Development of a low-cost virtual reality-based smart glove for rehabilitation

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ABSTRACT

Presented is the third version of a low-cost bimanual rehabilitation system designed for in-home use by post stroke patients to improve hand and upper extremity function. Companion virtual reality software is still in development. The mechanical characterization and healthy subject (n=24) testing of the system sensors is described. These sensors include potentiometer bend sensors for finger motions and inertial measurement units (IMUs) for hand/arm position and orientation. The system accurately measures larger finger angles and all functional ranges of hand orientation (yaw, pitch, roll). Measurement of small finger angles and position of the hand in space requires further refinement.

1. INTRODUCTION

In this paper we describe the development and testing of a prototype low-cost virtual reality-based (VR) glove device designed to meet the needs of millions of people worldwide who are left with weakness in their hand and arm following a stroke (CDC, 1999). In the United States alone, nearly 800,000 people experience a new or recurrent stroke each year (Lloyd-Jones et al, 2010). At six months post stroke, 55-75% of survivors still have impaired function in the arm (Lai et al., 2002), and in cases with initial UE paralysis, complete motor recovery has been reported at <15% of cases (Hendricks et al., 2002). A key component of this poor functional recovery is impaired use of the hand. Although long term rehabilitation has been shown to provide significant functional benefits to patients with stroke (Dobkin, 1995), access to such care in the future may be limited due to cost. In the US, estimated total costs for stroke care are now near $30 billion/year (Dobkin, 1995). A low-cost VR device that is designed to improve hand and arm function, which individuals with stroke could use independently at home or as an adjunct to ongoing rehabilitation, would help to meet the needs of such patients. Potential benefits of this device include the ability to provide a wide variety of motivating environments to encourage repeated practice, and enhancement of motor learning via augmented feedback (Holden, 2005 and Krakauer, 2006).

Devices used to assist hand and upper extremity rehabilitation takes many forms. Oess et al. (2012) fabricated a glove using the same bend sensors as our system and many of the same sensor issues arose. Shefer Eini et al. (2010) used a visual tracking system for wrist range of motion, forgoing any sensors mounted on the subject. Other researchers such as Standen et al. (2010) use a combination of visual infrared tracking and mounted sensors. Another system by Brown et al. (2010) created a target reaching apparatus with and several hand manipulation/discrimination modules that prompted the subject to move by use of custom software. These devices with the exception of Brown et al. are not meant for bimanual rehabilitation and none combine sensors for finger angle as well as orientation and position of the hand.

The purpose of this study was to assess the accuracy of the bend sensors and inertial measurement units (IMUs) used in our recently developed glove system, the ATLAS, and to begin development of the virtual rehabilitation scenes to be used with the system. We first tested the accuracy of the glove sensors in a mechanical set-up. Next, we assessed how well goniometric and distance measures of hand/ finger movements mapped onto the voltage outputs obtained simultaneously from the glove when it was on a human hand, and how this mapping was affected by different hand sizes. These data will be used in the future to develop a calibration algorithm that adjusts system outputs for differences in hand size. This method

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would improve the accuracy of mapping a subject's hand movements to the virtual scene, and presumably the overall effectiveness of the virtual training scenes used with the system.

2. METHODS

2.1 ATLAS System Description

Our bimanual glove system, version 3 (Fig. 1) has four components: gloves, IMUs, resting base for hands, and electronics unit. The gloves use potentiometer bend sensors (Flexpoint Sensor Systems, Draper, UT, USA) to measure finger joint angles and are mounted under a flap of fabric on the back of the glove (dorsal aspect of hand). The bend sensors have sleeves that run up the back of the index, middle, and ring finger, and the thumb. The sleeves allow the bend sensors to 'slide' on the fingers to accommodate length changes caused by finger flexion movements. During extension, the sleeves prevent the sensors from buckling upward and away from the fingers. This feature is designed to improve the fidelity of the finger motion monitoring.

Figure 1. *ATLAS bimanual glove system*

The IMUs (Sparkfun, Boulder, CO, USA) are contained within enclosures that mount on the back of the hand and are used to assess hand orientation (yaw, pitch, roll). The resting base for the hands and forearms is designed to standardize start position during training and to re-zero the IMUs before each block of trials, via a Hall Effect sensor. The IMU used in the system has nine degrees of freedom: 3 axis accelerometer, gyroscope, and magnetometer. The IMU contains an Arduino microcontroller that was used to write an algorithm to calculate orientation. We attempted to also measure hand position in space (x,y,z) via the IMUs, but these measures were not sufficiently accurate, and will require an alternate solution. Cables connect the IMU and Glove outputs to the electronics unit.

The electronics unit contains another microcontroller as well as the filtering and amplification circuits needed for the potentiometer bend sensors. The data from the gloves and the IMUs are combined by the electronics unit microcontroller and sent via USB to the computer. The system is powered by the USB connection allowing it to be connected to any powered USB connection on any laptop or desktop computer. The glove is designed to be low enough in cost to be a feasible purchase for patients to use in their homes (~$150/glove).

2.2 Mechanical Testing

Prior to healthy subject testing the ATLAS sensors were tested mechanically using custom designed test beds. The bend sensors were tested over a long duration trial of 60 minutes for signal consistency and tested using a cylindrical test bed to measure voltage output versus bend radius. The IMUs were tested using a two degree of freedom motorized test bed. Trials of the IMUs were run in the range of ±50 and ±75 degree in roll, pitch, and yaw. The mechanical testing was consistent with the results found from the healthy subject testing. For more information see Sivak (2012).

2.3 Human Subject Testing

The study was approved by the Northeastern University Office of Human Subjects Research Protection, and all subjects signed an informed consent prior to their participation. A total of 24 subjects (11 males, 13 females; mean age=25.5±6.9 yr) with a broad range of hand sizes, were tested. Hand tracings (Fig. 2) were obtained from subjects and marked with the following landmarks: styloid processes of the radius and ulnar; heads and bases of the first and fifth metacarpals, metacarpal-phalangeal (MCP), proximal-interphalangeal (PIP) and distal-interphalangeal (DIP) joints of each finger. Using these landmarks, a variety of anthropometric measures were calculated. To assess how well the hand sizes of our sample represented the overall population, we used a hand size calculation method similar to that used by the US Army, so our values could be compared to those of their large (n=3782) anthropomorphic database (Gordon, 1989). Length was measured from tip of the middle finger to the center point between styloid processes and width was measured from the fifth MCP to the second MCP (Figure 2, red dotted line). For our sample, mean width was 9.4 ±0.5 cm and length was 20.2±0.5 cm for males; for females, mean width was 8.4 ±0.5 cm and length 18.1 ±1.1 cm. In terms of percentiles, our female subjects hand size values ranged from the 5th to the 99th percentile of the army sample; males ranged from the 35th to 99th percentile of the army sample. Although smaller hand size for males was not represented in our sample, smaller hand size in general was represented by the female subjects. Because of this percentile distribution, our sample, though small, appears to be a fair representation of overall population hand size. Figure 3, below, shows the hand size distribution for our sample.

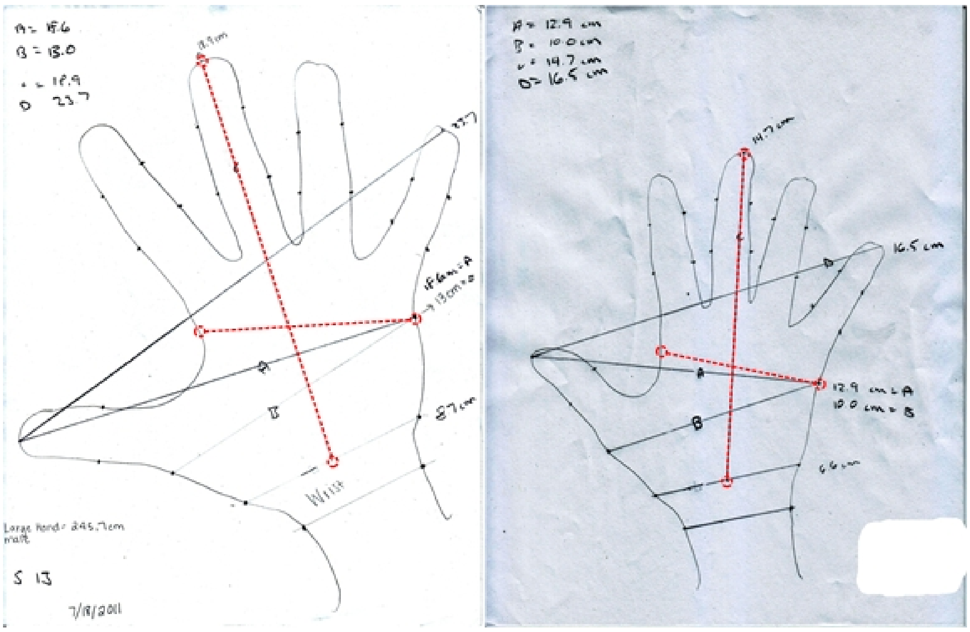

Figure 2. *Two subject's right hand tracings.*

2.4 Procedure

Testing of each subject was done in a single session of approximately two hours. After hand tracings (Fig. 2) were obtained, subjects donned the right or left glove and underwent one of two protocols, presented below.

2.4.1 Bend Sensor Protocol. This test consisted of placing each subject's hand on a series of templates for static angle measurements. Each of these templates was designed to place the subject's fingers in a desired position at which time measurements of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints were taken for the thumb, first, middle and ring fingers using a manual goniometer (Fig. 4). After the goniometer measurements were collected, the subject was asked to maintain the position for five seconds while the bend sensor voltage was recorded.

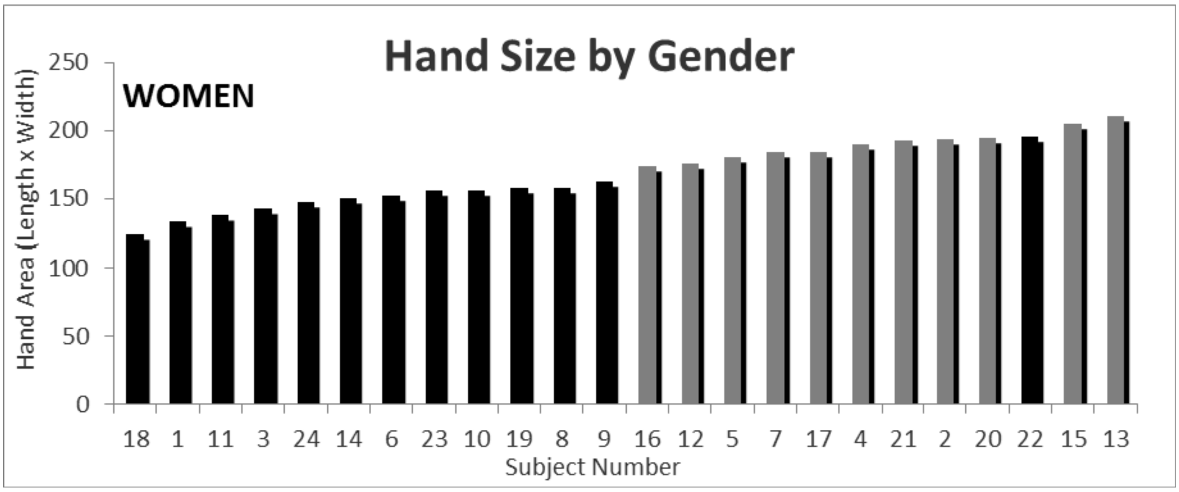

Figure 3. *Chart of hand size by gender*

Figure 4. *Examples of positioning templates and goniometric measurement*

For the bend sensor protocol, these measures were taken on the right hands of all subjects (n=24), and on both the left and right hands for n=12 subjects. The list of tests performed is below.

1. Baseline: all joints fingers and thumb at full extension (0° or 180° on the goniometer)
2. 45° MCP: all fingers at 45° template for MCP Flexion
3. 45° PIP: all fingers at 45° on template for PIP Flexion
4. 90° MCP: all fingers at 90 degrees on template for MCP flexion
5. 90° PIP: all fingers at 90 degrees on template for PIP flexion
6. Max Thumb MCP: instruct subject to flex thumb maximally at MCP, the goal is isolated MCP (subject may use passive motion to obtain maximal flexion)
7. Max Thumb IP: instruct subject to flex thumb maximally at IP, the goal is isolated IP
8. Max Thumb MCP/IP: instruct subject to flex thumb maximally at MCP and IP
9. Thumb 45° MCP / 45° IP: thumb MCP and IP at 45 degrees flexion
10. Thumb-small finger: thumb opposition to pinkie fingertip
11. Thumb-index: Thumb opposition to index fingertip
12. Max MCP / IP: instruct subject to passively flex thumb maximally in IP and MCP
13. 90° MCP / 90° PIP: place subject on the template device so that PIP and MCP of digits 1-3 are at 90°. Have this done with forearm in the vertical position.
14. 45° MCP / 45° PIP: place subjects hand on the appropriate template so that PIP and MCP of digits 1-3 are at 45°. This will also be done with forearm in the vertical position.
15. Dynamic open-close hand: Instruct subject to open and close hand fully for five seconds. The subject should start with the hand in a comfortable fist, all joints will then be measured before opening of the hand begins. The subject will then open and close their fist for five seconds. Movements are timed with computerized metronome, @ 1 Hz.

2.4.2 IMU Protocol. This test looked at the device's ability to measure hand orientation and position in space (n=12). First, subjects completed the bend sensor protocol using the right hand. Then, they completed the IMU hand in space protocol using the same (R) hand and arm. This consisted of moving the wrist and/or forearm/arm in six different ways: roll (supination/pronation), pitch (wrist extension/flexion), yaw (radial/ulnar deviation), medial-lateral (x), forward-backward (y), and up-down movements (z). The subject was asked to move through a distance of ±30cm for 5 seconds, hold the end position for one second, and return a total of five times for each test. Again, movements were timed using a computerized metronome. The list of tests is below.

1. Roll: Subject used a template to rotate forearm from pronation to supination and back (~180°)
2. Pitch: Subject used arm rest and template to facilitate wrist flexion and extension (full excursion)
3. Yaw: Subject performed radial and ulnar deviation on top of a guide (full excursion)
4. Side to side: Subject slid their hand from left to right 60cm
5. Forward-backward: Subject slid their hand forward and back 60cm
6. Up-Down: Subject slid their hand against a vertical guide for 60cm of movement

2.5 Virtual Scene Design

We planned a scene design that would allow us to test a new concept, that of direct or indirect mapping. For direct mapping, virtual scenes would be created which realistically mimicked subject movements in the real world by showing a virtual hand moving on the screen in concert with the subject's movements. For indirect mapping the subject's actual movement in real world would be mapped onto an avatar that could perform different movements. The advantage of direct mapping is that the visual feedback from the VR will be more accurate and understandable to the subject, and make it easier to correct mistakes, potentially enhancing motor learning. On the other hand, indirect mapping allows for more complex and interesting scenarios that may enhance fun and motivation. These factors may also enhance motor learning. We plan to test which of these approaches to virtual mapping is more effective.

3. RESULTS AND ANALYSIS

3.1 Bend Sensor Analysis

The bend sensor protocol was performed on the right hand of all 24 subjects and left hand of 12 subjects. For 0°, 45°, 90°, the targeted joint was positioned at that value while the other finger joints were positioned as close to 0° as possible. For the combination tests, 45°/45° and 90°/90°, MCP and PIP joints were simultaneously positioned at the same angle. Figure 5 below displays the data for the goniometric measures versus the test template for all the 45° and 90° tests.

Overall, the desired positions, especially at 45°, were achieved with good accuracy, but there was some variation due to differences in subjects' hand size, finger length, slope of MCP joints relative to the horizontal and other anthropometric factors. The 90^{o} positions were limited as well by the glove itself plus the liner glove which was worn for cleanliness. Therefore, we use the actual measured goniometric values for each joint to test the correlation with the voltage values at each static position tested.

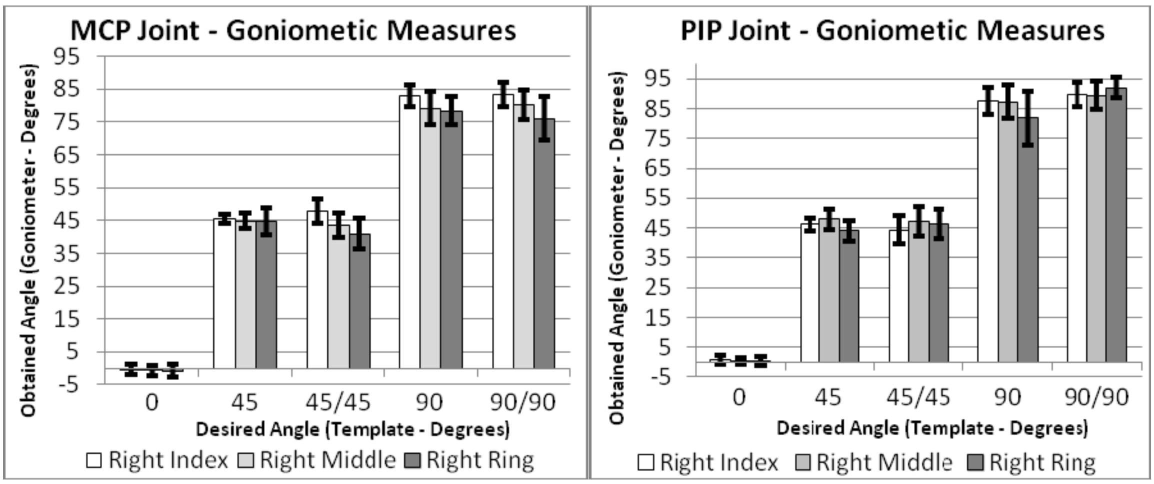

Figure 5. *Charts of goniometric measures vs. test template*

The amplification and filtering circuit of the potentiometer bend sensors creates an exponential output. After characterization testing of the sensors the circuit was created and the results of the characterization match the results found in the chart above. However, during the human subject testing it was found that the response of the sensor at low angles was too low. This is due to the minimum voltage being read by the microcontroller and has since been fixed by increasing the initial resistance. Figure 6, below, shows the exponential trend for each sensor on the right hand obtained from the human subject tests. Because the sensors are manufactured in batches the different batches can have different responses. This is the most likely reason why there is a difference in the sensors responses for the different fingers. This could also be due to fit of the glove and mounting of the sensor. However, we did examine Male vs Female data as a proxy for hand size, and found a similar curve fit, so hand size alone is not the likely reason.

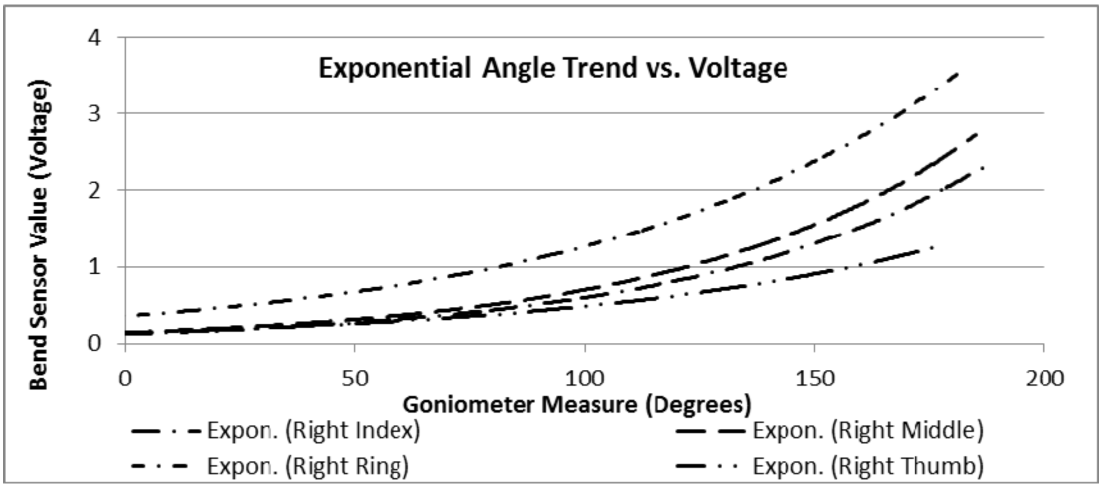

Figure 6. *Chart of exponential angle trend vs. sensor voltage*

3.2 Inertial Measurement Unit (IMU) Analysis

Data was collected over ten subjects for the IMU testing. The angles found in the charts below are based on Euler navigation angles where 180° corresponds neutral in the wrist for roll and pitch and true north in terms of yaw. The following charts display the results found from the IMU testing in Euler angles.

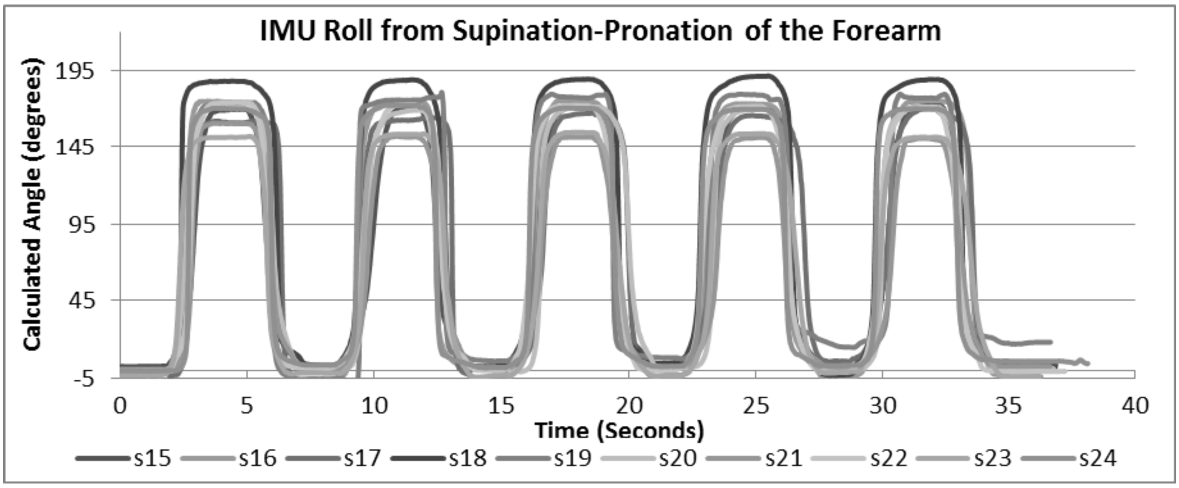

Figure 7. *Chart of IMU roll over five repetitions of forearm supination and pronation*

The chart above displays the results of the roll test across the 10 subjects. Each subject was able to maintain the cadence of the metronome that was used to time the movements and stayed within the expected range for supination and pronation (Norkin & White, 2009).

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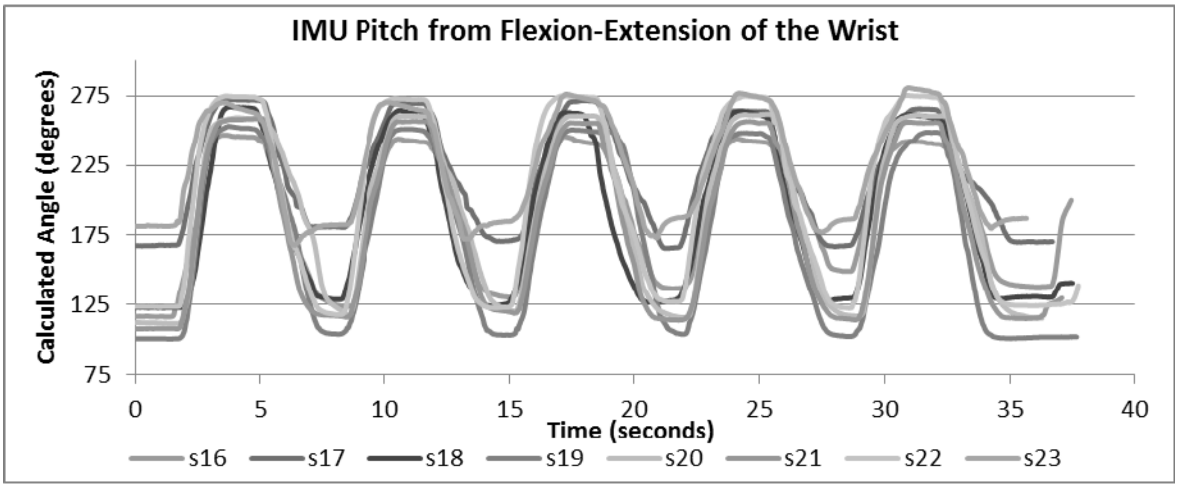

Figure 8. *Chart of IMU pitch over five repetitions of wrist flexion and extension.*

The pitch results, above, were only analyzed on 8 subjects as the data for two subjects was corrupted for this measure. As mentioned previously the angle corresponds to the Euler angle so that neutral for the wrist is 180°. Again the subjects were able to follow the cadence of the movement and the angles found were within the expected range for wrist flexion/extension (Norkin & White, 2009).

The results of the yaw testing are in the chart below. The Euler angle for the yaw test is 180° for true north. The variations seen in the initial angles of the tests are due variations of subjects' position relative to true north at the beginning of the test, not variations in wrist position itself. All subjects began in radial deviation, moved to neutral, then ulnar deviation, back to neutral, and so on. The subjects' range of movement was comparable to the guide used for the testing and the normal range expected for the movement (Norkin & White, 2009).

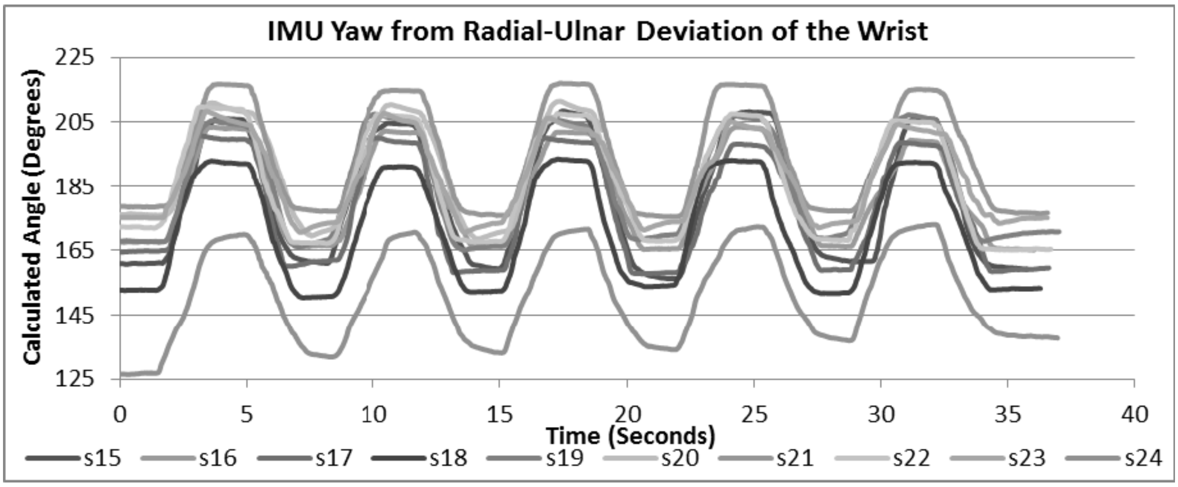

Figure 9. *Chart of IMU yaw calculation over five repetitions of radial-ulnar deviation*

3.3 Virtual Scene Development

Four scenes have been developed, 2 for direct and 2 for indirect modes. Figure 10, below, shows an example for one direct-indirect pair of scenes designed to train wrist extension with finger extension.

4. CONCLUSIONS AND FUTURE WORK

We plan to revise the electronics in the amplifier to yield a more linear response curve for the voltage-goniometer mapping, and assess further how hand size specifically affected this mapping. Finally, using these data, we plan to develop a calibration algorithm to adjust system output for variations in hand size, if it proves necessary to improve system accuracy.

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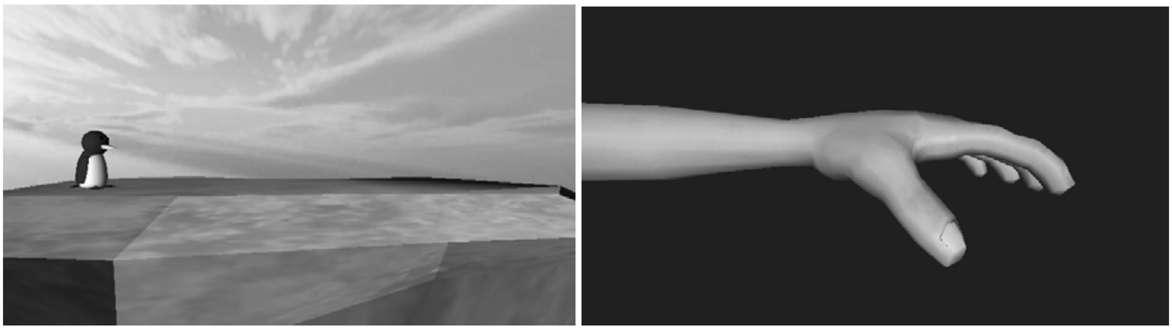

Figure 10. *Direct and indirect mechanics for a virtual scene for the ATLAS*

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