Determining Wrist Reference Kinematics Using a Sensory-mounted Stress Ball

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***Abstract*— One of the research voids in the study of home-based rehabilitation is the lack of benchmarks of the performance for various body kinematics. The objective of this work is to form a metric to evaluate the wrist motion for rehabilitation applications. The wrist motion components that were considered in this study are the angular velocity and acceleration in each plane of movement, namely Pronation/Supination, Flexion/Extension, and Radial/Ulnar Deviations. Two games were developed to measure wrist motion variables, namely the Cup and plate game (to measure the Supination/Pronation motions), and the Golf game (a horizontal version to measure the Radial/Ulnar motions and a vertical version to measure the Extension/Flexion motions). The derived values can serve as a motion benchmark to detect proper movement and steadiness of the wrist, in order to quantify the quality of patient performance.**

Keywords— Home-based rehabilitation, performance metrics, sensory stress ball, wrist training.

I. INTRODUCTION

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 years as a cost-effective and convenient alternative to traditional clinical rehabilitation [2]. 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 [3]), 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. Furthermore, 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).

Researchers have introduced a variety of sensory-based rehabilitation systems that use various types of interfaces to track the patient's training motion. One important limb to track is the hand due to the large number of patients who suffer hand impairments [5-6]. For instance, the authors in [7] proposed the use of an android-based mobile phone as a ubiquitous game therapy. Using the phone, a doctor can define a rehabilitation exercise where motion sequence is computed using the position and motion sensors already integrated in the phone. Patients should repeat the exercise at home and the performance logs are checked by the physician on the next appointment.

In another work, Morrow [8] chose an *Xbox* to run the graphics of a Virtual Reality (*VR)* game that could be controlled using a P-5 glove used for measuring the flexion of the fingers and the wrist position during the training session. *Xbox* is known to be widely popular among the young to middle age people but its acceptance among the elderly is not yet confirmed. Other group of researchers has chosen more complex systems that use expensive motion tracking cameras to detect the hand motions. For example, Duff [9] presented an adaptive mixed reality (physical and virtual) training system that uses multiple 3-D infrared-based motion capture cameras that were used to derive the kinematic features of the upper extremity movements. Alamri [1] used a tracking camera and a *Head-Mounted Display (HMD)* to design a framework that enables patients to perform a daily life exercise, such as moving a cup in an augmented reality environment. Despite the fact that a tracking camera provides robust results, operating the system is not straightforward as it requires an expert to setup and calibrate. Besides, the camera-based rehabilitation systems are generally expensive and unaffordable for a large number of people.

In this paper, we present our approach of hand rehabilitation using an intuitive and natural tool that patients are familiar with (a stress ball). Since the hand kinematics is complex, we focus on one particular joint, the wrist. We study the behavior of the human wrist in order to determine a set of reference values that can be used by therapists and designers as a benchmark with which the progress of a patient is evaluated. For this purpose, we have implemented a rehabilitation application that is comprised of both hardware and software. The hardware part consists of an improved version of the training stress ball discussed in [4]. In this version, the ball is mounted with 2 types of inertial sensors, an accelerometer and a *gyroscope*, and a *magnetometer*. The fused data allow the

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detection of wrist kinematics in all of the 3 Degrees of Freedom (DoF). The ball interface interacts with a set of two computer games specially designed to quantify the quality of performance of the wrist. We introduce and elaborate on the significance of a number of performance parameters (performance metrics) that can help identify potential impairments, both quantitatively and at a low cost.

The rest of the paper is organized as follows: Section II reveals the proposed home-based rehabilitation framework, Section III highlights the implementation details, Section IV elaborates on the users' evaluation and performance parameters, and finally, Section V draws the conclusion and our future work.

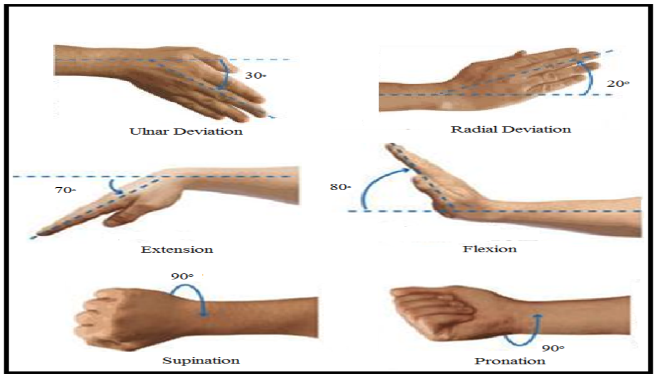


Fig.1. The 6 motions of the wrist

II. SYSTEM DESIGN

Passive devices, such as stress balls 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. Adding sensory capabilities to a stress ball has been attempted before by Wang [10] who deployed an air pressure sensor to detect the hand pressure exerted by patients over an air ball in order to manipulate a computer game. However, the functionalities of his tool were limited to the grip strength training only.

In this paper, we enhance the capabilities of the stress ball by adding three motion sensors that can detect the 3 DoF wrist kinematics (Figure 1). A 3 axis accelerometer, gyroscope and magnetometer were attached on the surface of the ball to provide all the necessary tilting and speed information. Specifically, the accelerometer's data together with the gyroscope were used to detect the angular tilting movements and their speeds. Rotation around the z axis is determined using the magnetometer. A pressure sensor was also mounted on the ball in order to allow intuitive grasping capabilities during the game. It is worth noting that capturing the gripping force of the user is not one of our objectives in this paper and will be left for future work. Figure 2 shows our proposed rehabilitation framework.

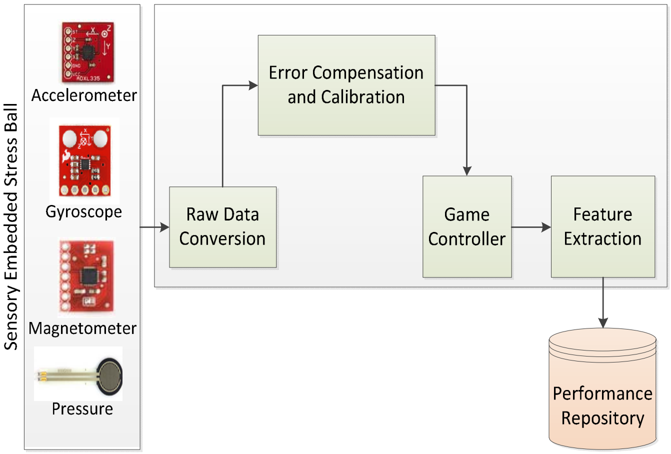


Fig.2. The proposed home-based rehabilitation Framework

A. Raw Data Conversion

The *Raw Data Conversion* first digitizes the analog signal generated by the sensors and then transforms the raw digital data coming from each device to appropriate units. The output of this module is a set of crisp values in degrees and degrees per second that represent the accelerations, speeds, and rotations on the three axes.

B. Error Compensation and Calibration

One important problem encountered with inertial and motion devices is that their accuracy is highly affected by external factors. For example, the accelerometer is very sensitive to vibrations and mechanical noise while a gyroscope drifts over time (rate of change does not go back to 0 when rotation stops). The *Error Compensation and Calibration* mechanism takes into account these factors by applying the necessary filtering for the data transmitted by those sensors to reduce the reading errors. Specifically, this mechanism applies a *fusion filtering algorithm* [12] to correct the angular readings of the accelerometer by checking the data coming from the gyroscope. The output of this mechanism is a decent estimation of the position and orientation of the user's wrist.

C. Game Controller

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

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 speed on each motion, the task error, the time, and the maximum ranges of motion (ROMs).

Fig.3. The sensory stress ball

III. IMPLEMENTATION

The sensory stress ball (Figure 3) was designed using a 6 DoF *Inertial Measurement Unit* (IMU) that is comprised of a 3-axis *ADXL 335* accelerometer and an *ITG 3200 Gyroscope* that were attached on the ball's top surface. We have attached a triple axis *MAG3110 Magnetometer* to the lower surface of the ball. The data fusion of the 3 sensors allows the detection of the three motions of interest (*pitch*, *roll*, and *yaw*). Tilt and drift errors were compensated using a *fusion* filter that was deployed on a *16 MHZ Arduino Pro-mini 328*. A *100 Lbs FlexiForce* force sensor was properly attached to go under the palm of the users.

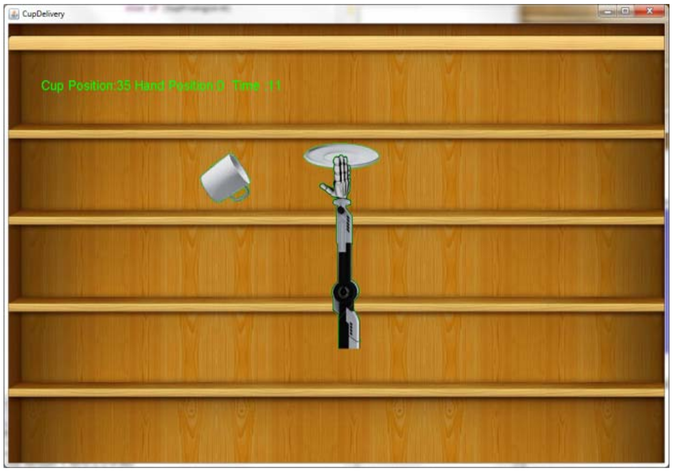
IV. BENCHMARKING REFERENCE KINEMATICS

In this section, we present an analysis for the performance metrics of the wrist kinematics. We also derive a benchmark that can be used to automatically measure the quality of wrist performance for wrist rehabilitation. The benchmark is composed of a metric of parameters whose ground-truth values that describe the performance of a ‘normal’ wrist motion are presented in this section.

Twelve participants, (2 females and 10 males), took part of the experimental evaluations. We have designed two games to focus on the six wrist movements, namely the Cup and plate game (to measure the *Supination/Pronation* motions) and a Golf game (a horizontal Golf game to measure the *Radial/Ulnar deviations* motions and a vertical Golf game to measure the *Extension/Flexion* motions). Each subject was asked to perform 3 tasks comprised of two sessions each that consist of different number of sets based on the scenario in effect. Below is a short description of each task.

A. Task1: The Cup and the Plate

The first task is based on the *Activity of Daily Life* (ADL) [11] concept and requires the patient to grasp a cup and place it on a plate (Figure 4). The task was divided into two parts (sessions) that aim to measure specific abilities on the *Supination* and *Pronation* motions. The user was asked to perform a set of *Pronation* movements in the first session followed by a set of *Supination* movements in the second.



Cup Position:35 Hand Position:0 Time :11

Fig.4. The Cup and Plate scenario. Here, the cup is positioned at 35 degrees from the plate.

At the start of each session, a hand and a plate are displayed vertically at the center of the screen with a cup placed at an initial position of ±*10* degrees from the plate (e.g. *+10* degrees when assessing *Pronation* performance and *-10* for *Supination*). The plate is always fixed at neutral position (e.g. at *0* degree) while the hand can move freely in a semi-circular pattern. To achieve the goal of the game, the user has to turn his/her wrist in the *Pronation* or *Supination* motion in order to reach the cup which can be grasped by exerting a certain amount of pressure on the ball. Then, he/she should turn his wrist in the opposite motion in order to reach the plate where the cup has to be released. Upon successfully completing a sub-task (set), a new cup is displayed with a *5* degree increment from the previous position. This task is completed once the user achieves a full rotation of *+90* and *-90* degrees on both motions.

B. Task2: Horizontal Golf

The Horizontal Golf game consists of a ball that the user has to simply drag to a hole by turning his wrist in the *Flexion* (Figure 5(c)) or *Extension* motion (Figure 5(d)). Here, the rotational movements of the wrist are mapped into translational displacements on the screen. Similarly to the Cup and Plate scenario, the hole is always fixed at the centre of the screen and the ball changes position at an incremental rate of 5 degrees every time a set is completed successfully. The first exercise (*Flexion*) ends when the user achieves *80* degrees while the other (*Extension*) is terminated when *70* degrees is reached.

C. Task3: Vertical Golf

The Vertical Golf game is the same as the Horizontal with the difference that the ball moves in a vertical direction. Therefore, to move the ball, the user should move his wrist in the *Radial* or *Ulnar deviations* motion (Figure 5(a) and (b)). These tasks end when the user achieves *20* degrees and *30* degrees on the *Radial* and *Ulnar deviations* motions respectively.

Table 1: Frequency domain analysis for measuring wrist motion tremor.

Motion	**Low Frequency Band (Joules)**		**High Frequency Band (Joules)**		**Tremor Index (LF/HF)**	
	Average	**StdDev**	**Average**	**StdDev**	**Average**	**StdDev**
Supination/Pronation (M1)	95390.94	58249.57	22778.49	13559.57	4.22	0.40
Radial/Ulnar (M2)	61908.47	26592.74	88494.04	50100.49	0.74	0.19
Extension/Flexion (M3)	36617.99	20716.72	25880.74	7733.33	1.41	0.15

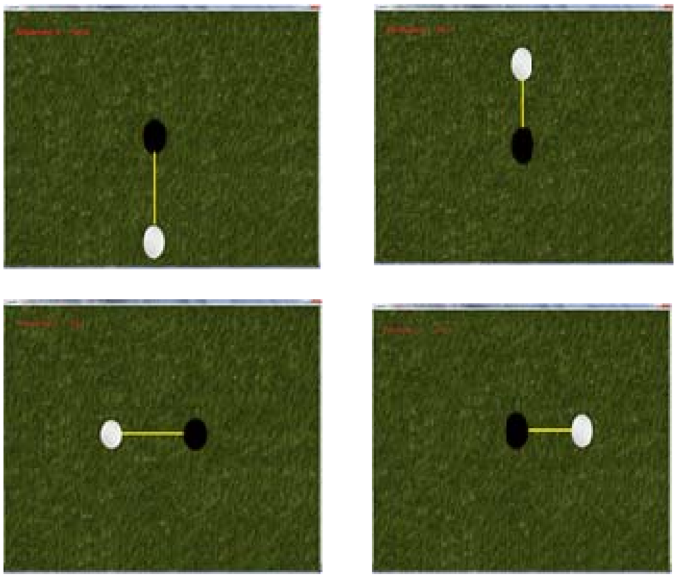


Fig.5. The Vertical and Horizontal Golf game.

D. Performance Parameters

Timely intervention is a very critical factor that can reduce the duration of the therapy if the impairment is verified at its early stages. Since therapists have very limited availability for each patient, it is very likely that they discover different impairments during the therapy but at late stages. We provide and measure potential performance rehabilitation parameters that can quickly visualize any potentially hidden deficiency while training with such tasks.

1. Angular Velocity

The *velocity* of the wrist provides a good indication on the ability of a patient to perform his/her daily life tasks in a timely manner. Achieving a speed close to a healthy person can avoid any clumsiness in the patient's hand movements.

2. Jerkiness

By definition, *jerkiness* (Equation 1) is the rate of change of acceleration and indicates in our case how smooth the velocity of the wrist is at a specific exercise.

$$J_M = \int_0^T \sqrt{\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^2} dt \qquad (1)$$

where J is the *jerkiness*, M is the motion (exercise), T is the time when the reaching state of an object is achieved, x , y , and z are the *3D* coordinates of the wrist trajectory. Jerkiness is a very well-known metric in biomedical engineering. The smaller its value is, the smoother the wrist velocity is.

3. Tremor Analysis

The goal of this analysis is to evaluate the steadiness of the wrist movement. Frequency domain analysis – Fast Fourier Transform (FFT) – is utilized to measure the frequency components of the wrist movement. Two frequency bands are considered: Low Frequency (LF) band and High Frequency (HF) band, where the Tremor index is defined as the ration LF/HF.

Figure 6 shows an example frequency spectrum plot for the overall wrist movement (including the 6 various wrist movements). It shows that a steady wrist movement has few low frequency components whereas the high frequency components are significantly lower. As shown in Table 1, the tremor index is a stable indication of the wrist steadiness (notice the low standard deviation). The results are shown for the three motions of the wrist: Supination/Pronation, Radial/Ulnar, and Extension/Flexion motions. Note that in Figure 5, a cutoff frequency of f = 0.4 Hz is used to divide the frequency spectrum into low frequency and high frequency bands.

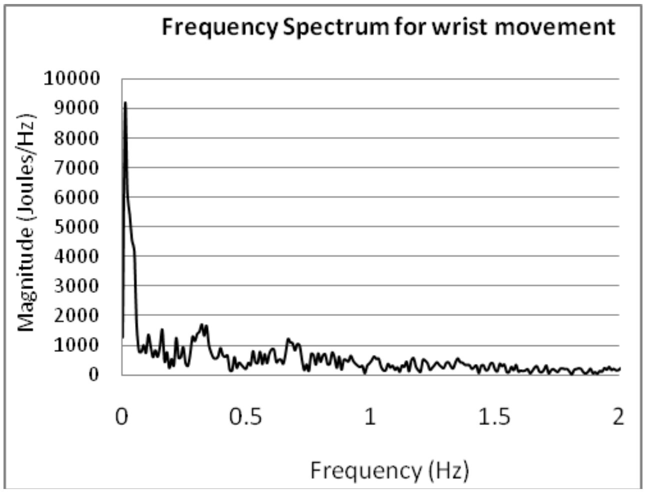


Fig.6. Frequency spectrum for wrist movement.

E. Findings

Figures 7 to 10 reveal the results obtained from our evaluations with the healthy subjects while performing the *Supination* and *Pronation* exercises. The graphs represent the mean values of all the *velocity* and *Jerkiness* captured data for all users over a reach angle between *10* and *90* degrees. The range between *0* and *10* degrees is omitted here because it is very small and therefore insignificant for such exercises. It can be intuitively realized from the experimental data in Figure 7 and 8 that the higher the task reach angle is, the faster the subjects tend to move their wrists. Similarly, *jerkiness* increases whenever the reach distance increases. In order to have a good estimate on what a normal *velocity* speed and *jerkiness* is at intermediate points, we apply a regression analysis for each of the graphs. The dotted curve represents the sketch of the resulting interpolation equation. The same approach has been applied for all of the remaining exercises. The following are the general interpolation equations for both the *angular velocity* and the *jerkiness* metrics:

$$\dot{\theta}_M = \phi \cdot e^{\theta / \tau_M} \tag{1}$$

$$J_M = \mu \cdot e^{\theta / \alpha_M} \tag{2}$$

where M is the type of motion (exercise), $\dot{\theta}$ is the *angular velocity*, J is the *jerkiness* of velocity, θ is the reach angle, α and τ are empirical coefficients, and ϕ and μ are the velocity and jerkiness coefficients respectively. Table 2 presents the values obtained after performing interpolation on the data captured from all the exercises along with the minimum and maximum values of the reach angle. We have noticed while performing *Radial* and *Ulnar Deviations* tasks that jerkiness was almost constant in both cases and was not really affected by the increase in angular movements or velocity. The *jerkiness* values found were *0.21* and *0.73* for *Radial* and *Ulnar deviations* respectively.

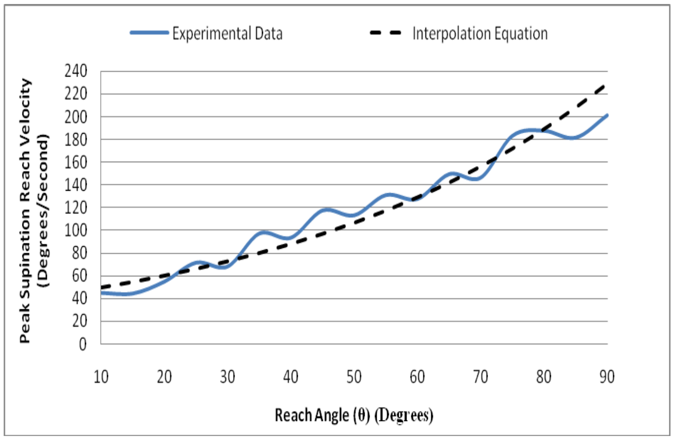


Fig. 7. The peak Supination velocity over different tilting ranges

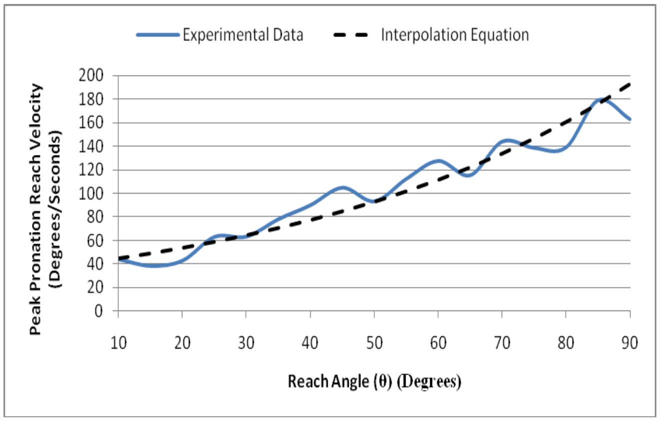


Fig. 8. The peak Pronation velocity over different tilting ranges

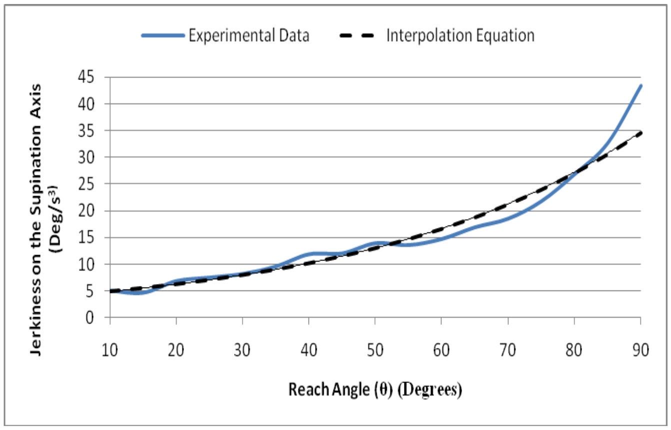


Fig. 9. Jerkiness on the Supination motion

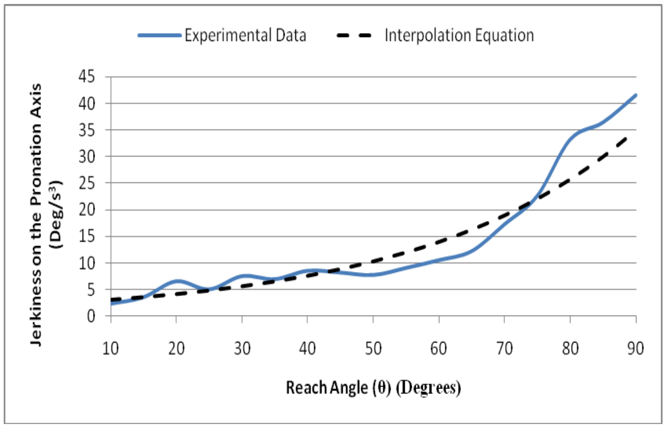


Fig. 10. Jerkiness on the Pronation motion

Table 2. Numerical values of the parameters of the velocity and jerkiness interpolation equations.

Type of Motion (M)	ϕ	τ	μ	α	**Reach Angle Constrains**
Supination	41.07	0.019	3.82	0.024	$10 \le \theta \le 90$
Pronation	37.16	0.018	2.20	0.031	$10 \le \theta \le 90$
Radial Deviation	23.62	0.037	0	0	$5 \le \theta \le 20$
Ulnar Deviation	32.95	0.017	0	0	$5 \le \theta \le 30$
Flexion	39.05	0.014	3.23	0.019	$10 \le \theta \le 80$
Extension	36.14	0.016	3.15	0.028	$10 \le \theta \le 70$

V. 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 wrist training system with a number of healthy subjects to determine a set of reference training data which could be used as a benchmark 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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