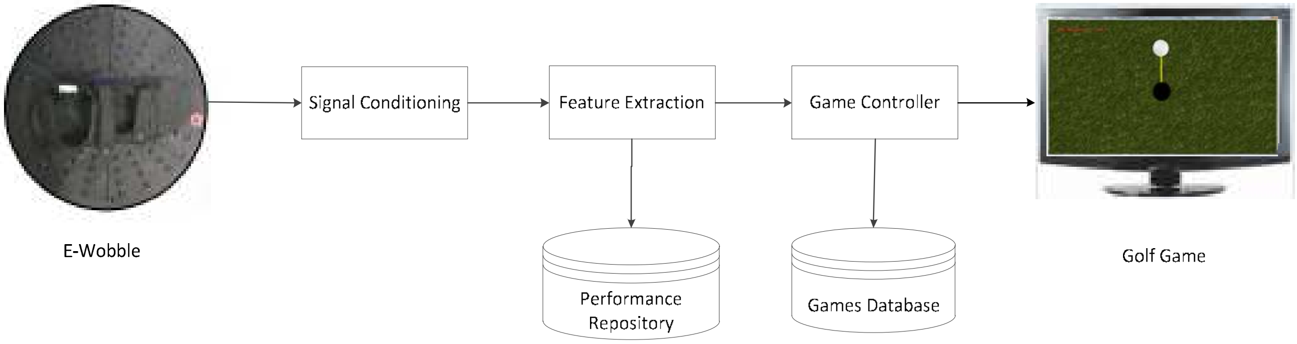


Fig.2. The framework deployed to capture the ankle's kinematics

years as a cost-effective and convenient alternative to traditional clinical rehabilitation [6]. Potential benefits associated with home rehabilitation include improved empowerment (earlier return to home and family), reduced cost (home rehabilitation costs have been shown in some studies to be lower than hospital based in-patient rehabilitation [7]), and minimized therapist to patient ratio (since the patient requires minimum supervision).

One way of making home-based rehabilitation systems more appealing to the patient is by choosing intuitive interfaces and games that do not require technical knowledge or computer skills. In addition, an effective home-based rehabilitation system should provide a means to measure the quality of patient's performance in order to help therapists easily monitor the patient's progress, identify any impairment, and suggest treatments (rehabilitation exercises). Based on these requirements, many researchers have introduced a variety of systems that use multimedia technology and Virtual Reality (VR) games aimed to provide a fun, yet effective ankle rehabilitation experience. For instance, Girone [8] presented his haptic rehabilitation tool called “Rutgers Ankle” which is based on the six degrees of freedom Stewart platform. The system incorporates a set of virtual reality (VR) games that deal with several types of ankle rehabilitation exercises, such as strength, flexibility, and balance. A force feedback is provided depending on certain states within the game. Choi [9] deployed the Rutgers Ankle interface to develop a virtual football stadium game. The Kickball game is a football stadium with four goals in each direction and a rectangular plate in the center. In the game, the virtual plate object is mapped with the ankle's four motions. The patient has to move his/her ankle to kick the ball depending on the instructions defined by the therapist. The Biodex Balance system [10] is a commercial tool used for lower extremity rehabilitation in general. It consists of a circular platform that the patient steps on with both feet, and a small screen where the games and the related training information are displayed. The system features a number of test protocols, six training modes, and an intuitive touch screen, and allows testing and training in both static and dynamic natures. Due to its relatively high price, the Biodex system is not affordable for many patients and is mostly found in clinics.

One of the most important aspects that most of the rehabilitation systems have omitted is to offer a list of reference performance kinematics that could possibly lead the therapist to easily compare and diagnose the patient's condition after training. In addition, such list could also help the patient comprehend the status of his/her progress in reference to a healthy person. In this paper, we introduce and capture a set of training performance parameters from a pool of healthy users while playing with our electronic wobble board system. The captured data are then used to derive a set of benchmark metrics that can be referred to by clinicians and patients after training with our system or with any similar rehabilitation application.

The rest of the paper is organized as follows: Section 2 reveals the proposed home-based rehabilitation framework, Section 3 elaborates on the users' evaluation and performance parameters, and finally, Section 4 draws the conclusion and our future work.

2. KINEMATICS CAPTURING FRAMEWORK

Passive devices, such as wobble boards are very common home-based training tools that physiotherapists recommend for their patients. However, their benefits can be really increased if they are able to track the patient's progress and provide some feedback about the performance after each training session. Fortunately, sensors technology has provided us with very small inertial and motion units that could be easily integrated with such devices to move them from a passive state to a reactive one.

The goal of this paper is to determine a set of ground-truth values that could be used by the therapist as a reference for evaluating the progress of a patient after training with specially developed software Golf Game or with any similar rehabilitation games. For this purpose, we enhance the capabilities of the wobble board by mounting it with the appropriate sensors that permit the detections of 4 movements of the ankle. Figure 2 presents the framework we have adopted to achieve the capturing of the metrics of interest. The detailed description of each module is discussed below.

A. The E-Wobble Board

E-Wobble [11] consists of a passive wobble board that allows 20 degrees of tilt. A 6 Degrees of Freedom (DoF) Inertial Measurement Unit (IMU) that consists of 3 axis - ADXL 335 accelerometer and a ITG 3200 gyroscope was attached on the board in order to capture the necessary tilting and speed information. An Arduino microcontroller is used as the microprocessing unit where all the signal processing mechanisms are implemented. A sandal that can be worn by the user is affixed on the top of the board in order to properly control the movement of the board when used with one foot. A detailed description of the board can be found in [11].

B. Golf Game

The Golf Game is developed based on the concept of the real game. To accomplish a task within the game, the patient must simply drag the ball and drop it inside the hole. This should be done by moving his ankle on the E-Wobble in the appropriate motion. The ball and the hole change positions depending on the type of motion or exercise. The 4 different types of exercises will be explained in more details in Section III.

C. Signal Conditioning

The accelerometer and gyroscope produce 4 analog signals (x(t), y(t), z(t) and v(t)) with values ranging between 0 and the input voltage V_{input}. These signals were digitized on a 10 bit microprocessor with a maximum sampling rate of 10 kHz. In order to properly calibrate the IMU, we need to remove the direct current offsets. For example, for the accelerometer this was achieved by removing the zero offset voltage from the output voltage supplied by the device using Equation 1.

$$V_{A(x,y,z)} = V_{out(x,y,z)} - V_{off(x,y,z)} \qquad (1)$$

where V_A is the actual voltage obtained after removing the voltage offset on a particular axis, V_{out} is the voltage outputted by the accelerometer, and V_{off} is the offset voltage as specified in the device's datasheet.

Accelerometers are known to be very sensitive to vibrations and mechanical noise whereas a gyroscope drifts over time (rate of change does not go back to 0 when rotation stops). Therefore, we deploy an open source filtering algorithm [12] that is very accurate, yet fast and can be implemented on small performance microcontrollers. The algorithm is based on the work of Mahoney [13] which has been extended by Madgwick [14]. We chose this algorithm because it is accurate and light at the same time which makes it possible to implement on an Arduino microcontroller.

D. Feature Extraction

The Feature Extraction is responsible of providing the Quality of Performance (QoP) feedback to the patient and the therapist. Since our target at this stage is to determine the reference kinematics of healthy users, the Feature Extraction will mainly generate a training performance report to the user that reveals the average angular velocity and the jerkiness on each axis. Herein, we describe briefly each parameter.

1. Angular Velocity

The average angular velocity $\dot{\theta}_M$ of the ankle's movements on each motion (M) can give an indication on the ability of the patient to achieve an appropriate walking behavior. Achieving a speed close to a healthy person can avoid any clumsiness in the patient's gait. The angular velocity on each motion was determined using Equation 2.

$$\dot{\theta}_M = \int_0^T \frac{d\dot{\theta}}{dt} dt \qquad (2)$$

Here, T is the time when the reaching state of an object is achieved (e.g. the ball is dropped inside the hole), and $\dot{\theta}$ is the instantaneous tilt velocity achieved on a certain motion (e.g. Eversion, Inversion etc…).

2. Jerkiness

By definition, jerkiness (J) (Equation (3)) is the rate of change of acceleration and indicates in our case how smooth the acceleration of the ankle is at a specific exercise (motion). The smaller jerkiness is, the smoother the movement of the ankle.

$$J_M = \frac{A_M(t_2) - A_M(t_1)}{t_2 - t_1} \qquad (3)$$

Where $A_M(t_1)$ and $A_M(t_2)$ are the accelerations at the time intervals t_1 and t_2 respectively.

E. Game Controller

The game controller receives the rotations and speeds measurements on the three axes and uses them to manipulate the game environment in effect.

3. BENCHMARKING THE ANKLE KINEMATICS

In this section, we present an analysis for the performance metrics of the ankle kinematics. We also derive a set of benchmarking equations and values that can be used to automatically measure the quality of ankle performance for ankle rehabilitation.

Fifteen participants, (4 females and 11 males), took part of the experimental evaluations. Each subject was asked to complete 4 sessions, each session comprised a number of tasks that focus on one type of exercise (motion). The subjects were all asked to use the right foot and to play with the E-Wobble while standing as was recommend by a therapist prior to the tests. The position of the ball and the hole were set depending on the type of exercise. Figure 3 shows 4 snapshots of the settings of the game in the 4 motions. As can be seen in Figure 3(a), the ball was placed vertically below the hole. Consequently, a plantar-flexion movement over the board would drag the ball vertically upward towards the hole. The yellow line was displayed to intuitively indicate the direction of the movement and to help the subject visualize any deviations from the right path. We have set the initial task angle for each exercise to 2 degrees which was incremented by another 2 degrees every time a task is finished. This was repeated until the subject reaches the maximum task angle of the session.

3.1. Findings

Herein, we present the outcome of the tests after all the participants finished all the sessions. Each metric was benchmarked first by determining its mean value over each task angle for all of the 15 participants and then, when applicable, by applying a regression analysis for each curve. The resulting interpolation equations of each metric provide the set of benchmark values with which the training performance of a task can be compared with while performing a certain exercise.

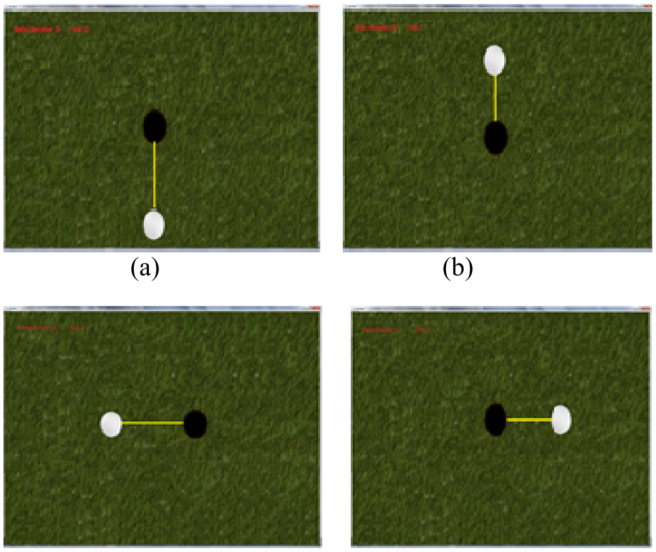
A. Session 1: Dorsi-Flexion Exercise

In this session, the task angles ranged between 2 and 20 degrees (the maximum tilt of the board). Figure 4 presents the curve of the dorsi-flexion's average-velocity $\overline{\dot{\theta}_D}$ of the 15 participants along with its interpolation. It can be seen that an increase in the task angle yielded approximately a logarithmic increase in the average velocity. Equation 4 reveals the resulting dorsi-flexion benchmark interpolation function.

$$\overline{\dot{\theta}_D} = 14.3Ln(\theta) + 7.8 \qquad (4)$$

where θ is the task angle.

On the other hand, we realized that the mean jerkiness maintained a constantly small value over the range of all task angles for all the participants. This might be due to the simplicity of the exercise for the healthy users on this motion which did not really cause them to do any jerky movements. The mean benchmark Jerkiness ($\overline{J}$) was found to be 0.48 g/ms (i.e. gravity/millisecond).



(a) (b)

(c) (d)

Fig.3. The 4 different settings of the ball and the hole. Position (a) was displayed during a plantar-flexion session exercise, (b) during a dorsi-flexion, (c) during an inversion and (d) during an eversion exercise.

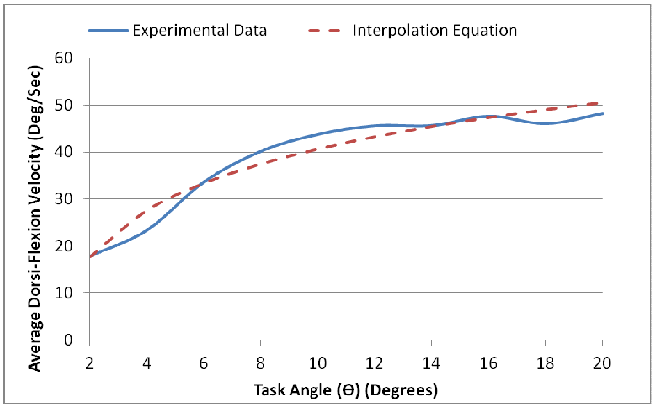


Fig.4. The average dorsi-flexion velocity over the various task angles

B. Session 2: Plantar-Flexion Exercise

Similarly to the dorsi-flexion exercise, the average plantar-flexion velocity ($\overline{\dot{\theta}_P}$ (Figure 5) took an increasingly logarithmic pattern over the task angle ranges and the jerkiness maintained a constantly small value with an average of 1.88 g/ms. Equation 5 presents the resulting plantar-flexion benchmark interpolation function of the velocity.

$$\dot{\theta}_P = 15.1Ln(\theta) + 9.2 \qquad (5)$$

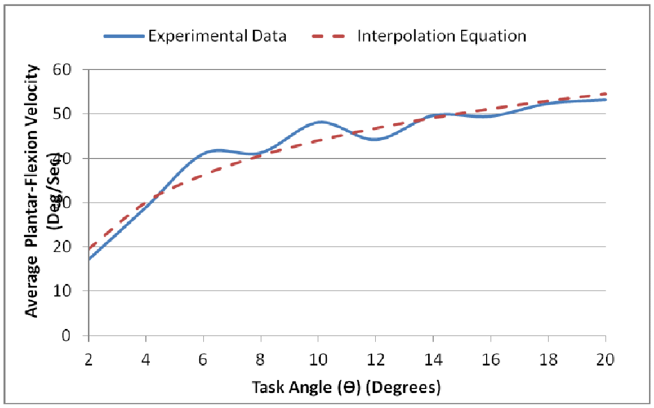


Fig.5. The average Plantar-flexion velocity over the various task angles

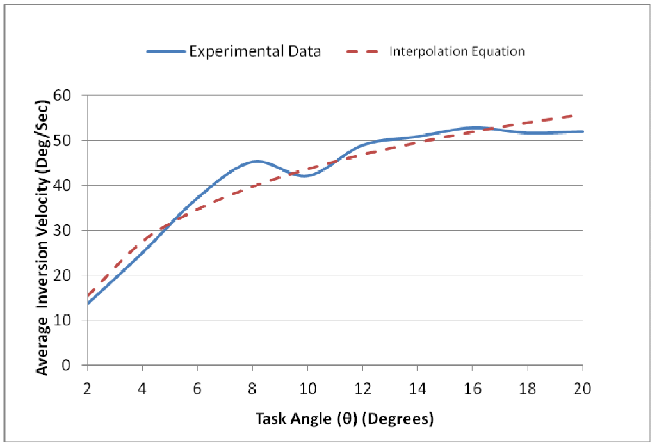


Fig.6. The average inversion velocity over the various task angles

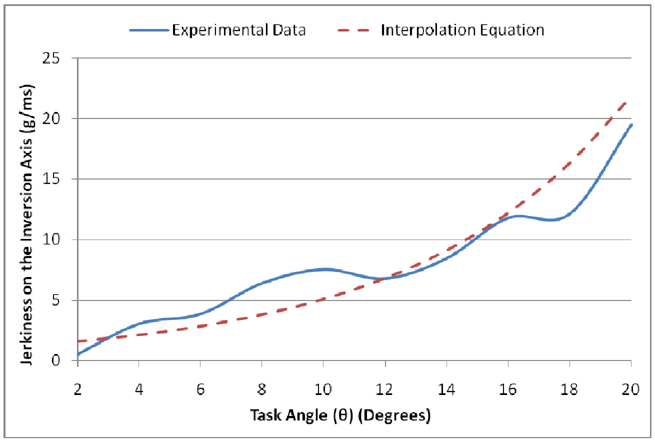


Fig.7. The mean inversion jerkiness over the various task angles

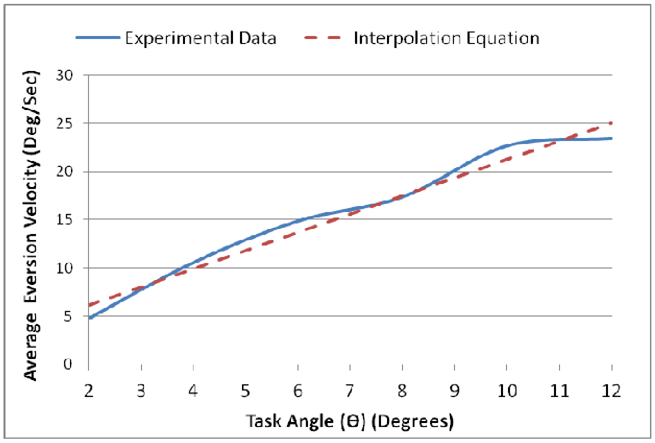


Fig.8. The average eversion velocity over the various task angles

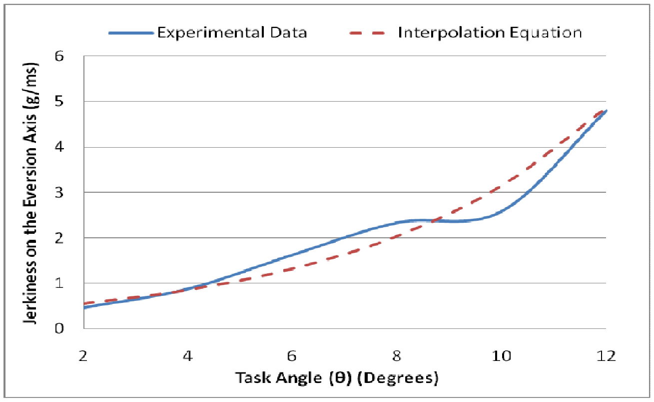


Fig.9. The mean eversion jerkiness over the various task angles

C. Session 3: Inversion Exercise

The inversion average velocity ($\overline{\dot{\theta}_I}$) took a logarithmically ascending pattern in function of the task angles which was the case for previous exercises (Figure 6). Nonetheless, the mean jerkiness increased exponentially with the angles (Figure 7). The reason of this increase in jerkiness here might be due to the difficulty of inverting the ankle which forced the subjects to do more ankle jerks while reaching high task angles. Equations 6 and 7 presents the resulting inversion benchmark interpolation function for the average velocity and jerkiness respectively.

$$\dot{\theta}_I = 17.5Ln(\theta) + 3.42 \tag{6}$$

$$J_I = 1.18e^{0.15\theta} \tag{7}$$

D. Session 4: Eversion Exercise

The eversion exercise was the most difficult one as we have learned from most of the participants. The majority of the subjects were able to reach 12 degrees only as a maximum task angle. Figure 8 and 9 presents the outcome of this exercise. Unlike, all the previous velocity curves, the average eversion velocity ($\overline{\dot{\theta}_E}$) followed a linear form which resulted in the benchmark interpolation function presented in equation 8. On the other hand, jerkiness increased exponentially as in the case of the inversion exercise and its interpolation resulted in Equation 9.

$$\dot{\theta}_E = 1.9 \times \theta + 2.4 \tag{8}$$

$$J_E = 0.36e^{0.22\theta} \tag{9}$$

4. CONCLUDING REMARKS AND FUTURE WORK

Home-based rehabilitation systems can enhance the therapy outcome if they support an efficient performance analysis that can help both the patient and the expert visualize the training progress. In this paper, we have tested our E-Wobble ankle training system with a number of healthy subjects to determine a set of reference training data and equations which could be used as benchmarks when examining patients' training performance. Our future work includes conducting more tests with a larger number of users to identify other major rehabilitation parameters. In addition, a fuzzy logic-based adaptation inference engine, whose membership functions are based on the obtained metrics, will be implemented to enhance the therapy experience and hasten the recovery period.

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