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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

A SENSOR-BASED LAP COUNTER AND TIMER FOR USE IN SWIM TRAINING

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ABSTRACT

The ability to analyze a swimming workout is of interest to competitive and recreational swimmers alike. Traditional methods of workout analysis including video review and manual lap and stroke count are tedious, time consuming, and subject to human error. To improve the analysis, several studies have been conducted involving sensors to track swimming data, and products have been released on the market. The studies and products currently available have used sensors such as accelerometers, gyros, and magnetometers to track swimming data, yet no publication directly compares the outputs from each simultaneously to determine the most effective sensor and axis on which the data analysis can be based. This research study shows that it is possible to create a swimming lap counter which only uses antero-posterior acceleration data and a computer algorithm to determine the type of swimming stroke used, number of length completions and durations, and number of rest completions and durations. A unique prototype and analysis algorithm are also developed.

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Chapter 1

Introduction

1.1 Purpose

For years in the world of competitive swimming, coaches and swimmers have been using technology to track swimming performance and analyze technique. Traditionally, the analysis approach has involved manually counting laps and/or strokes per lap, either by the swimmer or coach during the workout or post-workout through video review. These methods are tedious, time-consuming, and subject to human errors in counting and timing. Also, only one swimmer can be accurately evaluated at a time (Pansiot et. al., 2010).

Swimming is also a popular recreational activity during which the swimmer may not have a coach present. If the swimmer does not have a coach, in order to accurately record data length-by length or even set-by-set, they have no choice except to commit all of the data to memory, record data after every set, or manually analyze a video of themselves post-swim. Any one of these methods would discourage the swimmer from completing a full analysis of their daily workouts, limiting their ability to identify weaknesses, track progress, and ultimately improve as a swimmer.

The purpose of this study is to design a swimming lap counter which uses sensors to accurately track data for multiple strokes and turn types while being minimally disruptive to the swim in-progress. Several studies have previously been performed with similar objectives, and this study hopes to expand on the knowledge base of that research. Also, some lap-counting technologies currently exist which perform similar functions to those intended in this study, but the research hopes to provide additional insight into the functioning of these devices and provide a unique solution.

1.2 Swimming Basics

In order to begin, certain basics of swimming technique are useful to keep in mind: the components of a workout, the stroke types, and the turn types. Each is discussed here briefly.

There are three basic components to a swimming workout: free-swim, turn, and rest. The free-swim includes the portion when the swimmer is moving directly toward one wall or the other. The turn involves when the swimmer quickly changes direction to begin swimming toward the opposite wall. Rest involves the swimmer remaining stationary at the wall for an appreciable amount of time before beginning the free-swim again.

There are also three different stroke types used in basic swimming sessions: freestyle, breaststroke, and backstroke. The fourth stroke, butterfly, is not considered in this study because of the stroke's limited application in recreational swimming. All three stokes involve the swimmer moving in the anatomical superior direction. However, the freestyle and breaststroke have the swimmer's anterior direction pointing down, whereas the backstroke involves the anterior direction pointing up. During the free-swim, the swimmer's orientation remains relatively consistent until a turn is made or a rest is taken.

There are two different turn types: the "open-turn" and the "flip-turn". The open-turn can be used with any of the strokes, but is most commonly used with the breaststroke. Novice swimmers may favor an open-turn style because the technique is simpler than the flip-turn. The basic technique of an open-turn involves: contacting the wall with the hand, bending the legs and swinging the hips underneath the torso until the feet touch the wall, then pushing off the wall with the feet to propel the body in the opposite direction (Luebbers "Swimming", 2012). The basic technique of a flip-turn involves: approaching the wall, dipping the head and pulling the body into a tuck to perform a “flip” along the body’s medio-lateral axis, kicking off of the wall with the feet as they swing around, and then rolling the body along the superior-inferior axis to return to the free-swim orientation (Luebbers “Freestyle”, 2012).

The changes in orientation and direction associated with all of the components are particularly useful in this study since the sensors tested (accelerometers, gyros, and magnetometers) react to changes in these properties.

Chapter 2

Previous Research

Several experiments have already been conducted to monitor swimming activity using varying technologies. Some of these experiments used complex, multi-faceted systems which provided detailed results but would be impractical for recreational swimming use. Other studies employed simpler data acquisition systems, but the experimental scopes had limitations. It is from this latter group of experimental technologies that the inspiration for this design project was derived. This section provides an overview of the relevant, previously published studies and summarizes the ways in which this study hopes to expand the knowledge base.

One study, performed by researchers in Nathan, Australia, used a multi-axis accelerometer paired with a data-collecting device worn on the lower back of the swimmer to record acceleration data while swimming. The results of this experiment were promising, and the resulting graphs could be interpreted to determine when a turn was performed, and even the type of stroke being performed during free-swim. One key contribution from this study was that a spike in the acceleration data for the antero-posterior axis corresponded to when a turn was at its maximum, and that a spike in the acceleration data for the superior-inferior axis marked a push-off from the wall. However, this study was limited to using only “elite level” swimmers performing the freestyle stroke for a single set and using flip turns (Davey et.al., 2008).

Another study, performed by researchers at the Kaunas University of Technology, introduced the use of a multi-axis gyro in addition to a multi-axis accelerometer to record swimming data. This device was also mounted on the swimmer’s lower back. The purpose of this study was to determine if tracking swimming data was feasible using kinetic sensors. The main difference between this study and the aforementioned study was the introduction of a gyro into the data analysis. Again, the results proved successful, but the added benefit of including a gyro was not significant. The data analysis algorithm used in this study was also not explicitly stated, although the use of MATLAB software to create the algorithm was mentioned (Daukantas et. al., 2011).

Yet another study, performed by researchers at Imperial College London, was conducted with similar intentions to the previous two, except the tracking device was placed on the user's goggles near the ear. The experiment proved successful in recognizing the occurrence of a wall push-off as well as the type of stroke being performed (Pansiot et. al., 2010).

One more study, performed by researchers at the University of Oulu, once again intended to determine if tracking swimming data was feasible using kinetic sensors. This study was unique in that it tested the positioning of a multi-axis accelerometer both on the swimmer's back and on the swimmer's wrist. The results showed that the back-worn device more accurately determined the stroke being used, but both the back-worn and wrist-worn devices showed equal accuracy in counting the number of strokes performed. Also, the experiment tracked the data using variable sampling frequencies and determined that a sampling frequency as low as 5Hz could be used to accurately determine the stroke count and type (Kinnunen et. al., 2011).

These four studies summarize most of the unique, relevant observations presented in previously published research articles. The purpose of this research project is to expand the scope of the existing knowledge in the following manner: inclusion of multi-sensor analysis (accelerometer, gyro, and magnetometer), determination of the most useful sensor, inclusion of all three of the basic stroke types (freestyle, backstroke, and breaststroke) as well as the two turn types (open and flip) in the data analysis, and the inclusion of rest-period recognition between swimming sets.

Chapter 3

Current Products and Patents

3.1 Current Products

There are several types of lap counters currently available on the market, each employing slightly different technologies. One such technology which is on the market today is a touch-based sensor which is placed on the wall of the pool and makes a time record of every lap completed (such as the “Lap Track by Finis, see Figure 3-1). This device helps the swimmer keep track of the number of laps completed and the time of each, but is inherently limited to only those functions. Also, the swimmer must press that particular spot at the completion of every lap for the device to function (“Lap Track”, 2013).

Figure 3-1: “Lap Track” by Finis

Another technology involves a stopwatch-style device, which can be worn on the swimmer’s wrist or finger (such as the “Chrono 100” by SportCount, see Figure 3-2). This technology is limited to the same functions as the touch-based sensor on the pool wall, except instead of needing to hit a particular spot on the wall, the user must remember to press the button at the completion of each lap, introducing human error as well as potential disruption of turn technique ("Lap Counters & Timers", 2013).

Figure 3-2: "Chrono 100" by SportCount

The last type of technology available is a stopwatch-style device which uses sensors to automatically time swimming laps. This technology is the inspiration for this study. There are several different models available including the “PoolMatePro” by Swimovate (see Figure 3-3).

This model senses lap completions and uses an algorithm to provide various statistics about the workout. The model also comes with a software package which provides the results in a graphical display for a user-friendly interface ("PoolMatePro", 2013).

Figure 3-3: "PoolMatePro" by Swimovate

This research project targets the development of a device similar to the PoolMatePro while providing additional insight into data acquisition using different sensor types as well as the development of a unique analysis algorithm for swimmers of all ability levels including all strokes and turn styles.

3.2 Patent Search

The current products on the market use some of the available patented technologies, such as the "Swimming Lap Counter". The patent for this device includes the use of a two-axis magnetometer within a wristwatch configuration to distinguish when laps are completed. The data is processed in real-time via a microprocessor contained in the wristwatch, and the results are displayed on the screen (Chan, 2012). Another patent, the "Motion Analysis Device for Sports," uses an accelerometer to accomplish the same goal (Christopher and Irlam, 2012). These patents are good examples of the technologies that may be utilized in the PoolMatePro.

Other technologies have been patented which do not currently have products associated with them. For example, the "Electronic Timing Swimmer's Goggles" combines an accelerometer-based lap counting system, heart-rate monitoring system, and real-time digital display all incorporated into the swimmer's goggles (Taba, 1997). This system seems relatively complex and difficult to manufacture, which are most likely two reasons why a product using it does not exist. Another patent, the "Lap Counting System," uses radio signals the determine lap completions. With this device, when the swimmer (wearing the radio transmitter) gets too close to the receiver (placed outside the pool), the communication range is breached and a lap is recorded (Lee, 1990). This patent's technology is also not in production, possibly due to the extra manufacturing costs of creating two separate devices to count laps.

There are many issued patents and patent applications which attempt to perform a similar function. The practicality, cost, and marketability of these technologies have caused some of them to fail where others succeeded. Clearly there is much interest in the swimming community for automatic counting and timing of laps.

Chapter 4

Initial Data Acquisition

4.1 Setup Considerations

Based on the conclusions from previous studies, several initial considerations have been applied to simplify the testing process:

1. This study places the sensor/logging system on the swimmer's lower back because that location has been shown to yield more accurate results than other locations on the body (Kinnunen, 2011).
2. A sampling frequency of 10Hz is used because a previous study has shown that this frequency will both provide sufficient data for analysis and avoid an unnecessarily large amount of data points (Kinnunen, 2011).
3. Three different sensor types (accelerometers, gyros, and magnetometers) will be tested to determine which provides the most useful data in differentiating the three components of a swim workout (free-swim, turn, and rest), as well as recognizing the stroke type used. No previous study has recorded data from all three sensor types simultaneously and compared the results side-by-side.

4.2 KinetaMap Test

In order to confirm the experimental accelerometer results shown in many of the previously conducted studies, a KinetaMap was used in initial testing. The KinetaMap is an easy-to-use data logging tool made by SparkFun Electronics. The device is equipped with an ADXL345 tri-axial accelerometer, an EM408 SiRF III Global Positioning module, and 1GB of flash memory. The device appears as a USB drive when plugged into the computer and all of the data is stored in comma separated variable (CSV) files for easy access and analysis ("KinetaMap User Guide").

The accelerometer was calibrated by sequentially resting the device on each of its sides for a brief period of time. A simple analysis of the output data showed the axes' orientations and also provided a conversion factor to convert the raw acceleration output values into "Gs" (1G = 9.81 m/s^2, Earth's gravitational acceleration).

The KinetaMap was placed in a sealed plastic bag and worn on the swimmer's lower-back with the following orientation (See Figure 4-1):

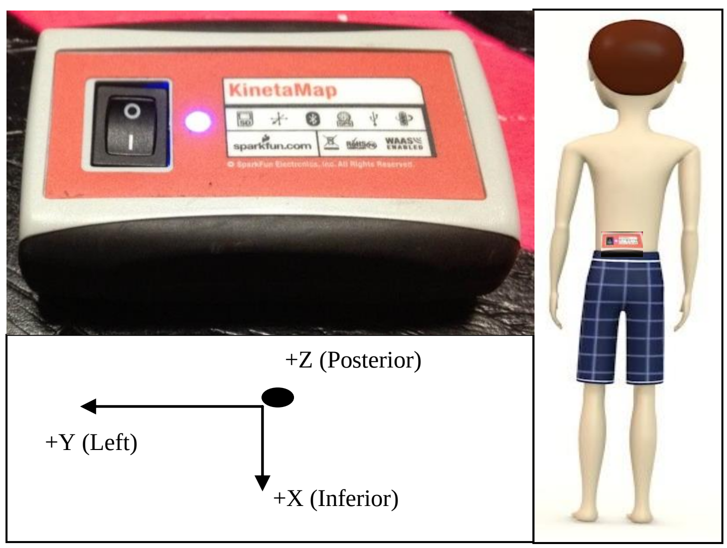

Figure 4-1: KinetaMap Device Orientation

The actual swimming test was performed with the following progression (shown in Table 4-1):

Table 4-1: KinetaMap Swim Test Progression

Length:	Stroke:	Turn Style:
Start (Rest)		
1-4	Freestyle	Flip-turn
Rest		
5-6	Freestyle	Flip-turn
Rest		
7-10	Freestyle	Push-turn
End (Rest)		

The example results are shown in Figure 4-2 and confirmed the acceleration patterns presented in the previous studies and added insight into how push-turn data differed from flip-turn data.

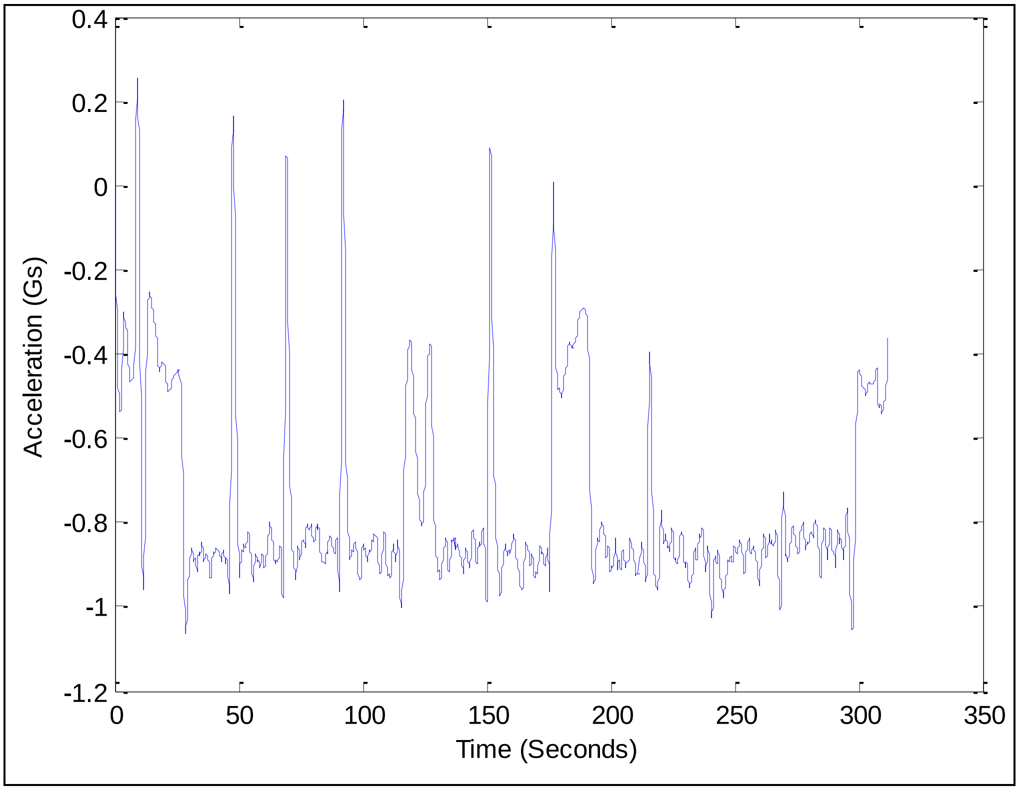

Figure 4-2: KinetaMap Test Results (Z-Axis Acceleration, 2nd Order Butterworth Filter Applied to Data)

All three phases of the swimming workout were easily recognizable upon visual inspection of the data (free swim, turn, and rest). For the antero-posterior (-/+Z) axis, the turn and rest periods corresponded to respective short-lived and long-lived peaks in the acceleration data, whereas the data collected during free swim hovered around a recognizably lower average value. Based on visual data observation, it was confirmed that acceleration data collected from the swimmer's lower back could be used to analyze the desired properties of the swimming workout. Complete testing results can be found in Appendix A.

4.3 Alpha Prototype Test

Although the KinetaMap test confirmed the results of many of the pre-existing studies, one of the goals of this study was to determine which type of sensor (accelerometer, gyro, magnetometer, or a combination of these) provided the best data for swimming workout analysis. In order to compare data from all three sensor types, a simple Alpha Prototype was constructed using a Razor IMU (SparkFun Electronics) in conjunction with a Logomatic v2 Serial SD Data logger and a 3.7V LiPo battery pack (see Figure 4-3). The Razor IMU provided all 9 degrees of measurement desired through inclusion of an ITG-3200 tri-axial gyro, an ADXL345 tri-axial accelerometer, and an HMC5883L tri-axial magnetometer ("9 Degrees of Freedom - Razor IMU"). The data was logged using a Logomatic, a multifunctional board which records digital or analog data onto an on-board SD card in text file format (.txt). These data logging features proved convenient because the board appears as a flash drive when plugged into a computer, and the text files can be converted into CSV files using Microsoft Excel. The board also acts as a battery charger with built-in overcharge protection ("Logomatic v2").

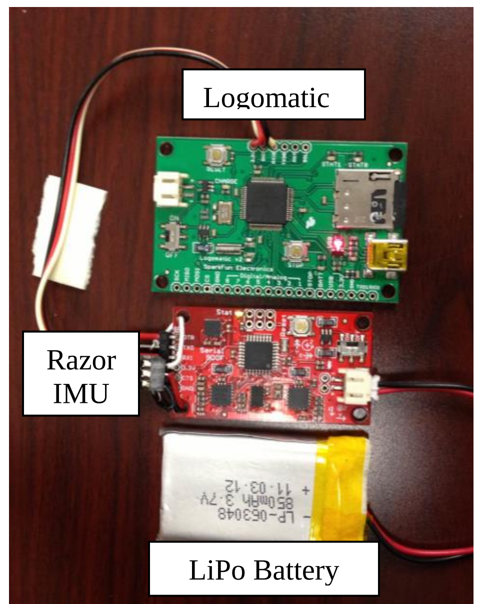

Figure 4-3: Alpha Prototype Setup

By modifying the output code for the Razor IMU's built-in Arduino processor, the desired data from all three sensors was sent serially to the Logomatic's digital acquisition port and recorded in a text file. A swimming test was performed by packaging the prototype in a sealed plastic bag and positioning it on the swimmer's lower-back. In this trial, the prototype was oriented in the following manner (see Figure 4-4):

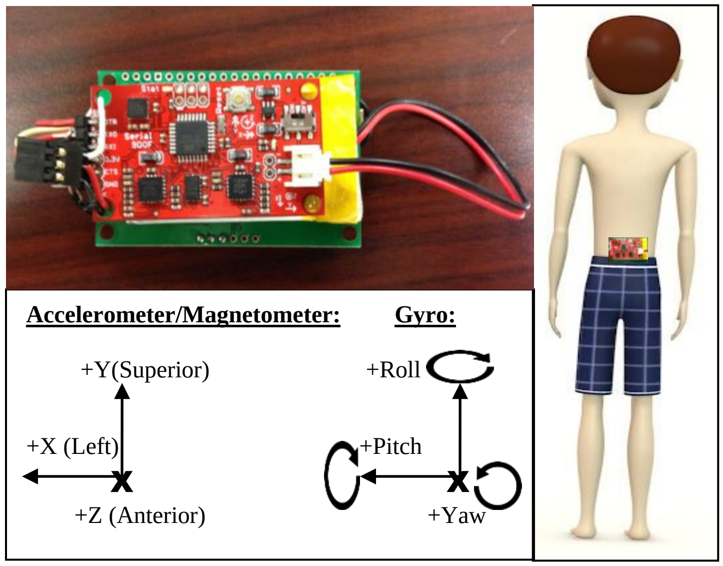

Figure 4-4: Alpha Prototype Orientation

The test was performed in the following manner:

Table 4-2: Alpha Prototype Swim Test Progression

Length:	Stroke:	Turn Style:
Start (Rest)		
1-6	Freestyle	Flip-turn
Rest		
7-12	Freestyle	Push-turn
Rest		
13-18	Breast-Stroke	Flip-turn
Rest		
19-24	Breast-Stroke	Push-turn
Rest		
25-30	Back-Stroke	Flip-turn
Rest		
31-36	Back-Stroke	Push-turn
End (Rest)		

The resulting data provided insight into the event-tracking capabilities of all nine axis of measurement. The discussion of the results and the selection for the final prototype is discussed in Chapter 5.

Chapter 5

Beta Prototype Creation

5.1 Component Selection

Using the data gathered from the Alpha Prototype, a final sensor selection was made. Although all of the axes showed visually noticeable patterns across each of the swimming phases, it was apparent that the antero-posterior (-/+Z) accelerometer axis independently provided the clearest, most consistent patterns across all stroke and turn types (see Figure 5-1).

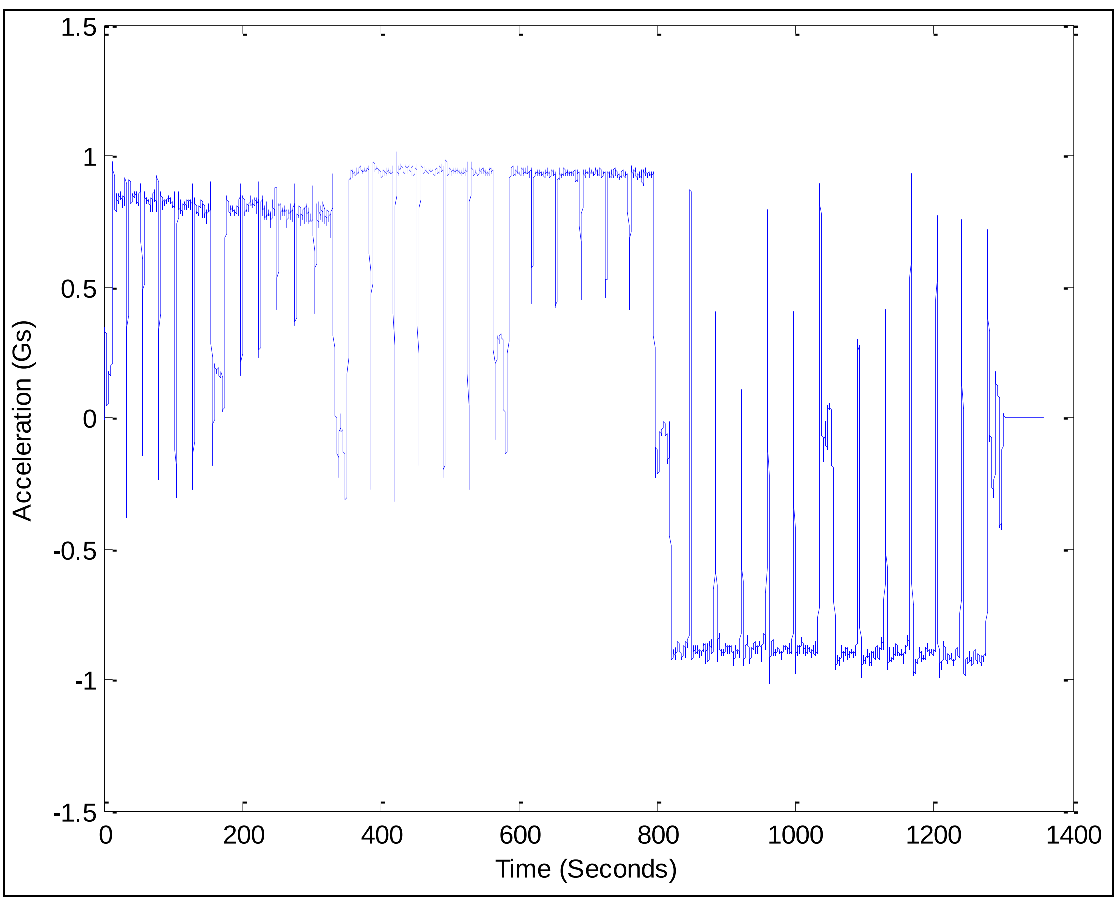

Figure 5-1: Alpha Prototype Test Results (Z-Axis Acceleration, 2nd Order Butterworth Filter Applied to Data)

The data sets generated by the magnetometer and the gyro were also considered but ultimately deemed superfluous. For example, the magnetometer axis-1 data set, shown in Figure 5-2, provided promising results for the sheer number of laps completed. However, upon observation of this data stet, it is difficult to determine when rest periods were taken because the rest signature is very similar to that of the free-swim signature. Also, the different stroke types are less distinguishable than they are using the z-axis acceleration data because the magnitudes of the readings are similar for all stroke types.

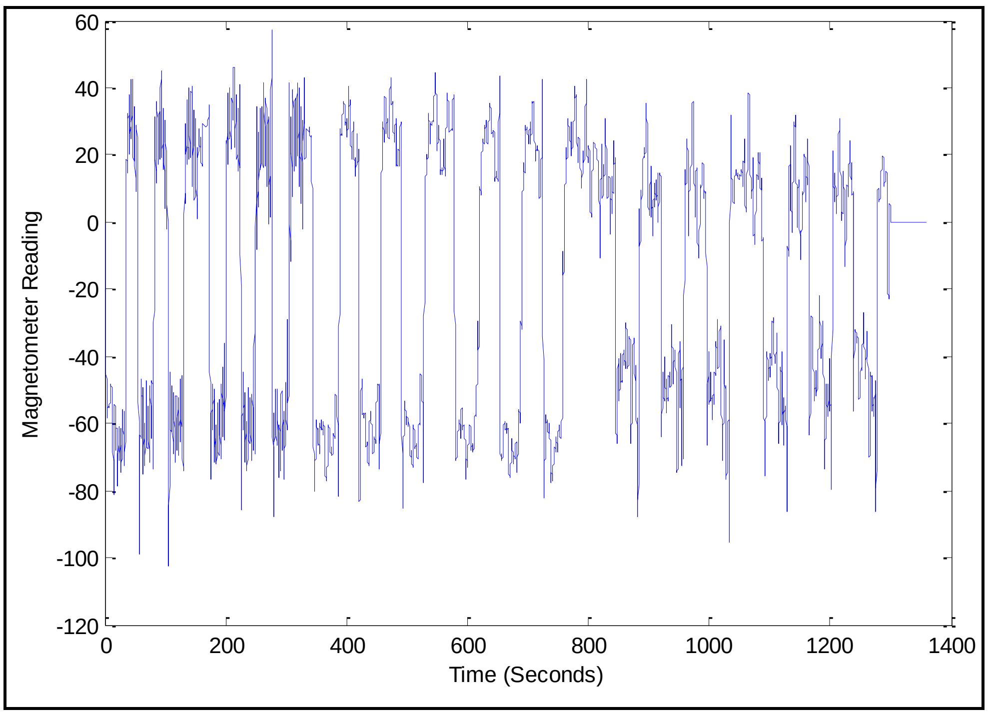

Figure 5-2: Alpha Prototype Magnetometer Axis 1 Data (2nd Order Butterworth Filter Applied)

Additionally, the data from the gyro was deemed superfluous because the small inconsistencies in swimming technique provided data that less distinguishable than the z-axis acceleration data. For example, Figure 5-3 shows the roll-axis data collected during the Alpha Prototype test. Although the swimmer's motion along the roll –axis is prominent with both turn types, the data set proved to be less discernible than the z-axis acceleration data with more recorded noise.

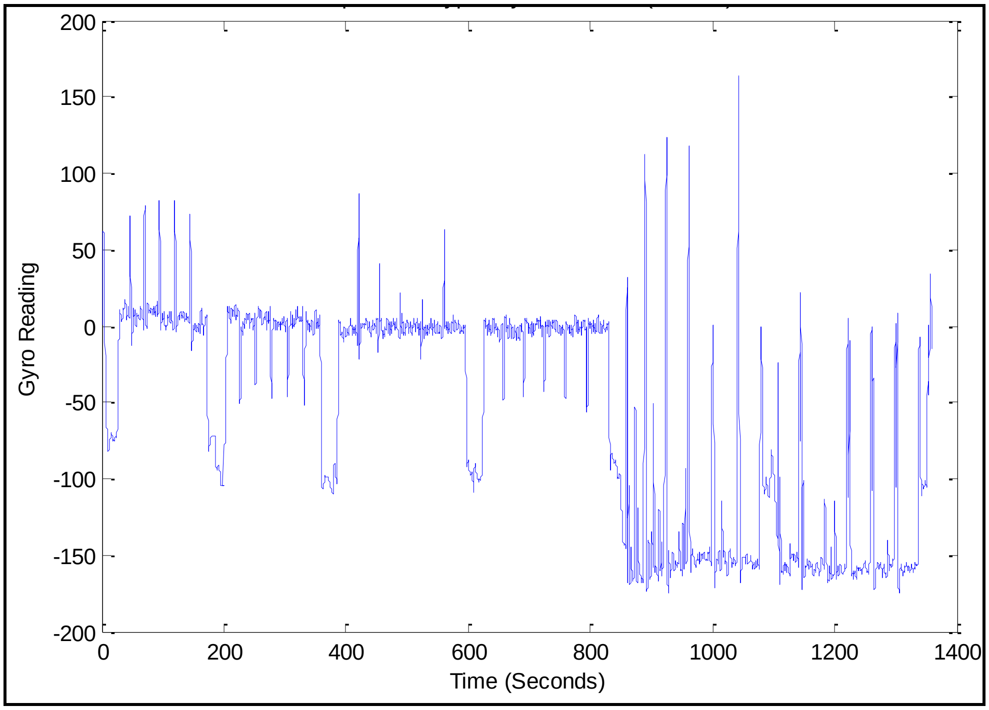

Figure 5-3: Alpha Prototype Gyro Roll Data (2nd Order Butterworth Filter Applied)

Since the z-axis of the accelerometer alone provides distinguishable data for all strokes, turn types, and rest periods, it was chosen as the final sensor to be used. Also, the use of a single sensor which can provide adequate data simplifies the design of the final prototyope. Therefore, the ADXL 335 accelerometer was selected as the sensor to be used in the final prototype design. Complete testing results can be found in Appendix B, showing the data collected across all nine axes by the three sensors.

In addition, the Logomatic was selected as the most desirable data collection device. The Logomatic incorporates all of the functions desired in the final device, is practical, has a relatively small dimensional footprint, and provides user-friendly data accessibility.

Also, a 3.7V, 850mA LiPo battery was selected as the final power source because it provided an adequate usage time (over 700 minutes per charge) and fit within the dimensional footprint of the Logomatic. Figure 5-4 shows voltage depletion versus time of the final configuration under normal use.

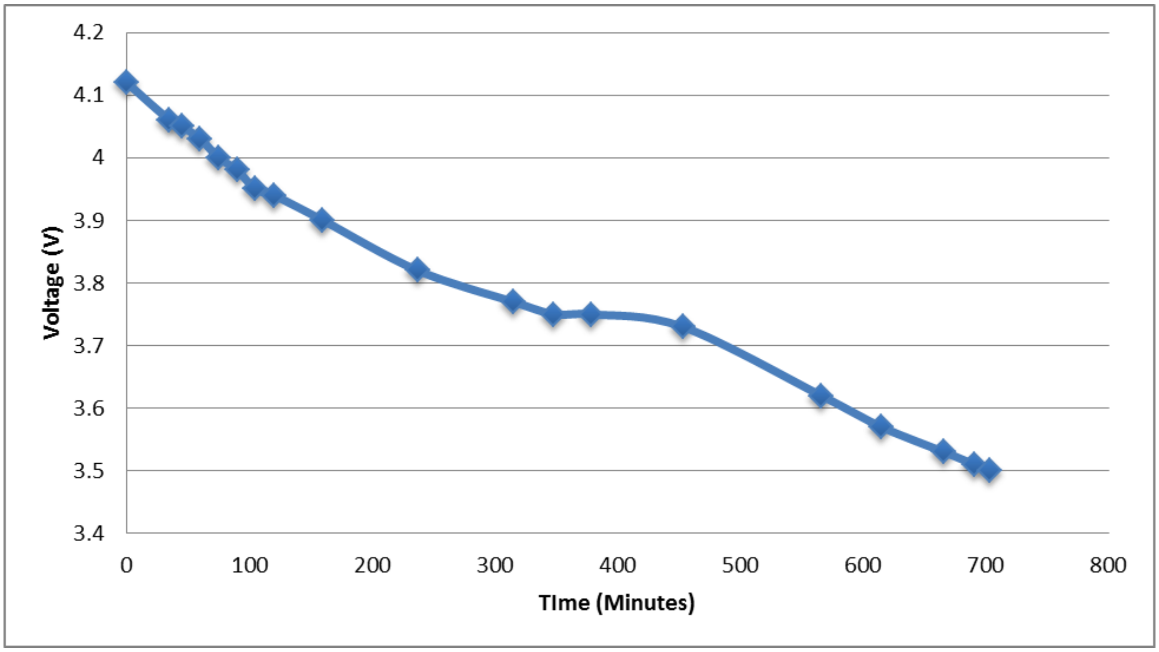

Figure 5-4: Beta Prototype Voltage Depletion Curve

5.2 Packaging

The combination of these components allowed for a compact final packaging size (7.5cm x 3cm x 5.5cm) as compared to one of the similarly functioning devices used in other research studies (20cm x 17.5 cm) (Davey, 2008). A rectangular enclosure was fabricated by rapid prototyping on a Fused Deposition Modeling (FDM) machine. A clear acrylic cover was glued to the enclosure with clear adhesive. The enclosure features a small rectangular hole for access to the USB port (outfitted with a rubber plug to maintain water-tightness) as well as a water-tight, single-pole, single-throw external switch used to turn the device on and off. The prototype also uses an elastic strap with a plastic buckle to secure the device to the swimmer. The device is fastened to the strap using Velcro for easy removal. Pictures of the final prototype can be found in Figure 5-5.

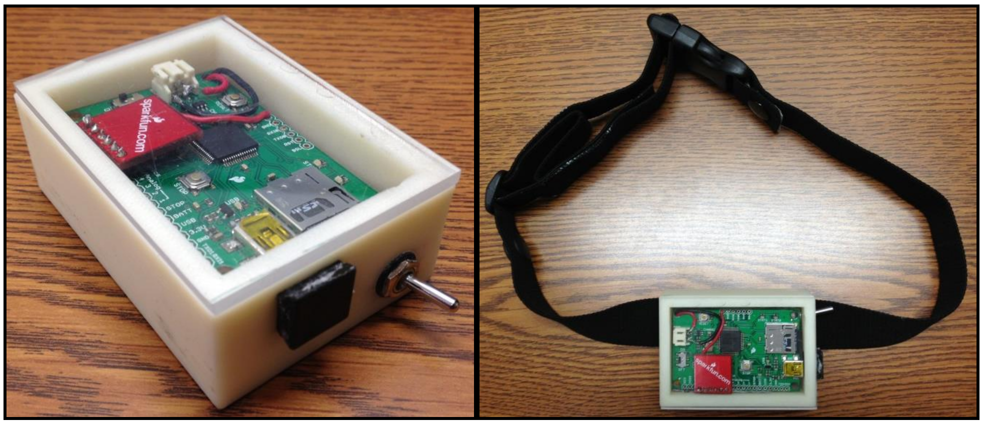

Figure 5-5: Beta Prototype Pictures

5.3 Beta Swim Test Results

The Beta Prototype functioned as predicted, in a very similar manner to the Alpha Prototype except only antero-posterior acceleration data was recorded. The same testing procedure was used for the Beta Prototype as the Alpha Prototype for comparison.

Figure 5-6 shows the orientation of the prototype during testing:

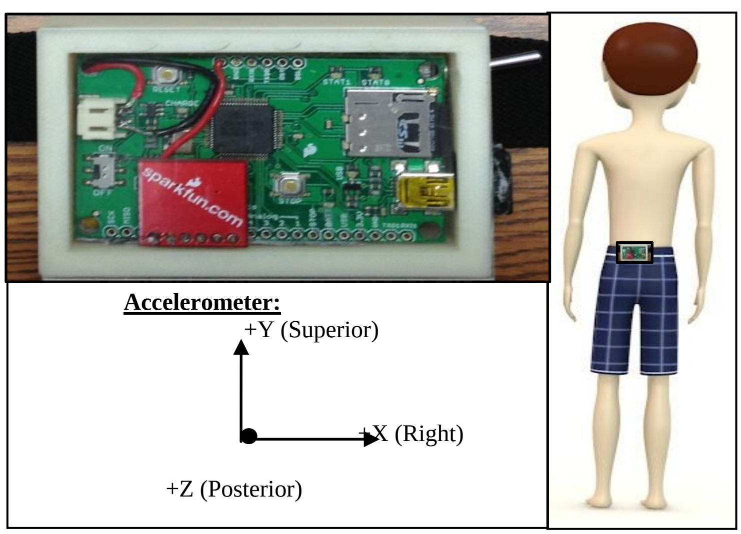

Figure 5-6: Beta Prototype Orientation

Table 5-1 shows the progression of the actual swimming test.

Table 5-1: Beta Prototype Swim Test Progression

Length:	Stroke:	Turn Style:
Start (Rest)		
1-6	Freestyle	Flip-turn
Rest		
7-12	Freestyle	Push-turn
Rest		
13-18	Breast-Stroke	Flip-turn
Rest		
19-24	Breast-Stroke	Push-turn
Rest		
25-30	Back-Stroke	Flip-turn
Rest		
31-36	Back-Stroke	Push-turn
End (Rest)		

Figure 5-7 shows the graphical display of the acceleration data versus time, and Figure 5-8 shows the output from the data analysis algorithm.

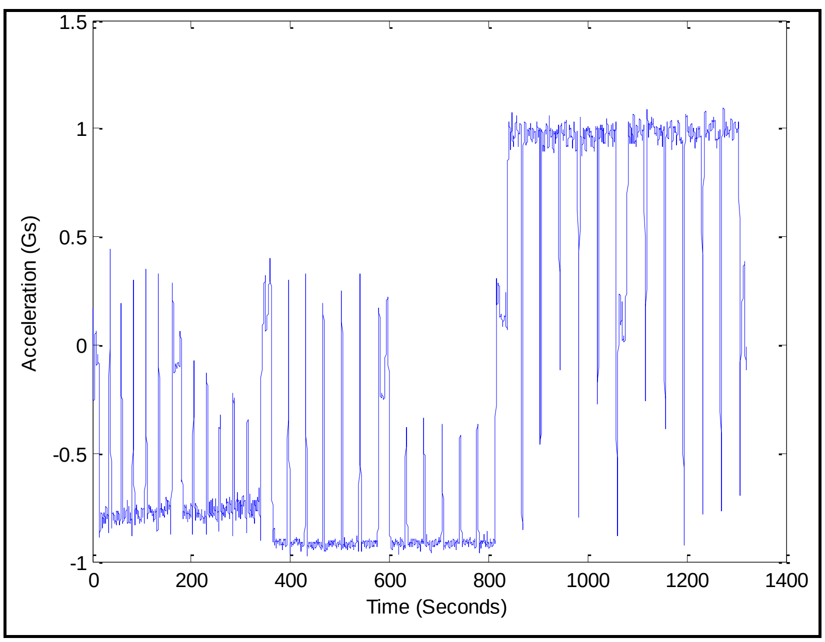

Figure 5-7: Beta Prototype Test Results (Z-Axis Acceleration, 2nd Order Butterworth Filter Applied to Data)

```
>> Swim_Analysis

Column1=Length(#), Column2=Time(sec), Column3=Pace(m/s), Column4=Stroke

Stroke Key: 1=Freestyle, 2=Breaststroke, 3=Backstroke

length_times =

          1.00         17.20          1.45          1.00
          2.00         16.80          1.49          1.00
          3.00         18.20          1.37          1.00
          4.00         19.70          1.27          1.00
          5.00         19.70          1.27          1.00
          6.00         21.80          1.15          1.00
          7.00         20.60          1.21          1.00
          8.00         21.50          1.16          1.00
          9.00         20.70          1.21          1.00
         10.00         22.80          1.10          1.00
         11.00         22.50          1.11          1.00
         12.00         23.40          1.07          1.00
         13.00         29.20          0.86          2.00
         14.00         29.30          0.85          2.00
         15.00         29.90          0.84          2.00
         16.00         31.90          0.78          2.00
         17.00         30.90          0.81          2.00
         18.00         32.50          0.77          2.00
         19.00         30.70          0.81          2.00
         20.00         32.50          0.77          2.00
         21.00         32.40          0.77          2.00
         22.00         31.90          0.78          2.00
         23.00         29.70          0.84          2.00
         24.00         32.50          0.77          2.00
         25.00         24.90          1.00          3.00
         26.00         31.00          0.81          3.00
         27.00         33.50          0.75          3.00
         28.00         32.90          0.76          3.00
         29.00         33.00          0.76          3.00
         30.00         33.00          0.76          3.00
         31.00         32.00          0.78          3.00
         32.00         33.60          0.74          3.00
         33.00         31.80          0.79          3.00
         34.00         32.00          0.78          3.00
         35.00         31.00          0.81          3.00
         36.00         32.50          0.77          3.00

Total_Distance_Meters =

        900.00

Total_Swim_Time_Minutes =

         16.66

Average_Pace_M_per_S =

          0.94
```

Figure 5-8: MATLAB Data Analysis of Beta Prototype Swim Test

The details of the algorithm’s function are outlined in Chapter 6. The algorithm successfully plotted the acceleration data and accurately counted, timed, and determined the stroke used during each swim length. A user manual for the Beta Prototype is provided in Appendix C.

Chapter 6

Algorithm and Data Analysis

After selecting the optimal data set for analysis, an algorithm was developed to decipher the different swimming phases and stroke types. MATLAB software was used to create the algorithm, and the final, successful version uses statistics and realistic parameters to determine key events.

The program then analyzes the data in the following manner. See Appendix D for full MATLAB code.

1. The data is accessed from the CSV file and stored in a matrix. Indices and time values are assigned to each data point based on the sampling frequency (10 Hz unless otherwise noted).
2. A 2^{nd}-order Butterworth filter with cutoff frequency of 0.5 Hz is applied to the acceleration data to reduce noise.
3. The absolute value is taken of the filtered data to compensate for the potential presence of back-stroke data.
4. The mean of the resulting data is computed and then is subtracted from each data point to normalize the data about the mean.
5. The resulting data is squared to accentuate the peaks associated with turns.
6. The data set is thresholded at 0.3 standard deviations above the mean. This value was chosen because it consistently provided the best results over multiple experimental workouts. The threshold creates a true-or-false (0-or-1) version of the data set, where if the data point is above the 0.3 standard deviation mark, it is recorded as a “1”, and if it is below the 0.3 standard deviation mark, it is counted as a “0”.

7. A loop is run that evaluates each of the data points chronologically in the following manner:

    a. If the data point is a “1”, a “not-free-swim” counter is recorded

    b. If the data point is a “0”, a “free-swim” counter is recorded and a “not-free-swim” counter is recorded. The purpose of the “not-free-swim” counter during this step is for later subtraction to determine if a swim length has actually been started and also to determine the time of a rest period.

    c. If the previous data point is a “0” and the current data point is a “1”

        i. If the “free-swim” counter exceeds the lower threshold (13 seconds for a length – deemed a reasonable lowest potential value of a length time), a matrix is created to store the data as a “swim length”, grabbing all of the data spanning from the previous “1” data point to the current “1” data point (meaning that the data has been recorded as a “0” for more than 13 seconds, indicating that a length was being swam during that time)

            1. If the difference between the “not-free-swim” count and the “free swim count” at this point is less than 5 seconds (using the reasonable assumption that no turn takes longer than 5 seconds), a new “turn” matrix is created and the data of the previous set of “1” values are recorded in the matrix.

            2. If the difference between the “not-free-swim” count and the “free swim count” at this point is greater than 5 seconds (using the reasonable assumption that no turn takes longer than 5 seconds), a new “rest” matrix is created and the data of the previous set of “1” and/or “0” values (preceding the last large set of “0” values) is recorded in the matrix.

ii. The “free-swim” and “not-free-swim” counts are reset to 0, signifying the end of a length and preparing to initialize a new length or rest.

d. The “free-swim” count is reset to 0, indicating that an event of “1” had been recorded, so a swimming length could not have been happening at that time.

e. The loop is restarted to evaluate the next data point.

8. After all data points have been evaluated and filtered data placed in “swim”, “turn”, or “rest” matrices:

   a. The initial and final times for each rest matrix and the time of the peak of each turn are extracted and placed in a matrix.

   b. The exact elapsed time for each length is computed by taking the difference: between two turn times, between the end of a rest and the following turn or rest, or between a turn and the following rest

   c. The average of the raw data is taken for each of the time slots that were deemed to be swim lengths. Based on the average value, the stroke being performed during the length is determined (a negative mean corresponds to back-stroke, a mean above 0.8Gs corresponds to breast-stroke, and a mean above 0Gs and below 0.8Gs corresponds to freestyle).

9. The final results of the data analysis are displayed for the user, including:

   a. A length-by length breakdown of the stroke performed, elapsed time, and average pace

   b. Lengths of rest periods

   c. Time, pace, stroke, and distance of each set (all of the lengths performed between two rest periods are grouped as a “set”)

   d. Total workout time and distance

By through the use of this algorithm, the data analysis program provides an instantaneous, comprehensive break-down of the workout. All of the data provided is useful to the swimmer in keeping a log of their workouts and tracking their training progress.

Chapter 7

Conclusions and Suggestions for Improvement

7.1 Conclusions

This research study has shown that it is possible to create a swimming lap counter which uses only antero-posterior acceleration data and a computer algorithm to determine the type of swimming stroke used, number of length completions and durations, and number of rest completions and durations. The device is accurate, compact, and user-friendly. Previous studies concerning sensor-based swimming analyses did not publish a simultaneous comparison of three different sensor types. Research also identified current products and relevant patents to provide inspiration for the creation of a unique prototype. By collecting data from three different sensors simultaneously and comparing the results, the knowledge-base on sensor-based swimming analysis was increased. Also, a sensor-based swimming lap counter which is unique in its components, packaging design, and data analysis algorithm was created.

7.2 Suggestions for Improvement

After completing this study, a few improvements should be made to the design of this particular prototype to make it more competitive against products currently on the market:

1. The inclusion of an inductive charging system and Bluetooth or infrared data transmission system to improve the waterproof nature of the product and minimize human error during use.
2. A more extensive and user-friendly software program to complete and store workout analyses.

3. A smartphone application which possesses the same software for easy viewing and tracking on-the-go.
4. A new enclosure designed with injection molding.

Appendix A

KinetaMap Test Results

Figures A-1 through A-3 show all of the acceleration data collected during the KinetaMap swim test.

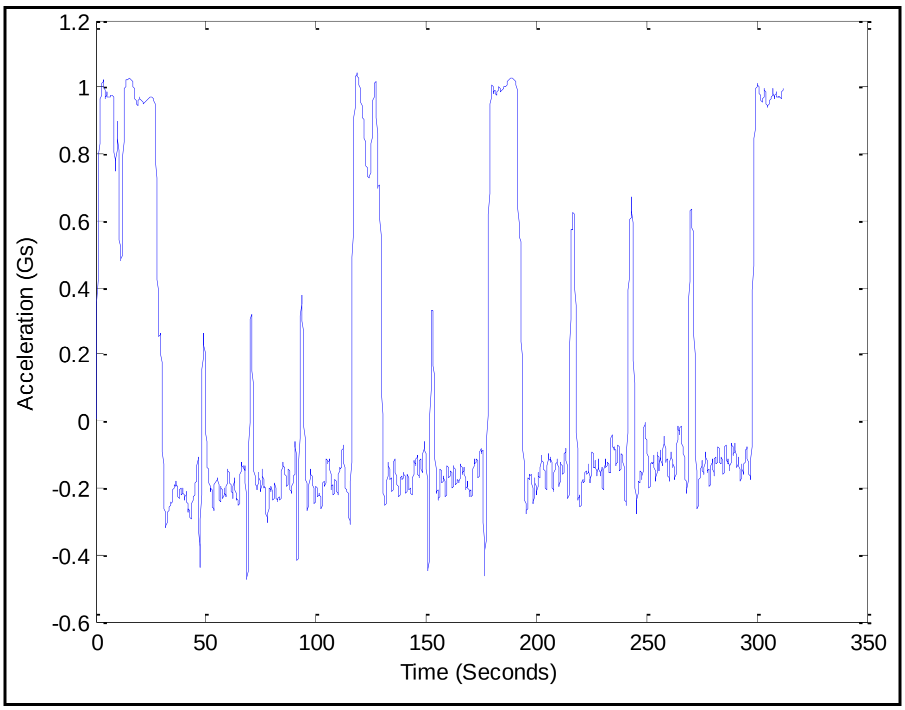

Figure A-1: KinetaMap X-Axis Data (2nd Order Butterworth Filter Applied)

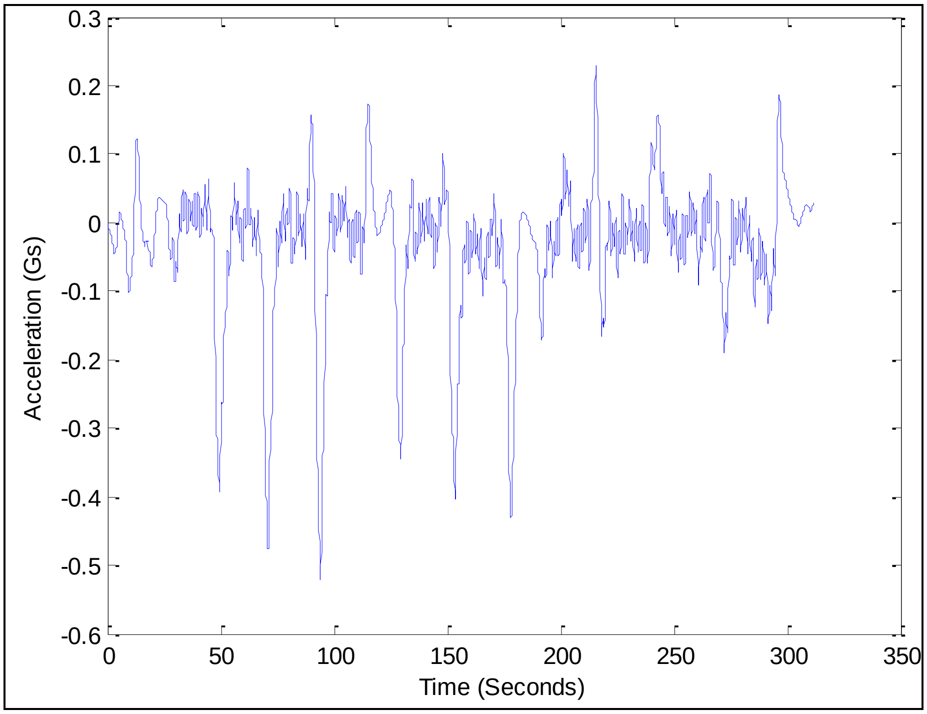

Figure A-2: KinetaMap Y-Axis Data (2nd Order Butterworth Filter Applied)

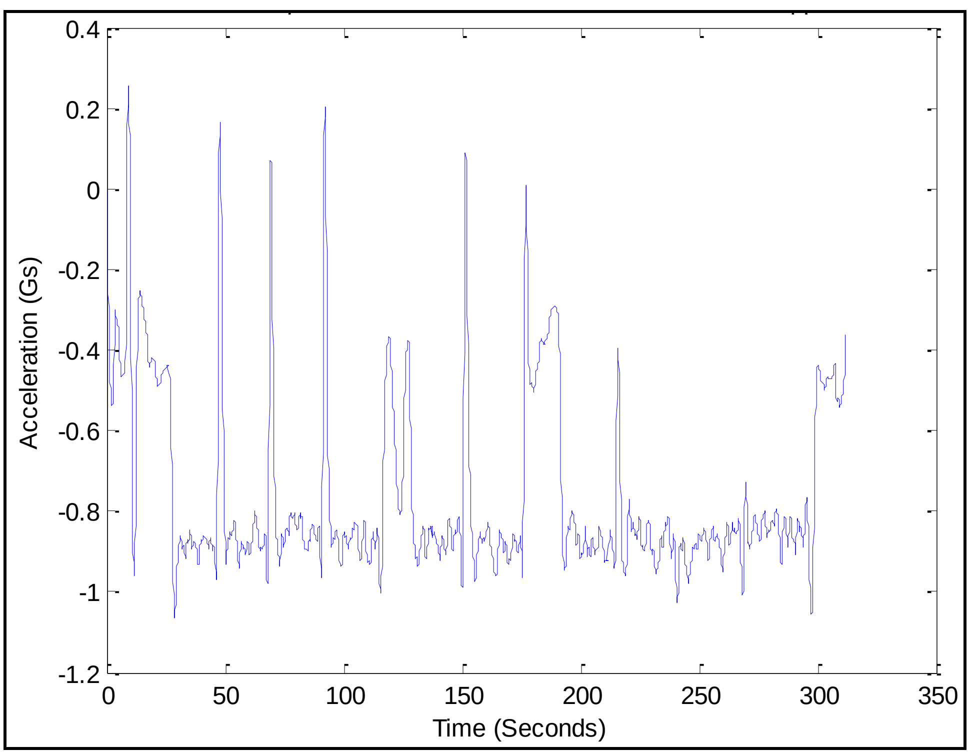

Figure A-3: KinetaMap Z-Axis Data (2nd Order Butterworth Filter Applied)

Appendix B

Alpha Prototype Test Results

Figures B-1 through B-9 show all of the data collected from all three sensors during the Alpha Prototype swim test.

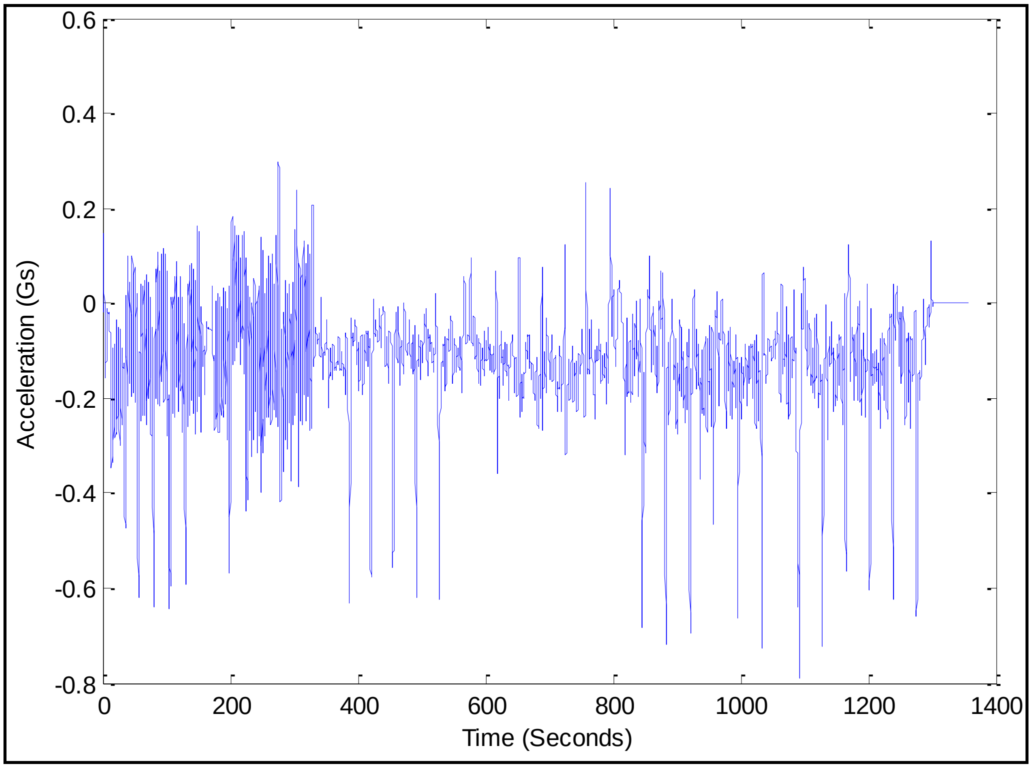

Figure B-1: Alpha Prototype X-Axis Accelerometer Data (2nd Order Butterworth Filter Applied)

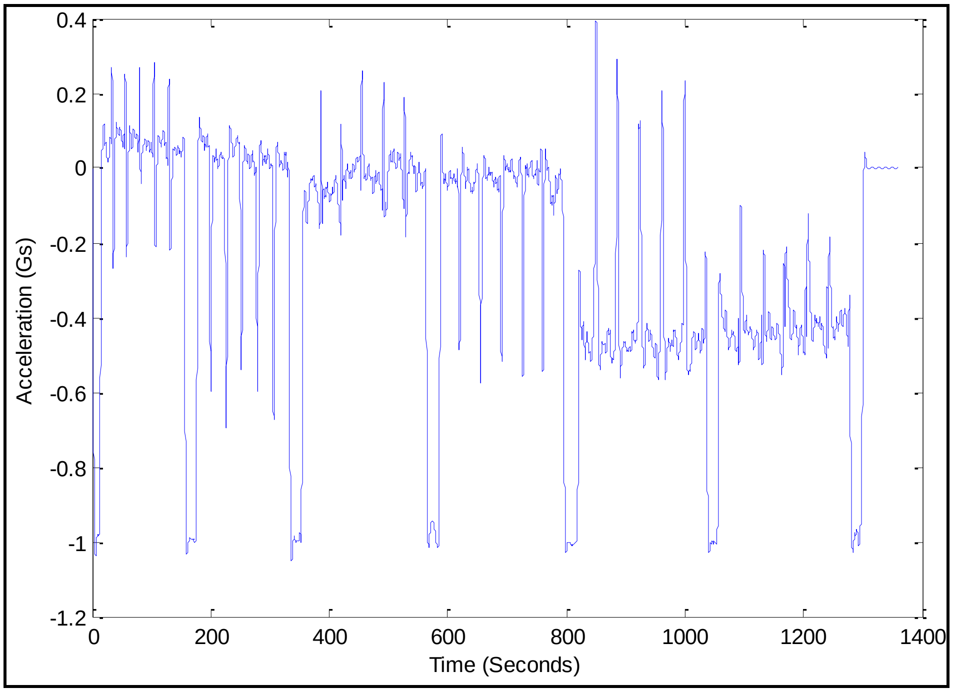

Figure B-2: Alpha Prototype Y-Axis Accelerometer Data (2nd Order Butterworth Filter Applied)

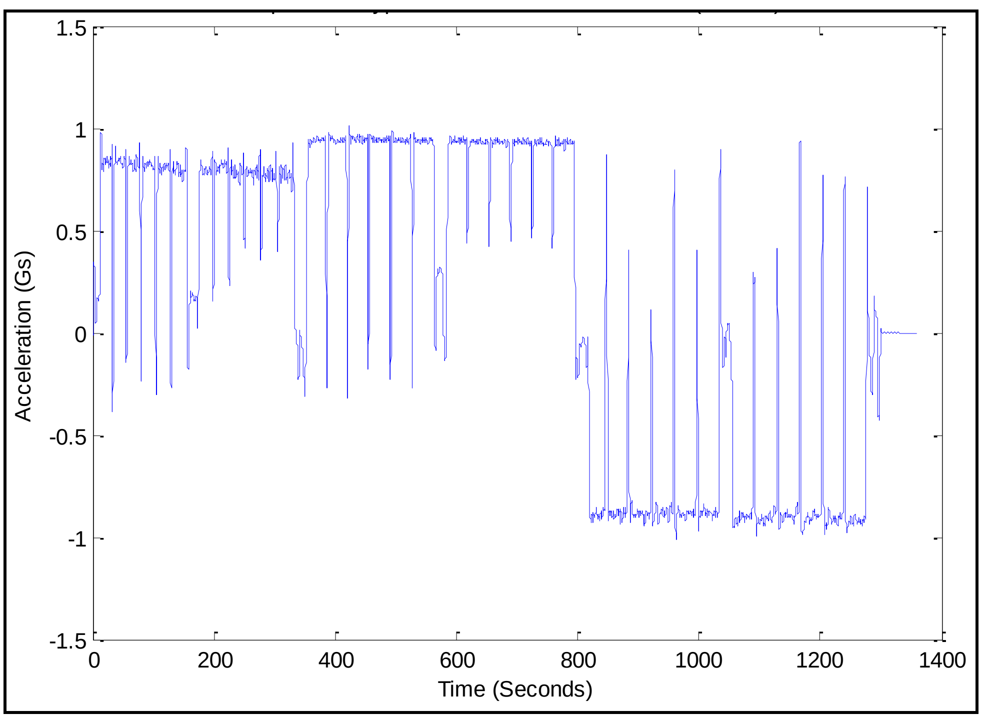

Figure B-3: Alpha Prototype Z-Axis Accelerometer Data (2nd Order Butterworth Filter Applied)

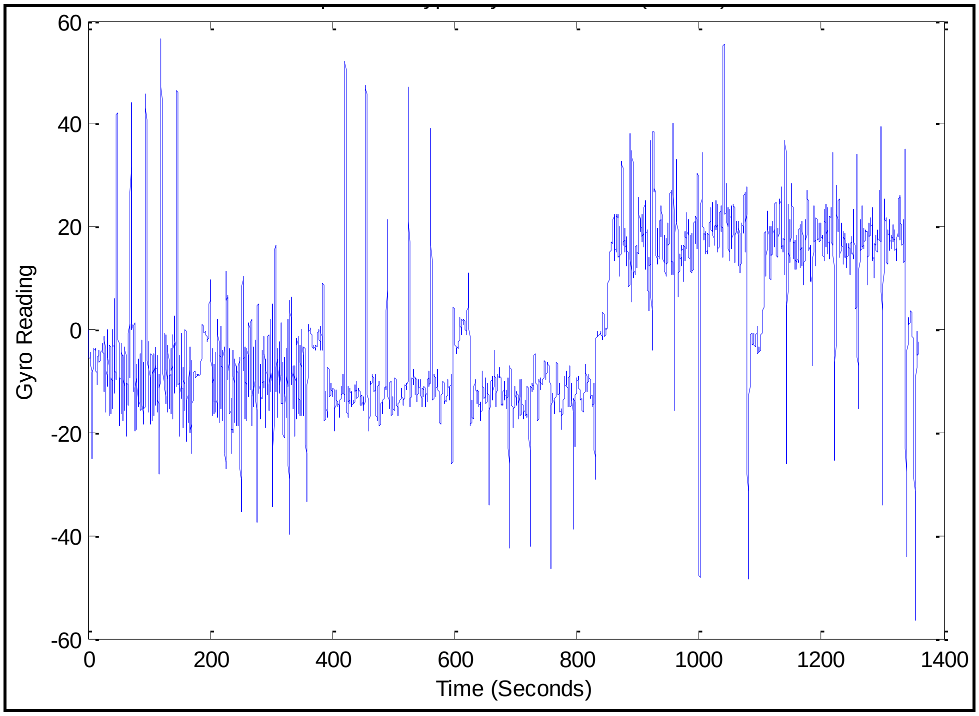

Figure B-4: Alpha Prototype Gyro Pitch Data (2nd Order Butterworth Filter Applied)

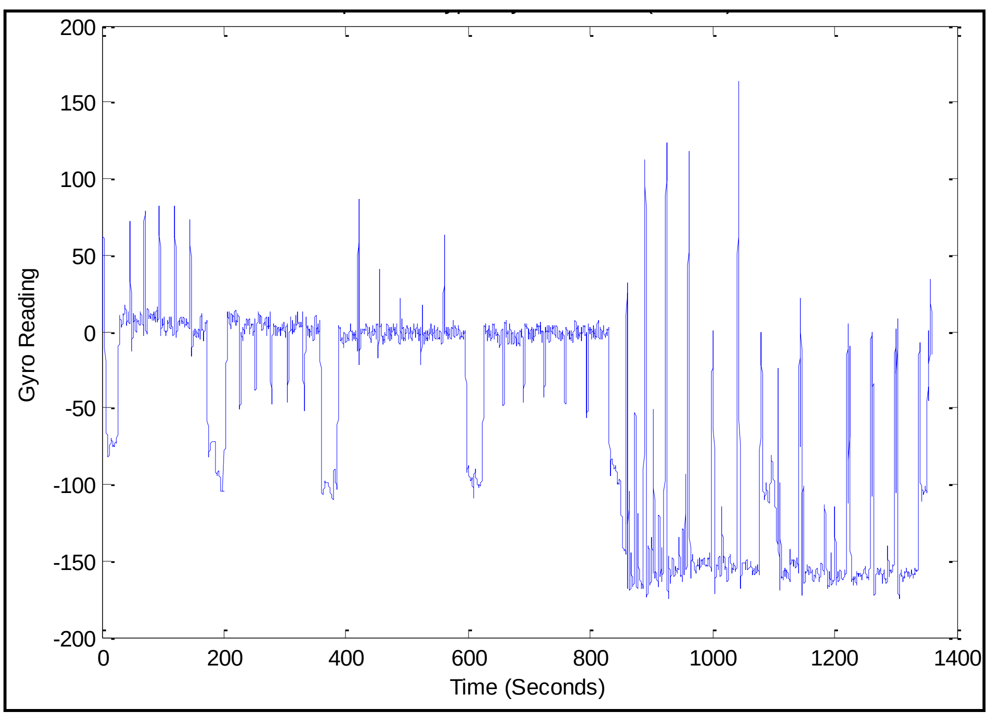

Figure B-5: Alpha Prototype Gyro Roll Data (2nd Order Butterworth Filter Applied)

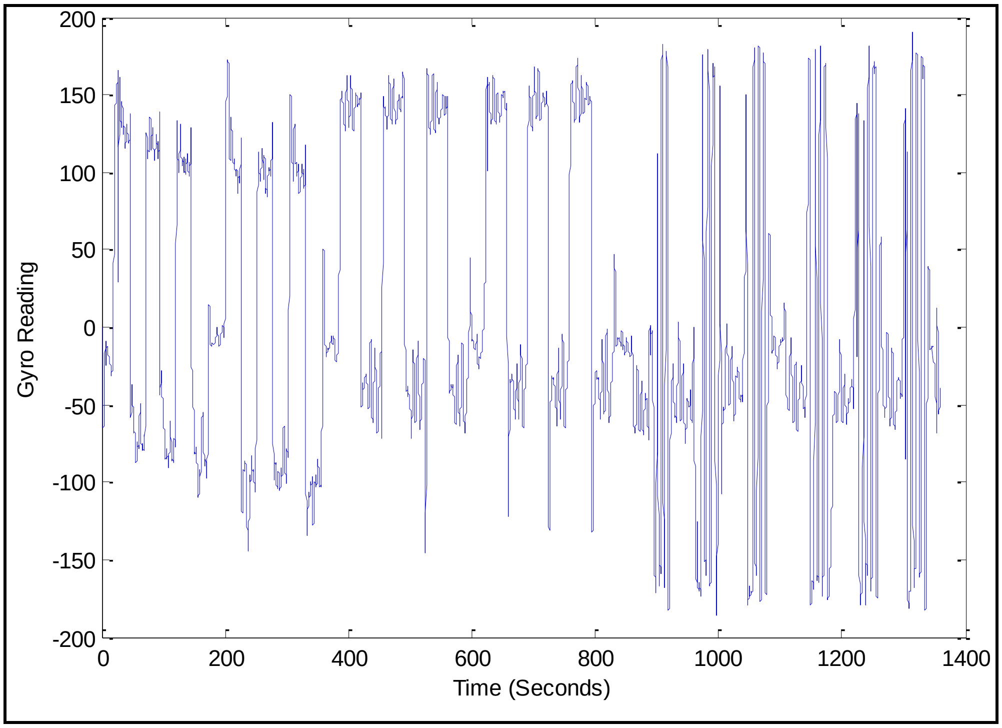

Figure B-6: Alpha Prototype Gyro Yaw Data (2nd Order Butterworth Filter Applied)

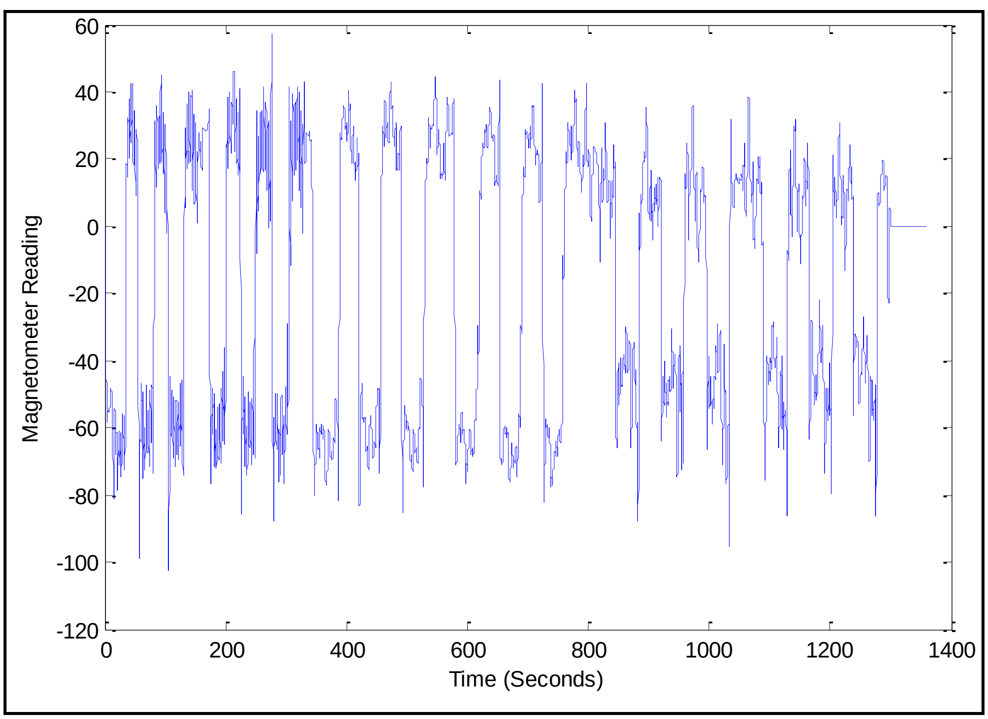

Figure B-7: Alpha Prototype Magnetometer Axis 1 Data (2nd Order Butterworth Filter Applied)

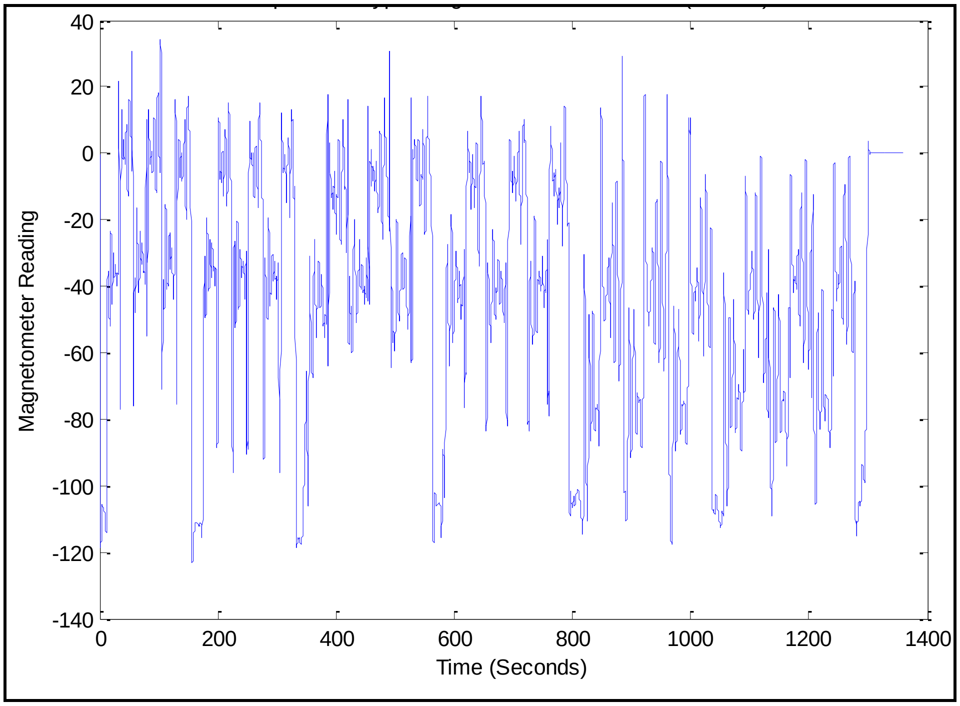

Figure B-8: Alpha Prototype Magnetometer Axis 2 Data (2nd Order Butterworth Filter Applied)

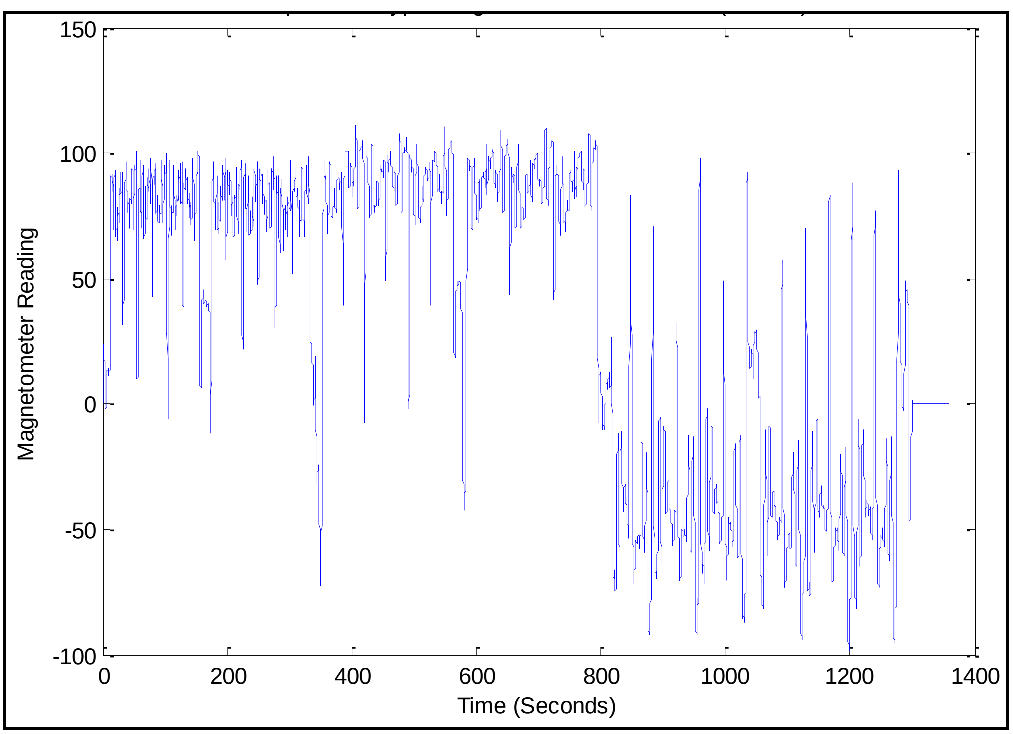

Figure B-9: Alpha Prototype Magnetometer Axis 3 Data (2nd Order Butterworth Filter Applied)

Appendix C

Beta Prototype User Manual

Track a Swimming Workout:

*Note: Before submersion in water, check that the rubber plug is fully inserted into the USB port hole.

1. Adjust the strap so that it fits snugly around your waist
2. Buckle strap ends together around the front of your waist so that the device is located in the middle of your lower back and the switch is on your right side.
3. When you are ready to begin swimming, flip the switch to the "ON" position (down) and wait for 5 seconds for the device to initialize.
4. Conduct your swimming workout as normal.
5. When you are finished with your swim, flip the switch to the "OFF" position (up)

Analyze a Swimming Workout:

1. Remove the rubber plug from the USB port hole on the device.
2. Connect the device to the computer via the USB port using a mini USB to USB cable. (The device will automatically begin charging when the device is plugged in and will stop charging once the battery is at full charge (4.12 V). The "charge" LED on the device will light up when the device is charging and will turn off once it is finished.)
3. Switch the device to "ON".
4. Open the most recent data text file, select all, copy, and then paste the data into a spreadsheet software (such as Microsoft Excel). The data should be copied into a single column with one data point per row.

5. Save the file as a comma separated variable file (.CSV) with the title “Beta_Input.csv”.
6. Open MATLAB and import “Beta_Input.csv” into the MATLAB document library.
7. Open the file “Swim_Analysis.m” and edit the “pool_length” variable to match the length of your pool (in meters or yards).
8. Save the “Swim_Analysis.m” file and hit “RUN”.
9. Your workout will be analyzed and the result presented in a table. A plot of your filtered acceleration data versus time will also be displayed.

Appendix D

MATLAB Code

This Appendix includes the MATLAB code used for data analysis.

```
% Swim_Analysis
% RWN 3/18/2013

% NOTE: save swim data as a 'Beta_Input.csv'

clear

pool_length = 25;
%% Import time and accelerometer data from Beta_Input.csv
swimdata = csvread('Beta_Input.csv');

% Create time matrix
time = [];
for j=1:length(swimdata(:,1));
    time(j,1) = 0.1*j;                  % units [sec]
end


% Create acceleration matrices - may need to change column if file has x and y data
% x_accel = swimdata(:,2);              % units [Gs]
% y_accel = swimdata(:,3);              % units [Gs]
z_accel = (swimdata(:,1)-500)/100 ;     % units [Gs]

figure(5);
plot(time,z_accel);
title('Raw Accelerometer Data');
%% Butterworth filter of data
[B,A] = butter(2,.05);
butt_z_accel = filter(B,A,z_accel);

% Plot data from butterworth filter
figure(1);
plot(time,butt_z_accel);
title('2nd Order Butterworth Filtered Data');

% Find mean and standard deviation of butterworth filered accelerometer data
mean_butt = mean(butt_z_accel);
std_butt = std(butt_z_accel);

%% Find mean and standard deviation of the absolue value of the butterworth filered
accelerometer data
abs_mean_butt = mean(abs(butt_z_accel));
abs_std_butt = std(abs(butt_z_accel));

% Plot the accelerometer data (with applied butterworth filter and absolute value)
figure(2);
plot(time,abs(butt_z_accel));
title('Absolute Value of 2nd Order Butterworth Filtered Data');

%% Normalize the 'Absolute Value of 2nd Order Butterworth Filtered Data'
% around the mean of the 'Absolute Value of 2nd Order Butterworth Filtered
% Data' and square it.
n = length(butt_z_accel);
norm_abs_butt_z_accel = [];
for j=1:n;
```

```
    norm_abs_butt_z_accel(j,1) = (abs(butt_z_accel(j,1))-abs_mean_butt)^2;
end;
mean_mean_norm_abs_butt = mean(norm_abs_butt_z_accel);
std_mean_norm_abs_butt = std(norm_abs_butt_z_accel);

figure(3);
plot(time,norm_abs_butt_z_accel);
title('Absolute Value of 2nd Order Butterworth Filtered Data: Subracted Mean and
Squared');

count = [];
for j=1:n;
    if
norm_abs_butt_z_accel(j,1)>=(mean_mean_norm_abs_butt+(0.3)*std_mean_norm_abs_butt);
        count(j,1)=1;
    else
norm_abs_butt_z_accel(j,1)<(mean_mean_norm_abs_butt+(0.3)*std_mean_norm_abs_butt);
        count(j,1)=0;
    end;
end;

figure(4);
plot(time,count), axis([0 1100 -0.1 1.1]);
title('Floor or Ceiling: Taken at 0.3 Standard Deviations Above the Mean');

%% Differentiating swim, turn, and rest

% Create "swim" and "not swim" matrices (retrieve time and acceleration data
% based on 0 or 1 in "count" matrix)
swim_trig = 0;
not_swim_trig = 0;

m_swim = [];
m_not_swim = [];
m_zeros = zeros(n,1);

for j=(1:n);

    % Enter data into "swim" matrix
    if (count(j,1) == 0);
        m_swim(j,1) = time(j,1);
        m_swim(j,2) = butt_z_accel(j,1);
        m_not_swim(j,1) = m_zeros(j,1);
        m_not_swim(j,2) = m_zeros(j,1);
    end;

    % Enter data into "not swim" matrix
    if (count(j,1) == 1);
        m_not_swim(j,1) = time(j,1);
        m_not_swim(j,2) = butt_z_accel(j,1);
        m_swim(j,1) = m_zeros(j,1);
        m_swim(j,2) = m_zeros(j,1);
    end;
end;

swim_count = 0;
length_count = 0;
length_data = [];
length_times = [];
length_type = [];

for j=(1:n);
    if (m_swim(j,1) ~= 0);
        swim_count = swim_count + 1;
    end;

    if (m_swim(j,1) == 0);
        swim_count = 0;
    end;
```

```
    if (swim_count == 130);
        length_count = length_count + 1;
        length_data(1:100,1,length_count) = time((j-99):j,1);
        length_data(1:100,2,length_count) = butt_z_accel((j-99):j,1);
    end;

    if (swim_count > 130);
        length_data(j,1,length_count) = time(j,1);
        length_data(j,2,length_count) = butt_z_accel(j,1);
    end;
end;


for j=(1:length_count);

    length_times(j,1) = j;
    length_times(j,2) = (max(length_data(:,1,j))-length_data(1,1,j));
    length_times(j,3) = (pool_length/(max(length_data(:,1,j))-length_data(1,1,j)));

    if (mean(length_data(1:100,2,j)) > 0);
        length_times(j,4) = 3;
    end;
    if ((mean(length_data(1:100,2,j)) < 0) && (mean(length_data(1:100,2,j)) > -0.8));
        length_times(j,4) = 1;
    end;
    if (mean(length_data(1:100,2,j)) < -0.8);
        length_times(j,4) = 2;
    end;

end;

csvwrite('Beta_Output.csv',length_times)
format bank;
'Column1=Length(#), Column2=Time(sec), Column3=Pace(m/s), Column4=Stroke'
'Stroke Key: 1=Freestyle, 2=Breaststroke, 3=Backstroke'
length_times
Total_Distance_Meters = length_count*pool_length
Total_Swim_Time_Minutes = sum(length_times(:,2))/60
Average_Pace_M_per_S = sum(length_times(:,3))/length_count
```

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- Schreyer Honors College Scholarship: Provided by donors to students in the Penn State Schreyer Honors College (2008-2012)
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