# Wearable Inertial Sensors for Exergames and Rehabilitation*

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*Abstract*—**This paper presents the design and development of an exergame for the wearable inertial sensor (WIS) system for performing range of motion (ROM) exercises. The salient features of the exergame include: (*i*) a sensor calibration user-interface (UI); (*ii*) a sensor mounting UI, (*iii*) a patient gaming UI; (*iv*) an instructor playback UI; and (*v*) an instructor exercise development UI. Along with the WIS system, the developed exergame UIs enable a user to perform ROM exercises in clinical and home-based environments. The exergame UIs can also be employed in a telerehabilitation setting for remote monitoring and assessment. Preliminary results on the efficacy of using the exergame environment is documented with: (*i*) sensor calibration time; (*ii*) sensor mounting and alignment time on the human body; and (*iii*) examination of user adherence to instructor programmed exercise routines.**

*Clinical Relevance*—**This paper describes an exergame platform suitable for technology translation of the wearable inertial sensor system for range of motion assessment and telerehabilitation.**

## I. Introduction and Background

Arm movements are crucial for performing several activities of daily living (ADL). Each ADL has minimum range of motion (ROM) requirements for the upper extremity (UE) joints to successfully complete the task [1]. However, neurological events such as stroke, multiple sclerosis, spinal cord injury, nerve damage, etc., can limit an individual's ROM, which in turn prevents them from performing several ADLs and lowers their quality of life. The pathway for recovery of lost motor skills includes: (*i*) determining the movement limitations to facilitate development of a treatment plan and (*ii*) gauging recovery to tailor treatment changes based on patient progress. The anatomy of the human arm with seven degrees of freedom requires advanced motion capture systems to measure the complex movements at the shoulder, elbow, and wrist.

Existing tools for ROM assessment used in clinical practice include: (*i*) hand-held measurement devices such as a goniometer [2], inclinometer [3], etc.; and (*ii*) video analysis software such as the Dartfish [4]. However, these devices do not capture all the degrees of freedom of arm motion. In a research setting, several commercially available motion capture devices are used that can be broadly classified under: (*i*) marker-based optical motion capture systems; (*ii*) electromagnetic position tracking systems; (*iii*) markerless motion capture systems; and (*iv*) inertial sensing systems. However, these systems require trained personnel for setup and data processing, which prohibits their translation from research to clinical practice and home-based environments.

A review of wearable sensors for applications to rehabilitation is provided in [5], which outlines the importance of deploying wearable technologies in home and clinical environments for data-driven rehabilitation. Moreover, providing healthcare rehabilitative services for the aging baby boomer population requires tech-savvy solutions to augment the therapists and clinicians for effective remote monitoring and telemedicine. Video and computer gaming facilitate an entertaining and engaging user experience while performing monotonous repetitive exercises and improve the therapeutic benefits of the treatment [6].

In this paper, we detail the salient features of an exergame (exercise combined with game) that extends our prior work in developing a wearable inertial sensors (WIS) system [7]. The International Society of Biomechanics has recommended the use of the joint coordinate system (JCS) for comprehensive visualization of the triplanar limb movements [8], [9]. In recent work [7], we developed a mechatronics-based WIS system that utilizes JCS for ROM assessment. Section II briefly outlines the mechatronics-based WIS system, section III itemizes the various interfaces developed for the exergame, section IV describes preliminary experimental testing and results, and section V provides some concluding remarks and discusses future directions for clinical and home-based evaluation using this system.

## II. WIS System and Exergame Design Motivation

The WIS system developed for UE motion capture and ROM assessment comprises of five wearable sensor modules, each consisting of a printed circuit board fitted in a 3D printed enclosure. Four UE arm sensors (left, right, upper, and lower arm segments) and one back-mounted sensor are used. These sensor modules are integrated with Bluetooth-enabled microcontrollers to stream their absolute orientation quaternions relative to the earth's magnetic and gravitation fields. In [7], we demonstrated the WIS system's ability to measure real-time triplanar UE ROM using the JCS [8], [9]. The absolute quaternions were further converted to relative quaternions to obtain the joint angles of each arm segment [7]. Furthermore, the results of a pre-clinical study on testing the usability and accuracy of the WIS system in contrast to an alternative motion capture technology is presented in [10].

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Figure 1 shows a user wearing the WIS system in neutral pose and the calibration holder for the WIS system. The WIS modules, each fitted with a BNO055 inertial sensor [11], require an initial calibration of their built-in tri-axial magnetometer, accelerometer, and gyroscopes (MARG) sensors for accurate absolute orientation measurement. Furthermore, precise mounting on the human body is crucial for accurate measurement of ROM. Our prior experimental study leveraged MATLAB-based user-interfaces (UIs) for data acquisition, calibration, and in-situ sensor mounting on the user's body [7]. The MATLAB-based UIs were best suited for experimentation with researchers, but less suitable for use by patients and therapists. Moreover, another prior study found that the use of an animated virtual coach for ROM training improves system usability [10]. Our design motivation for the exergame is to develop a holistic application that integrates multiple interfaces for sensor calibration, sensor mounting, and sensor data collection to assist patients and clinicians. Furthermore, such data-driven rehabilitative approaches will enable clinicians to tailor personalized exercises to patients' needs paving a pathway for precision rehabilitative treatment.

(a) (b)

Figure 1. (a) WIS modules worn by a user for range of motion assessment and (b) WIS modules placed in a sensor calibration holder

## III. EXERGAME DESIGN AND DEVELOPMENT

We have developed an exergame environment using the Unity3D software application to retrieve the data from the WIS modules and display the same with unique interfaces: (*i*) calibration UI for visualization and assistance with sensor calibration; (*ii*) sensor mounting UI for guided mounting of WIS modules on the human body; (*iii*) patient UI for practicing ROM exercises; (*iv*) playback UI for visualization of patient's performance by clinicians; and (v) instructor UI for creation of customized exercises for patients.

### *A. Calibration user-interface*

The WIS modules consist of tri-axial MARG sensors with each sensor yielding a calibration status ranging from zero (calibration not initialized) to three (all three axes calibrated). An intuitive design with horizontal progress bars is used to represent the calibration status for all the WIS modules. A 3D printed calibration or sensor holder is designed to house the five WIS modules and perform the calibration. The calibration routine for each sensors requires a specific procedure as follows: (*i*) the sensor holder needs to be placed stationary for calibration of the gyroscope; (*ii*) the sensor holder needs to be rotated to ≈45° about each axis for calibration of the accelerometer; and (*iii*) the sensor holder requires random movement in 3D space for calibration of the magnetometer. The users can utilize the visual feedback representing the calibration status of the sensors to perform the calibration routine swiftly. Figure 2 shows the calibration UI with indicators for five WIS modules, each with three sensors, with horizontal progress bars that have a discrete resolution of zero (full grey), one/two (partial grey/green), and three (full green).


Figure 2. Sensor calibration user-interface for visualization of sensor calibration status of five wearable inertial sensor modules each containing three MARG sensors

### *B. Sensor mounting user-interface*

Precise sensor mounting on the human body is critical for accurate measurement of joint ROM. Prior literature has explored the use of standard initial position [12] and determination of joint-to-sensor transformation using specific pre-determined movements prescribed to the user [13]. However, users with movement limitations may not be able to achieve a standard start pose or perform specific actions for anatomical calibration. An in situ technique can be used to mount WIS modules to human body for accurate measurement of joint angles [7]. The technique to mount the sensor on the forearm is intuitive due to the anatomical landmark created by the wrist joint on the forearm. However, the sensor placement on the upper arm segment proximal to the elbow requires precise mounting, which is difficult due to skin movements that result in erroneous internal-external rotation angles. To address this challenge, a UI is created for the users to visualize all the JCS joint angles (shoulder: plane, elevation, and internal-external rotation; elbow: flexion-extension, pronation-supination, and carrying angle). Next, the orientation of the UE joints in 3D space is replicated by an animated human model and the UI provides visual cues for rotating the left arm (LA) and right arm (RA) sensors until shoulder internal-external rotation is within $\pm 5°$ for the neutral pose. These visual cues allow the user to adjust the LA and RA sensors to achieve precise alignment with the arm. Figure 3 shows the sensor mounting UI with an animated model in neutral pose and the directional cues for the LA and RA sensors.

### *C. Patient user-interface*

A game environment emulating a virtual gym is developed for users to practice rehabilitation exercises. The virtual gym includes two human models that can be animated: (*i*) patient and (*ii*) instructor, both in the 3D environment allowing real-time visualization of their movements. The WIS module's absolute quaternions are wirelessly streamed and converted to relative quaternions of the shoulder and forearm movements, which are in-turn utilized to compute the JCS-based joint angles and ROM as in [7]. The UI facilitates a drop-down

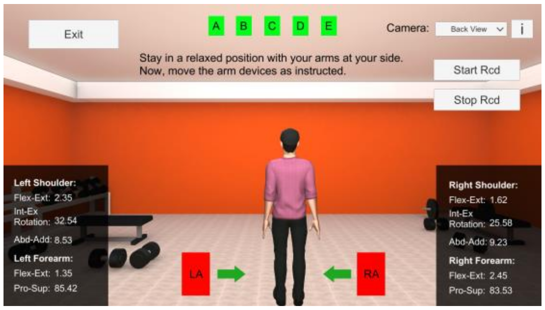


Figure 3. Sensor mounting interface showing directional cues for adjusting the sensor mounting on the subject's body

menu for selecting ROM exercises such as shoulder abduction-adduction, flexion-extension, forearm pronation-supination, etc. The relative quaternions are utilized to animate the patient model to provide real-time visual feedback on the movements being performed. The instructor model demonstrates the ROM exercise selected by the user. During a typical treatment session, the user observes the instructor model performing the selected ROM exercise and examines his/her own movements reflected on the patient model with the data streamed from the WIS modules. Since the movements are reflected on a standard model, the data is de-identified. The interface also provides different viewing angles such as front, back, left, and right views. A screenshot of the developed application showing the instructor and patient user from the back view is presented in Figure 4. The data from the patient UI is captured in the JCS framework as quaternions and saved for off-line asynchronous playback and evaluation by the clinicians at their convenience.


Figure 4. Patient user-interface with human models of patient and instructor performing shoulder abduction-adduction movements

## D. Playback user-interfaces

The playback UI facilitates the replay of the recorded ROM activity using the patient UI. The saved quaternion data is unpacked to create an interface similar to a media player with pause and play buttons. Additionally, a seek bar allows the clinician to navigate to specific temporal locations during the exercise for detailed examination of the movement. All the joint angles computed and saved during the exercise are displayed on the left and right panels corresponding to their respective joint angles. An information button "i" allows the user to toggle on/off the display of the joint angles. The camera view can be changed using the dropdown menu on top left (available views: back, front, left, and right). In Figure 5, the playback interface shows a patient human model

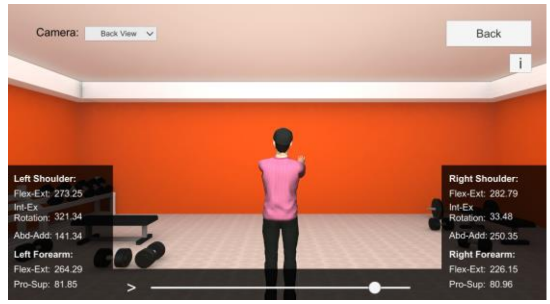


Figure 5. Playback user-interface for visualization of patient performance by the therapist

performing an exercise, the joint angles are displayed on each side.

## E. Instructor user-interface

An instructor UI is designed for clinicians to develop exercises that are personalized for individual patients based on their therapy needs. This UI consists of a virtual human skeletal model that utilizes the relative quaternions between the sensors to determine joint movements. It allows the clinician to enter the name of the exercise, select key points in the movement, and the time interval between the key points. Each key point saves joint positions of the UE enabling the clinician to create the desired exercises with very little effort. Once completed and saved, the exercise routine consists of the arm passing through the key points, with a set time interval between key points. Spherical linear interpolation, a Unity3D built-in quaternion interpolation, is performed between the key points for the set time interval to facilitate a smooth movement between all the key points from start to end. A screenshot of the instructor UI with an exoskeleton human model for adding key points is shown in Figure 6.

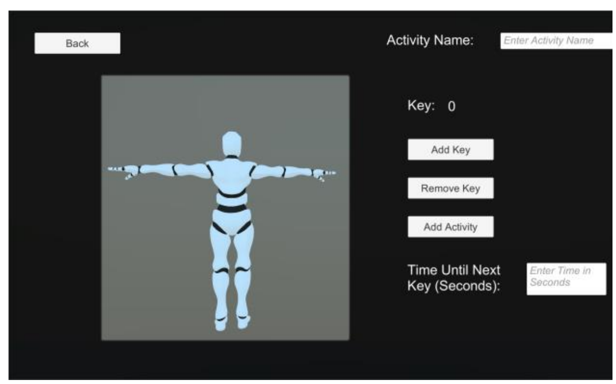


Figure 6. Instructor user-interface for creation of ROM exercises by therapists/clinicians

# IV. Experimental Testing and Results

## A. Experimental study

To validate the effectiveness of the developed UIs, two experiments were conducted which document the improvements in (*i*) calibration time and (*ii*) time taken for sensor mounting on the human body as well as (*iii*) examination of user adherence to instructor-programmed exercise routines.

## *B. WIS module calibration time*

In [7], we utilized text output to observe the calibration status. To quantify the effectiveness of the newly developed calibration UI, we compared the time taken for calibration between the prior approach, wherein one observes calibration status from text output communicated via serial port, *versus* the use of the calibration UI. With the UI, calibration time was initialized to zero upon turning-on the devices and the completion time was determined upon successful calibration of all the five WIS modules. The procedure was repeated for five trials and the resulting mean $\mu$ and standard deviation $\sigma$ for the time taken with both approaches are given in Table I.

## *C. WIS module mounting time*

In [7], a MATLAB-based real-time animated plotting interface was created to visualize the joint angles, and based on the resulting plot sensor mounting was adjusted. To evaluate the effectiveness of visual cues for sensor mounting on the human body, we compared the time taken for sensor mounting between the MATLAB-based interface *versus* the newly created sensor mounting UI. The time taken was recorded from the start of the UI to the successful alignment of the device, i.e., once internal-external rotation reaches within $\pm 5^o$. The procedure was repeated for five trials and the resulting $\mu$ and $\sigma$ of the time recorded with both approaches are provided in Table I.

TABLE I. COMPARATIVE SENSOR CALIBRATION AND MOUNTING TIMES WITH EXERGAME AND PRIOR INTERFACE OF [7]

| **Task** | **Time taken in sec. for the task ($\mu \pm \sigma$)** | |
|---|---|---|
| | ***MATLAB-based UI*** | ***Exergame UI*** |
| Sensor calibration | $41.34 \pm 4.17$ | $32.74 \pm 3.61$ |
| Sensor mounting | $23.95 \pm 2.13$ | $13.23 \pm 1.74$ |

## *D. Results*

The results in Table I indicate that the exergame interfaces improve the system performance. A media file of various exergame UIs is provided at https://youtu.be/SRaNKvxGtFY, showing the use of an instructor programmed ROM exercise routine being followed by a user. An experimental trial was conducted to assess the user's adherence to an instructor programmed exercise routine involving shoulder abduction-adduction with maximum ROM of ≈90° for six trials. Using the patient UI, the user performed six repetitions of the exercise. The ROM angle achieved by the user across six repetitions was found to have $\mu \pm \sigma$ of $(97.34 \pm 5.12)^o$.

# V. CONCLUSION AND FUTURE DIRECTIONS

This paper presents the design and development of exergame interfaces for effective use of the WIS system for ROM assessment. Additionally, the exergame interfaces capture triplanar movements crucial for understanding movement limitations in the JCS framework. The WIS system measurements facilitate data-driven methods for telerehabilitation. We recently developed a grasp rehabilitation device for stroke rehabilitation [14] and it is being used for a clinical trial involving patients with multiple sclerosis in a telerehabilitative setting [15]. Similar clinical trials can be performed using the WIS system for commercialization and broader adoption. We have also demonstrated the potential of using smartphones for data-driven therapy for children with autism [16]. Unity3D's capability to deploy applications on smartphones will be leveraged for developing these exergames as smartphone and tablet applications for use by patients and clinicians. Such systems will improve the connectivity between clinicians and patients to facilitate precision rehabilitation.

# DISCLOSURES AND DECLARATIONS

Drs. Raghavan and Kapila have patented technology for a Game-Based Sensorimotor Rehabilitator through NYU.

This paper on engineering design and testing of exergame interfaces did not entail experiments with human subjects. Preliminary experiments for data collection were performed by the authors themselves. Experiments involving human subjects using exergames will be conducted following the Institutional Review Board approval and reported elsewhere.

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