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MotionScan: Towards Brain Concussion Detection with a Mobile Tablet Device

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MOTIONSCAN: TOWARDS BRAIN CONCUSSION DETECTION WITH A MOBILE TABLET DEVICE

by

Shantanu Saxena

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Computer Science

Approved:

Dr. Amanda Hughes Major Professor	Dr. Curtis Dyreson Committee Member
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ABSTRACT

MotionScan: Towards Brain Concussion Detection with a Mobile Tablet Device

by

Shantanu Saxena, Master of Science

Utah State University, 2016

Major Professor: Dr. Amanda Lee Hughes
Department: Computer Science

This thesis reports on a study to determine the viability of using a mobile tablet device as a brain concussion detection tool. The research builds upon the results of a prior method of collecting data for measuring motion sensitivity, where a user presses and releases a force sensor to balance a rising and falling line on a computer display. The motion sensitivity data collected using this force sensor device was shown to have less irregularity in persons with concussion. The MotionScan application, developed for this research, uses the accelerometer of a tablet device to record motor movement of a user while the user tries to control a free-moving ball on the tablet screen to trace a line.

Data collection sessions were conducted with 20 participants, where researchers recorded motor performance data for similar tasks using both the MotionScan application and the force sensor device. Researchers analyzed the performance outcomes on the tablet application and force sensor device, and validated that they both record motor movements similarly. Participants were also asked for their feedback on the interface of MotionScan and the data collection process, which was used to improve the usability of MotionScan and data collection processes. The research demonstrates that a tablet device can measure the variability in a person's motor sensitivity and with more research could be used as a concussion detection tool.

(134 pages)

PUBLIC ABSTRACT

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Data collection sessions were conducted with 20 participants, where researchers recorded motor performance data for similar tasks using both the MotionScan application and the force sensor device. Researchers analyzed the performance outcomes on the tablet application and force sensor device, and validated that they both record motor movements similarly. Participants were also asked for their feedback on the interface of MotionScan and the data collection process, which was used to improve the usability of MotionScan and data collection processes. The research demonstrates that a tablet device can measure the variability in a person's motor sensitivity and with more research could be used as a concussion detection tool.

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Shantanu Saxena

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CHAPTER 1

INTRODUCTION

Brain concussions, especially mild traumatic brain injuries (mTBI), in sports and recreation-related activities have gathered considerable attention in recent years. Annually, around 1.6-3.8 million recreation-related concussion cases are reported in the United States[1]. Out of the 2.4 million sports-related emergency department (ED) visits for age group 5-18 years during 2001-2005, 135,000 cases involved concussion in one form or another. A large number of concussion cases are not even diagnosed before the patient starts showing persistent problems and the long-term consequences can be dire. Injuries on a sports field can vary from mild to severe and can even cause death. Even mTBIs can cause life-long damage such as memory impairment, balance disorders and neurologic disease. A second mTBI sustained shortly after the first can result in a longer recovery time and the potential for second impact syndrome, a condition that can result in mental disability or even death. The Center for Disease Control and Prevention reported around 50,000 deaths in 2010 in the United States by Brain Injuries either alone or in combination with other injuries and the numbers have increased over time.

The American Association of Neurological Surgeons defines concussion as a clinical syndrome characterized by immediate and transient alteration in brain function, including alteration of mental status and level of consciousness, resulting from mechanical force or trauma[2]. Concussion is typically categorized using the Glassgow Comma Scale (3-15) which is a head injury scoring system that ranks responsiveness

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[1] http://www.brainline.org/content/2008/12/concussion-and-sports.html
[2] http://www.aans.org/Patient%20Information/Conditions%20and%20Treatments/Concussion.aspx

based on eye opening, verbal and motor function. Lower scores on this scale represent more severe head injuries. The major categories include Mild Traumatic Brain Injury, Moderate Traumatic Brain Injury and Severe Brain Injury.

Concussions are primarily diagnosed through the observation of various symptoms displayed by the injured person. Clinical tests aid in detecting the presence of a concussion and include objective measures to assess brain function and balance/coordination impairment. Clinical methods[3] like Diffusion Tensor Imaging and Magnetoencephalographic (MEG) Virtual Recording are used for examination of specific symptoms and produce very broad predictions on certain anomalous behaviors of the brain. However, to categorize brain anomalies found with these methods into a positive concussion case, other diagnostic tools are required. Tools like the Sports Concussion Assessment Tool (SCAT2), King Devick Test and Balance Error Scoring System (BESS) assess balance and coordination and can be used in combination with clinical methods to formally diagnose concussion. One advantage of these tools is that they can be used along the sidelines of a playing field. Another method that has shown recent promise for detecting concussion is measuring a person's visual-motor coordination through non-linear time series plots. The research proposed here builds upon this new approach by developing a tool that can collect time series data that measures the visual-motor sensitivity of an individual.

1.1 Research Questions

This study aims to answer the following research question:

[3] http://www.ncbi.nlm.nih.gov/books/NBK185340/?report=printable

How can mobile tablet device sensors be used to assess visual-motor sensitivity and potentially detect concussion?

1.2 Research Overview

This research develops an interactive mobile application prototype to collect data on the sensitivity of an individual's visual-motor coordination to detect brain concussion. A contribution of the research is to evaluate the capabilities of mobile devices to produce enough granular data for non-linear analysis of visual-motor coordination. Following development of a prototype, pilot testing was done to find usability issues with the application and to refine the testing protocol for testing with real users. The application was modified based on the findings of the pilot testing. Finally, the application was tested with a mixed pool of users, including those with a history of concussion and those with no history of concussion. This research validates non-linear parameters like Sample Entropy, Root Mean Square Error, Power on Frequency etc. on motor data captured by the use of the accelerometer of a mobile tablet device and will allow researchers to further study visual-motor distinctions between people with concussion and people with no history of concussion.

1.3 Thesis Overview

This thesis document contains six additional chapters following this introduction. Chapter 2 contains the literature review, which describes ongoing research to find more reliable concussion detection tools. Chapter 3 describes the tablet application we developed to collect visual-motor data. Chapter 4 outlines the pilot testing of the application, test setting of the lab and testing protocols to be followed while collecting the visual-motor data of participants. Chapter 5 reports the feedback on the interface of the application and the testing process. Chapter 6 summarizes the interpretation of data we collected and the correlation of non-linear parameters on motor data collected by the mobile tablet device and the same parameters collected by an alternative device that uses a force sensor. Finally, Chapter 7 concludes the research document with findings and future work.

CHAPTER 2

LITERATURE REVIEW

Variations in the non-linear time series plots of various physical behaviors have produced useful screening results for medical issues like heart dysfunction, gait abnormalities etc. Variations such as unexpected changes in amplitudes, fluctuations in frequencies and the delay between fluctuations are found in long-range plots of the various anatomical functions. These variations can screen anomalies in neurological and physiological processes. Similarly, motor sensitivity is also one characteristic predictive of various physiological phenomena. For example, a person's ability to perform complex motor-movements declines with concussion. A person who is concussed experiences changes in his or her response to different visual-motor tasks, especially where conscious control of movement is required. More conscious controlling of motor-movements is represented by less automaticity in motor-movements control and less adaptation to complex motor tasks.

1.4 Related Work

Several research studies [1, 2] are exploring ways to detect concussion symptoms using cognitive and motor behaviors post-concussion. Parker et al. [3] has shown that variation in cognition, gait stability and other motor movements in combination can produce accurate results for differentiating between people with concussion and with no history of concussion. Patterson et al. [4] are using the accelerometers on smartphones to study post-concussion postural sway and Samadani et al. [5] are using eye-tracking to detect brain concussion symptoms.

Studenka and her lab [6] have developed a method for collecting variations in non-linear time series plots to help in detecting concussion. Their approach involves having an individual press his or her index finger laterally against a force sensor for a period of time to capture motor sensitivity on a force-time series. Higher frequencies (8-12hz) in force time-series represent better automaticity in motor performance on a task (better responses) while lower frequencies (0-4Hz) are evident for using a feedback mechanism to learn and then perform (reduced performance). Through testing, Studenka found that the average performance of visual-motor tracking tasks in non-concussed individuals, such as error scores, continue to improve over 5 days of practice (125 trials), whereas measures of non-linear time-series structure such as approximate entropy (ApEn, a measure of regularity) remain stable over multiple days. Results suggest that non-linear measures may be more reliable than using performance outcomes. Based on these results, Studenka hypothesized that abnormalities in ApEn and other non-linear parameters can be used to indicate concussion symptoms in a person. Our research also validates visual-motor data collected by mobile devices on these non-linear parameters

1.5 Trends in Mobile Health Applications

With the increasing potential of mobile devices as standalone user-friendly computers, the application market is growing exponentially in serving health specific user needs. Statistics provided by MobiHealthNews [7] show an increase of 156.6% in Google Play Store and an increase of 66.6% in Apple’s App Store for health applications. Not only to access vast amount of health related information on internet, intelligent applications are also available in the App market which can make important health related prediction. Lee et al. [8] have identified 155 applications providing support for concussion related problems and 18 of them qualify to produce results useful for practitioners. The research proposed here builds a mobile application to collect motor movement data and validates it on non-linear parameters to develop an effective tool for detecting concussion in the future.

CHAPTER 3

MOTIONSCAN

Our research builds on Studenka's force sensor device in Sensory Motor Behavior (SMB) Lab by creating an application, MotionScan, that collects the accelerometer readings of a mobile tablet device while the user attempts to balance a freely falling ball on the screen in the x (pitch) - z (yaw) axis and controlled speed in the y axis. The accelerometer data is used to produce visual clues (equivalent movement of a free object on the screen with the effect of device movement). In this application, the user is asked to balance a ball on different types of lines (sinusoid curve and straight line in our application) with the help of visual tracking provided on the screen. Because of the high sensitivity of the accelerometer, it is almost impossible to accurately track the curve but the user is asked to do the best he/she can. While the user tries to balance the freely falling object, the accelerometer captures the motor movements of the user and the application stores it with other relevant data in a file. Currently, MotionScan is used for data collection only, but in the future it will also analyze the data and produce concussion detection decisions in real-time.

1.6 Key Features of MotionScan

In this section, we describe the key features of MotionScan.

1.6.1 ***Performing Trials with Different Line Settings***

We implemented several features in MotionScan to make running trials and collecting data on the application easier. First, the participant is identified by a subject number which is entered into the first activity screen of the application (see Figure 1).

Next, the participant is presented with another screen where he/she can select testing parameters, including posture type, line type, and trial number based on the interviewer's suggestions (See Figure 2). The order of the test settings is pre-determined for every subject number and are randomized for different subjects to avoid any regularity based on the order of settings. After selecting the settings, the participant starts the test.

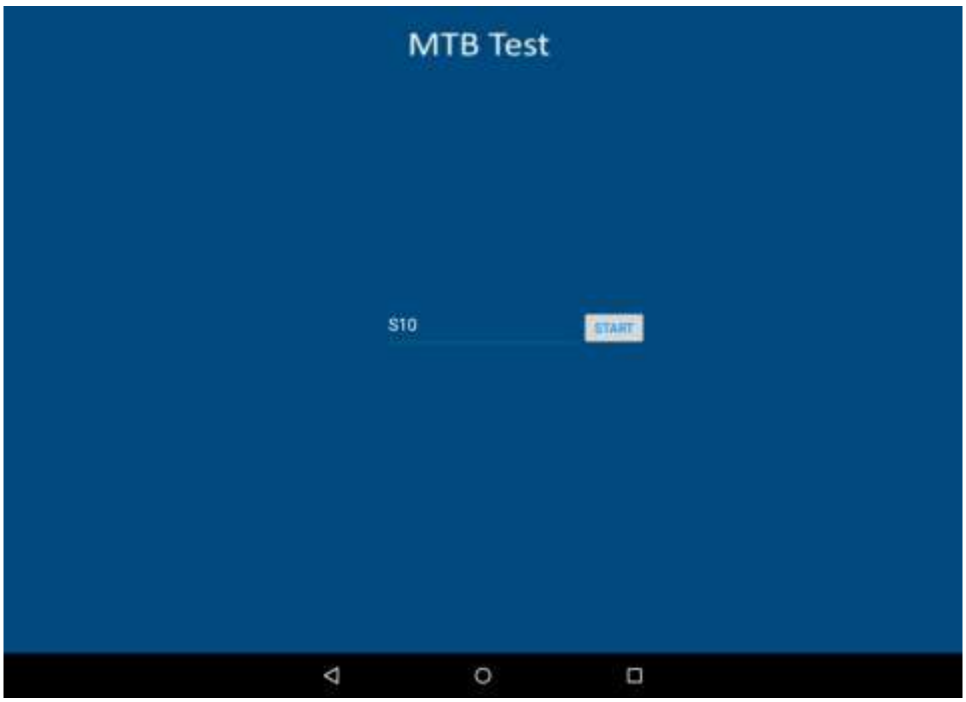

Figure 1: Welcome Screen on MotionScan

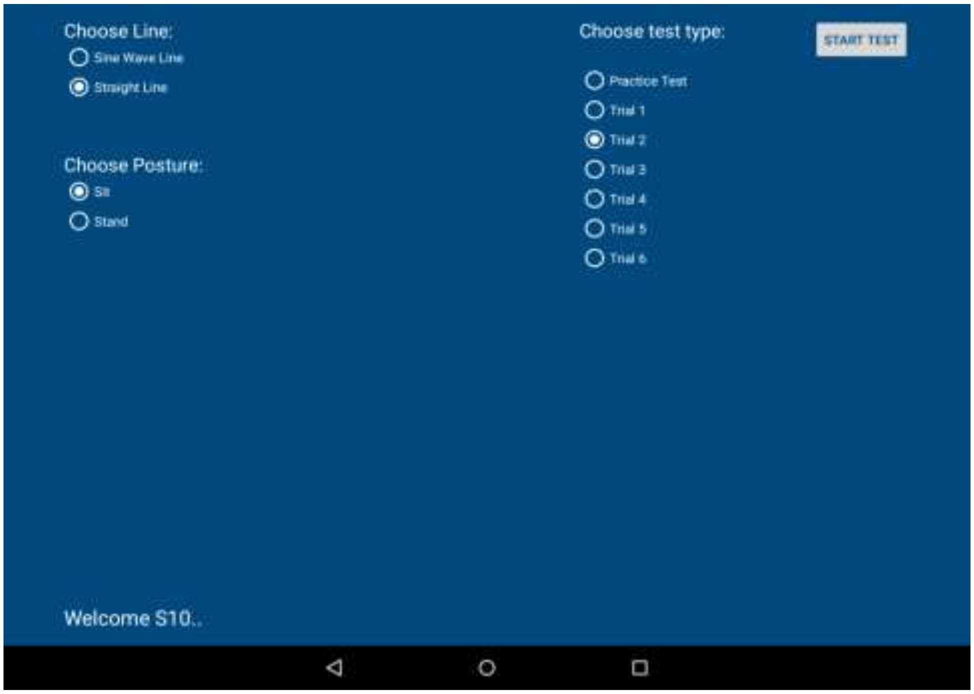

Figure 2: Test Setting Screen

The test screen initializes with the selected line type drawn on the screen in the landscape orientation of the device, with 1/6th of the screen size allotted as a calibration period (See Figure 3). The calibration period is provided to allow users to anticipate balancing the ball for the test and avoid any sudden reaction to new settings. The user starts the trial by sliding down his/her left thumb on the left-hand side of the screen (see Figure 3) which releases the ball from the top left corner of the screen. The ball moves in the horizontal direction with a constant speed (0.78 pixels on every accelerometer change event trigger). However, the ball is free to move vertically in both directions. The participant tries to control the vertical movement of the ball with subtle rotation along the pitch angle of the device. The rotation of the device is shown in Figure 4. The user tries to trace it along the line on the screen. While the user tries to trace the line, the movement of the device is captured by the accelerometer. As soon as the ball reaches the end of the screen, the motor sensitivity data is saved in a file. The name of the file contains the subject number and the parameters used for the test. Following the test, the application returns the previous screen and where the user can choose to perform further trials.

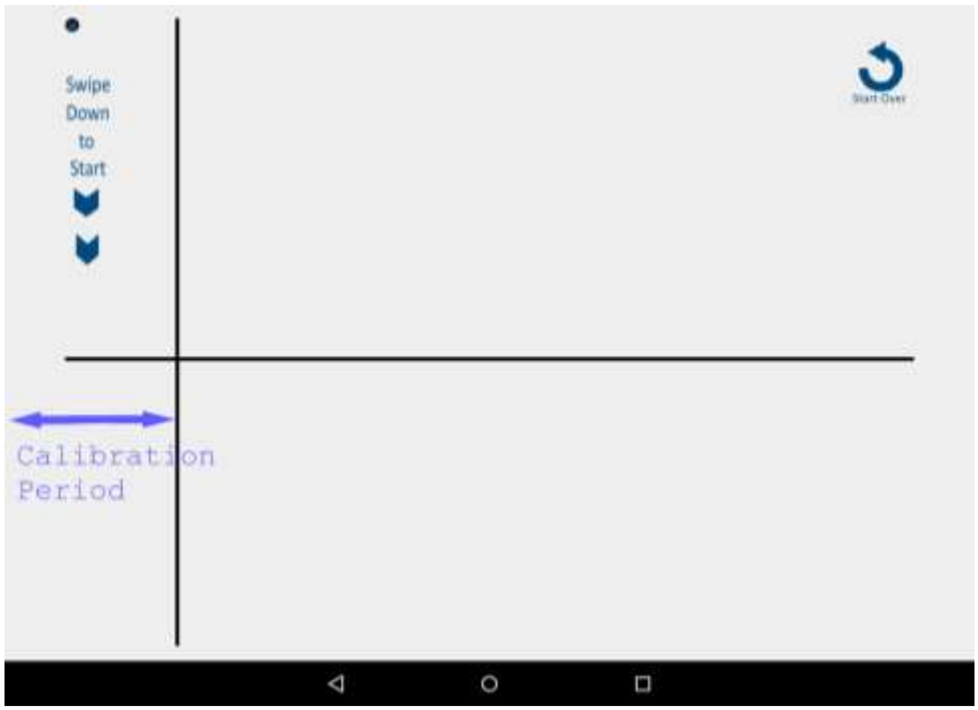

Figure 3: Test Screen showing calibration period and other controls

1.6.2 Rotation on the Device

The application lets the user balance a freely falling ball on the test screen on straight line and sine wave. For the straight line, the user tries to keep the ball as near as possible to a straight horizontal line while holding the device as still as possible. For the sine wave curve, the user twists the device inwards and outwards on the pitch angle (see Figure 4) of the device to control the vertical movement of the ball. Twisting sideways does not affect the motion in the horizontal direction because the ball moves with a controlled constant speed in the horizontal direction.

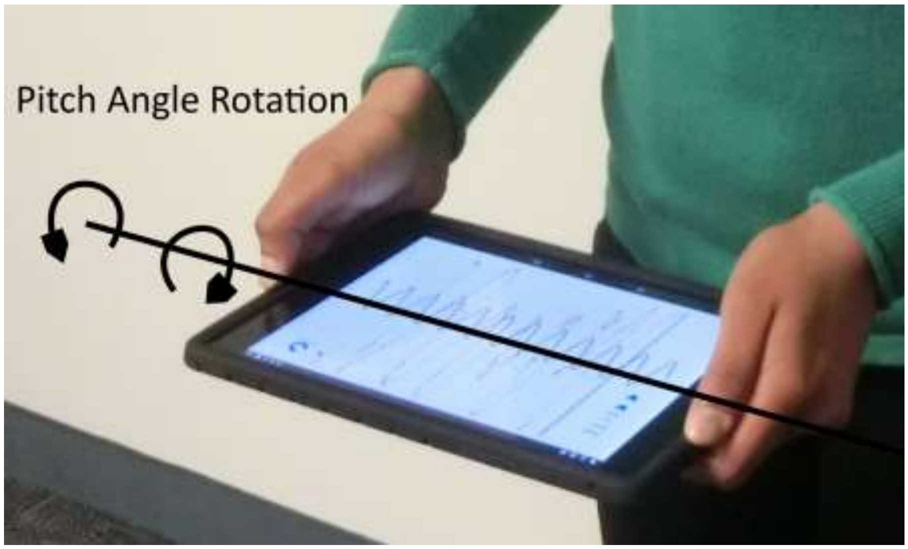

Figure 4: Allowed Rotation on the Tablet Device: Along Pitch Angle

1.6.3 ***Sensitivity of the Ball to Motor Movements***

MotionScan measures motor sensitivity by capturing accelerometer readings while a person performs a balancing task on the tablet device. While the person holds the device with both hands and controls the freely falling ball, most of the anterior and posterior muscle groups of the body are used while performing the task. MotionScan uses the highest sensitivity setting available on the tablet’s accelerometer (SENSOR_DELAY_FASTEST) and it magnifies the effect of user movement on the device while displaying the ball movement. These sensitivity adjustments make it more difficult to control the ball and they generate more motor responses from the user. Users of MotionScan reported that the device was very sensitive and that it responded to any kind of muscle movement—even talking and breathing affects the performance. Precise tracing of the curve is not expected, but we ask the user to do their best to trace the line. The force sensor device is also set to be highly sensitive to motor movements. Therefore, to make the data collected via MotionScan comparable to the force sensor device and to find the most accurate correlation, we also made MotionScan highly sensitive to user's motor movement.

1.6.4 Visual Feedback

Visual Feedback helps a user assess his/her performance while doing the balancing task. MotionScan provides a red line of the ball's movement on the screen (see Figure 5). When a user poorly traces the line with the ball, his/her brain uses the visual feedback provided by the application to improve his/her performance.

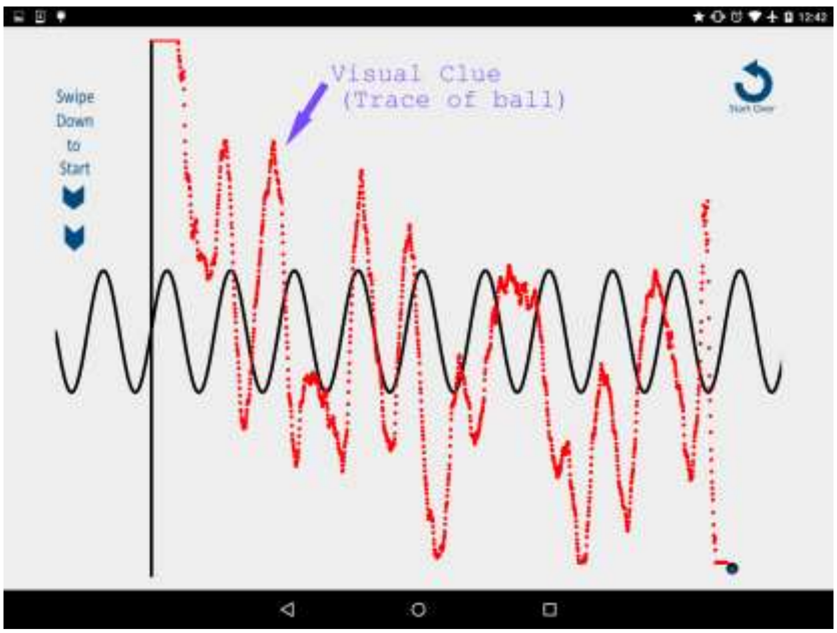

Figure 5: Screen Displaying Visual Performance Feedback

1.6.5 Data Files

The accelerometer data captured during trials is saved to a CSV file on the device. Each line in the file records a timestamp and an accelerometer reading. The accelerometer reading includes acceleration values for each of 3-axis (yaw, pitch and roll). For each accelerometer reading, MotionScan also records the location of the ball on the screen. The coordinates of the ball on the screen were recorded to analyze performance over time. All the readings are stored in a multi-line string with each line signifying a single accelerometer reading. Different fields are separated by commas to be processed as CSV file data. The file name contains all the selected settings of a particular trial. The Matlab code that the SMB Lab uses to analyze the data follows the standard naming convention we used to name the file. The format for the naming convention of a file is available in Figure 6.

<Subject Number> - <Line Type> - <Trial Number> - <Trial Posture>.csv

Figure 6: Naming Convention for Data Files

This format allows us to identify each data file with the selected trial settings, organize files for different settings and maintain the reference for future analysis.

1.7 Application Development

Before starting the development of the application, we learned how the SMB Lab uses a force sensor to capture motor movement data. We attended the data collection sessions with the force sensor device to understand the application logic and the choice of controls in the application interface. MotionScan should follow similar data collection protocols. Dr. Studenka from the SMB Lab gave us the data collection protocols and the requirements for developing MotionScan.

We started the development of our application in a cross-platform application deployment tool. The App development market is full of different alternatives like Apache Cordova, Corona, AndEngine etc. We chose Appcelerator for its vast open source support, extensive documentation and variety of available tutorials. It is a MVC framework based on JavaScript, XML and CSS. We initially developed a prototype application on the Appcelerator framework. But the platform does not support design choices like native development platforms do. Many of the application controls offered by Appcelerator were obsolete. Also, while working with the accelerometer sensor in Appcelerator, we noticed that the platform offers little control of the accelerometer sensor. Unlike the native development for any mobile operating system, it only offers a single sampling frequency for accelerometer readings. Appcelerator does not allow for control of the sensor sensitivity and the sampling frequency is very low and only suited for detecting orientation changes. This made Appcelerator unsuitable for developing MotionScan.

We chose to develop MotionScan using native Android development with the Android SDK. It provided us with the latest design choices and better control of the device sensors. We used a Nexus 9 tablet device to calibrate and test the application, because of its advanced hardware capabilities. Another reason to choose the Nexus 9 tablet was to get the highest accelerometer sampling rate for best granularity in our data.

1.7.1 Challenges

While developing the application, we encountered the following major challenges:

1.7.1.1 Drawing on the Canvas

To move the freely falling ball on the screen, we used the Canvas provided in Android SDK. Canvas can be used to render the object bitmap to be drawn on the screen by providing pixel locations. To move the ball on the screen, the bitmap of the ball image is created at one point, destroyed from that point and then re-created at a new position. With the sampling rate of 100Hz, the ball movement caused flickering instead of smooth motion. To fix this issue, we used animation of an imageview to remove flickering, as the animation call handles movement more smoothly. Now the movement of the ball is more intuitive and smooth in response to the user's handling of the device.

1.7.1.2 Isolating the Effect of Gravity

The accelerometer measures the acceleration applied to all three physical axis (x, y and z) of the device and it also includes acceleration due to gravity. With rotation of the device, we cannot just subtract the constant value of acceleration due to gravity (9.8 m/s^2) from the accelerometer readings as the effect of gravity gets distributed along the three axis of the device. The acceleration on device movement changes rapidly while the gravity force changes gradually as it is a constant force acting on the device. We filter out the slow changing force of gravity by using noise filters. First, we calculate the effect of gravity by using a low-pass filter, which removes the high frequency data of rapid changing acceleration on the device and produces low-frequency acceleration change due to gravity on the device. Then we subtract the low-pass filtered data from accelerometer readings to filter out the low-frequency gravity effect on the device and the resulting high frequency data represents rapid changing linear acceleration on the device. The following equation shows how the low-pass filter calculates the effect of gravity on the three axis of device:

Calculated Gravity = Alpha * Previous filtered value + (1- Alpha) * Accelerometer Reading

Figure 7: Gravity Calculation Equation

In the equation above, the value of Alpha is 0.8 calculated on t / (t + dT), t is the low-pass filter's time constant and dT is the event delivery rate. The previous filtered value is the last filtered value and it initializes with 0. The calculated gravity from this equation is then subtracted from accelerometer values on each axis to get the linear acceleration of the device without the effect of gravity[4].

Linear acceleration = Sensor Value – Calculated Gravity

Figure 8: Linear Acceleration Equation

1.7.1.3 Making the Ball Movement More Sensitive to Device Motion

As a part of requirements, the ball movement on the screen should be very sensitive to device movement. Even with the highest sensitivity of the accelerometer available (using SENSOR_DELAY_FASTEST) and the available sampling rate of 100Hz on the Google Nexus 9, the resulting sensitivity of the ball to the user's movement

[4] http://developer.android.com/guide/topics/sensors/sensors_motion.html

on the device is lower than required. We magnified the effect of device motion by multiplying the displacement values calculated from the linear acceleration of the accelerometer by a number (Magnification Factor). The Magnification Factor magnifies the effect of motion on the device, which is reflected in the movement of the ball on the screen. This makes the movement of the ball very sensitive to subtle movements on the device. The current Magnification Factor is 150, calibrated as per the requirements.

1.7.1.4 Addressing Issues with the Test Screen Controls

The Android Canvas is by default the primary display object of any activity in an Android application and all other layout controls are given priority for event triggers after the events of the Canvas are triggered. Even if the events of the Canvas are not handled or defined, the application makes calls to all the events like, touch, press, slide etc. The touch events for other layout controls are triggered only after all related events on the Canvas are triggered. We noticed that most of the button controls did not work properly due this prioritization on events. So, we removed the controls from the activity layout and created button images to be drawn as bitmaps on the Canvas. Then, the touch and slide events of the Canvas were checked for pixel locations on the screen to execute the functionality of the button images. For example, the Start-Over button (see Figure 3) at the top right corner is a bitmap on the Canvas, and when pressed, it triggers the touch event. The Canvas touch event processes the coordination of a touch on the screen, and if found to be on the button bitmap, it executes the code to restart a trial. Sliding down on the left side of the screen to start a trial is also triggered from the touch event of the Canvas.

1.7.1.5 Fixing the Delayed Loading of the Trial Screen

To calculate the non-linear parameters on the motor movement data plotted on a time-series, we also need the actual pixel point locations of the line to trace. So, we draw the curved line to trace on the trial screen by passing constantly incrementing values to a sine wave function and generating the related curve points. However, the calculation for the sine wave points significantly increased the loading time, even if passed into a different thread for calculation. In the data collection protocol, a single data collection session will involve performances on both a sine wave as well a straight line. So, now we started using a different thread to perform the sine wave calculations and a different thread to initialize the test screen. This reduced loading time of the trial screen but still gave a noticeable lag in loading the test screen. So, we generated the related sine wave values separately to store as permanent files for analysis. Currently in MotionScan, the sine wave in the test screen is drawn with arcs of the Canvas tool (with relative size and position) and not original coordinate values.

1.7.1.6 Interpolating Values to Achieve a Constant Accelerometer Sampling Rate

We checked different devices for their accelerometer sampling rate and found that the Nexus 9 promised the highest sampling rate. We tested the sampling rate of the device with an application called Sensor Kinetics (available on the Google Play store at: https://play.google.com/store/apps/details?id=com.innoventions.sensorkinetics&hl=en) and found that the Nexus 9 was able to achieve the sampling frequency of 100Hz. However, when examining the timestamp of these readings, we found that 100Hz is the maximum average sampling rate, and that the actual readings of the accelerometer are done at variable times. The reason behind variable sample rate times is that the operating system allots the CPU time to other background services along with the main application running and the timestamp are recorded along with other processes working. We tried disabling most of the background services and putting the device on airplane mode, but it had little effect. To work properly, the accelerometer samples need to be collected at a constant rate. The work around was to interpolate the data between readings to make a constant sample rate time in the values. We used Matlab’s native interpolation functions to generate points between data points to achieve a constant sampling rate.

1.8 Summary

In this chapter, we describe the features and development process of the tablet application MotionScan. We also discuss the major challenges in developing the application. The next chapters will discuss the testing of the application, data collection and analysis of the data.

CHAPTER 4

USER TESTING AND DATA COLLECTION

After developing MotionScan, we pilot tested the application with SMB Lab members to validate the functionalities of the application and refine the test and data collection procedures for the formal user testing. Next, we conducted user testing with 20 participants where we collected motor data using the application and the force sensor device in the SMB Lab. We tested the MotionScan application in standing and sitting positions to find correlations between data collection using the tablet in both the postures and data collection using the force sensor device. We also collected feedback on the usability of MotionScan. The motor data collected from the participants is analyzed in later chapters along with the participant feedback.

1.9 Pilot Testing

The pilot testing of MotionScan ensured that the application was usable and ready for formal user testing. The pilot testing also allowed us to calibrate the application for data collection and to improve the testing protocol. We pilot tested the application with 5 members of the SMB Lab. For each test, participants were asked to use the application to perform 2 trials with each posture (standing and sitting) and line setting (sine curve and a straight line). We asked them for feedback on the application’s interface, handling of the device and sensitivity of the device while performing trials. We also collected suggestions for what kinds of information we should collect in our interview guide. For example, we added a question to the interview guide about the participant’s experience with motion gaming because we found that this experience could affect performance on the trials. We collected the following feedback on MotionScan during our pilot testing:

1.9.1 ***Confirmation to Save the Data***

The data collected in each trial is saved in a file only when the trial finishes. Initially, we gave a confirmation message to save or discard the data, assuming that the interviewer would confirm that a trial was performed properly before saving it. However, based on feedback from pilot testing, this confirmation was replaced by automatic saving of the data after a trial finishes. We found that confirmation to save the data sometimes lead to participants accidentally discarding the data after a trial. Also, each participant is given a limited number of trials to perform with instructions to perform the trials. To ensure an equal number of trials for every user (given the same instructions), a trial should be saved and counted as a trial for analyses no matter how the user performs.

1.9.2 ***Vibration to Indicate the Start of a Trial***

The test screen initializes with the ball stationary at the top left corner of the screen. When the user begins the test the accelerometer is registered to start capturing motion and to start moving the ball accordingly. But, the tablet does not start recording in a trial (when the data starts to be collected) until after a calibration period, which is indicated by a vertical line. To warn the user in advance about the actual start of the trial, a ‘Get Ready’ message is shown for some time when the ball crosses the half way point of the calibration period. In addition, MotionScan produced a 300 millisecond vibration to indicate the start of the trial. This vibration was found to produce noticeable effects in the motor data recorded in a trial. Fluctuations were found in the plots altering the motor response. Also it made the users uncomfortable to hold the device when the recording starts. Based on this feedback, MotionScan now indicates recording with a message only, no vibration.

1.9.3 ***Sliding Gesture to Replace Pressing Start Button***

In the previous version of application, the ball was released for movement on the screen after pressing a button at the top left corner. Most of the users in pilot testing had to change their grip on the device to press the button. Pressing the button while maintaining the expected grip for testing was found to be very uncomfortable for the users. So, we replaced the button image with a sliding indicator image on the left most portion of the screen. Now the user can maintain the expected test grip on the device and slide with the thumb of left hand to start the trial.

1.9.4 ***Font Color on Parameter Selection Screen***

The color used for the text on the application screen to select posture, line and trial settings did not have enough contrast with the background color. We found during the pilot testing that this font color made the text hard to read. Therefore, we changed the text color to white (the screen background color is blue) which made the text more readable.

1.9.5 ***Stroke Width to Draw Trace***

The trace of the ball was drawn with a stroke width of 5 while the line to trace was drawn with a stroke width of 8. Although it gave the curve a smoother finish, it was not visible in the areas where curve and trace crosses. This was making tracing confusing and hard to focus. Thus, we changed the stroke size of the trace to be a width of 8 to improve the user experience.

1.9.6 ***Color of Trace***

The color of the trace and the color of the line to trace were both black in the initial version of the application. As reported by users in pilot testing, the trace was indistinguishable with the line they were being asked to trace because they were the same color. We changed the color of the trace to red to highlight the trace and provide better visual feedback.

1.9.7 ***Increase Sensitivity***

As discussed before, the MotionScan accelerometer was set to the highest sensitivity available programmatically. To make it equivalently sensitive to the force sensor device, we multiplied the displacement calculated from the accelerometer values by a factor (Magnification Factor). We started with a Magnification Factor of 10, 20 and so on. The application pilot tested had a Magnification Factor of 75. As per the feedback from pilot testing, the application needed to be more sensitive to the device motion. After trying different incremented values, we found the Magnification Factor of 150 produced the desired sensitivity of the ball to the device motion.

1.9.8 ***File Names***

In the previous version of the application, the files containing motor data after a trial were produced in different related directories with the user id to signify line and posture setting. With the feedback from pilot testing, we found that the files name should also contain the selected setting information for future organization and analysis. Now each file name contains the subject id, the selected posture, the selected line and trial number, making each file self-contained with all the information needed to interpret and analyze it.

1.9.9 Device Sleeping Problem

We noticed that the different settings (e.g., battery saving mode, low brightness settings, etc.) on the tablet device can cause the device to prematurely enter sleep mode. If the device sleeps while a user is performing a trial, the accelerometer service still captures the device movement and the ball keeps moving even though the screen is off. Device sleeping also disrupts the testing protocol and causes confusion (i.e., was the trail completed or not?). Now, we use the Power Lock feature of the Android SDK to stop the device from sleeping until a trial finishes.

1.10 User Testing

After completing the pilot study, we conducted formal user testing where we collected motor sensitivity data by using MotionScan and the force sensor device. The collected data was then analyzed using Approximate Entropy, Root Mean Square Error, proportion of power in different frequency ranges and mean frequency (see Chapter 6). Another major aspect of user testing was to collect feedback on the interface of the application, the handling of the device and the participant's history of concussion, if any. A single user test involved data collection on the tablet device in both sitting and standing position, data collection using the force sensor device and a follow up interview to collect background information and feedback. Each test took approximately one hour. The test protocol, described in the following section, was strictly followed to make sure all testing was done in a similar environment and so that results would be comparable.

1.10.1 Test Protocol

Testing took place in the Sensory Motor Behavior Laboratory space to ensure a similar testing environment for all the participants. The force sensor data collection task was performed at a fixed location desktop machine in the lab. The tablet tracking task was conducted only in a specific area of the lab. We drew a square box on the lab floor where the user should stand during the standing task and a square box to place the chair for the sitting task. The standing and sitting posture is demonstrated in Figure 9 and Figure 10. The chair had to be a desk chair without wheels to avoid chair movement during the test. The researcher explained the handling of the devices during the test, by having each test participant go through the steps to record trials and finally confirming with some practice trials to make sure the user understood it well.

Before conducting a data collection session, the interviewer makes sure that all the Data Collection instructions have been followed. The instruction sheet is attached in Appendix B. Once a participant arrived, we explained the testing process and the purpose of the testing/data collection to the participants. We explained the voluntary nature of the data collection session and how we maintain confidentiality of the participant's details throughout the research. Afterward, we asked him/her to sign a consent form. The consent form can be found in Appendix A. The testing session begins with a pre-trial interview, where we asked participants about their age, handedness and any mental/physical problem that they have that might affect the testing process or results. This information was used to change test settings before the testing actually began. The pre-trial interview form (see Appendix C) indicates the order in which each of the trials should be performed. This pre-trial interview form pre-randomizes the different trials on both the devices (tablet and force sensor) and the order of posture and line settings. For example, subject 1 might be given the first trial on the tablet for a sine wave curve in a standing posture, while subject 2 might be given the first trail on the tablet for a straight line in the sitting posture. This randomization was done before creating test sheets for all the participants and the created order was strictly followed throughout the data collection session to eliminate similarities in the data based on device, posture and line order.

Figure 9: Participant Performing Standing Trial

Figure 10: Participant Performing Sitting Trial

A participant is identified throughout the data collection and analysis by a subject number. The subject number is mapped to other details of the participant in a separate document to maintain anonymity of the data.

To begin the trials with MotionScan, the application is initialized by the researcher entering the subject number of the participant. Next, the trial procedure is explained to the participant and the participant is given the initialized application to perform the test by himself/herself. Through the application interface, the participant selects the trail, line and posture settings. It is important to have the users use the interface by themselves to obtain good feedback on the control and interface design of the application. The researcher then explains the testing procedure, how to select different parameters and how to perform the trials. A practice trial for each line type is given before the actual trials starts to confirm that the participant understands how to perform the trials. Only one practice test will be given for each line type and the practice trial of a specific line is always given before recording of an actual trial series on that specific line. The researcher notices (and takes notes) the participant performing a trial from a distance to avoid creating any distraction for the participants during the trials. After the researcher explains the process to the participant and gives the participant the device, the participant is asked to say the trial number out loud before actually starting the trial to let the researcher confirm the order of settings on the interview sheet. This process helps to ensure that the trials are recorded in the right order.

The tablet application has a welcome screen (see Figure 1) where the interviewer enters the subject number (e.g., S1, S2 etc.). On the next screen, the application activity initializes the test settings screen. The settings to specify contain (see Figure 2):

1. **Line:** We have two choices for the line type. The straight line trials capture motor sensitivity data based on the constancy of a participant’s grip on the device and their ability to trace a straight line. The other line type is a curved sine wave line. The curved line trials capture motor data based on a participant’s change in motor performance to accommodate a variable line.
2. **Posture:** MotionScan has standing and sitting posture options in the data collection screen. The standing posture can be difficult, as reported by many participants, due to the distribution of motor attention. We wanted to analyze the

performance outcomes of tracing task in both the posture to find the best posture setting for best accuracy in the results.

3. **Trial Selection:** The trial selection menu allows the user to select the trial order and practice mode. The researcher asks the participant to perform a practice trial on each line type before starting the formal trials. Extra practice will only be administered if the participant was not able to follow the instructions properly in a practice trial and is documented for future reference. The trials need to be done in the correct, pre-determined order. To facilitate this process, the participant will state out aloud the trial number to inform the researcher about the trial progression.

Once the test settings have been selected, the user is presented the testing activity. One design decision was to remove the button for starting the test and replacing it with a downward swipe on the left side of the screen. This option allows a user to not lose or alter his/her grip on the device to press the start button. Once the test starts, there is a calibration period where the participant can get used to the feel of the ball movement and motion. The accelerometer data is not recorded during the calibration period. The ball is moving along the horizontal axis with a constant speed. Just before the ball crosses the calibration zone, the user is displayed a text notification to ‘get ready’ for the actual trials. Once the ball reaches the trial zone, the ball starts leaving a trace line to give the user visual feedback (a red trace) on their performance. The accelerometer data generated during this trial is stored in a csv file. For each accelerometer reading, the following data is saved as a line in the data file:

Timestamp	Xposition on Screen	Yposition on Screen	Accelerometer-x value	Accelerometer-y value	Accelerometer-z value

Figure 11: Accelerometer Reading Format for Trial Data File

The file name contains the selected attributes for the associated trial. The attributes are appended in the filename as follows:

Tester ID	Curve Type	Trial number	Testing posture

Figure 12: Trial Data Filename Format

For example, the filename “S1-Sine-Stand-Trial6.csv” conveys that the data contained in the file is for participant S1 performing the 6th sine wave trial in a standing position. This filename convention helps to organize the files during data analysis and to preserve the metadata for future use.

After the trials are done, the researcher conducts a follow up interview using the interview guide found in Appendix C. First, the researcher asks the participant about his/her history of concussion. This information will be used while analyzing the data to determine if the data is different based on past concussion. Next, the researcher asks the participant about their experience with motion gaming. This information will help us to understand if prior motion gaming experience correlates with improved performance on trials. Finally, the researcher will ask for the participant’s feedback on the controls and interface of the tablet application and the force sensor device. Most of the questions in the interview guide are open-ended questions and the interviewer is free to pursue other question to collect as much relevant feedback as possible.

1.10.2 Comparison of Two Devices

Central to this user testing is the comparison of two different methods (i.e., the MotionScan application and the force sensor device) for collecting motor sensitivity data. Both of the methods, even though based on a similar concept, have very different user interfaces and have been developed with different requirements for data collection. The force sensor device collects the motor movement of the index finger pressed laterally against the sensor. To perform the trial using the force sensor device, the participant controls a rising and falling force line by subtle pressure on the force sensor. More force on the sensor lifts the force line, while releasing the sensor drops the force line (see Figure 13). The force sensor passes the data to a Matlab program on a computer for real-time analysis and screen presentation on a display unit for the changing force. The user tries to control the rising and falling line to trace it on the screen along a plotted curve.

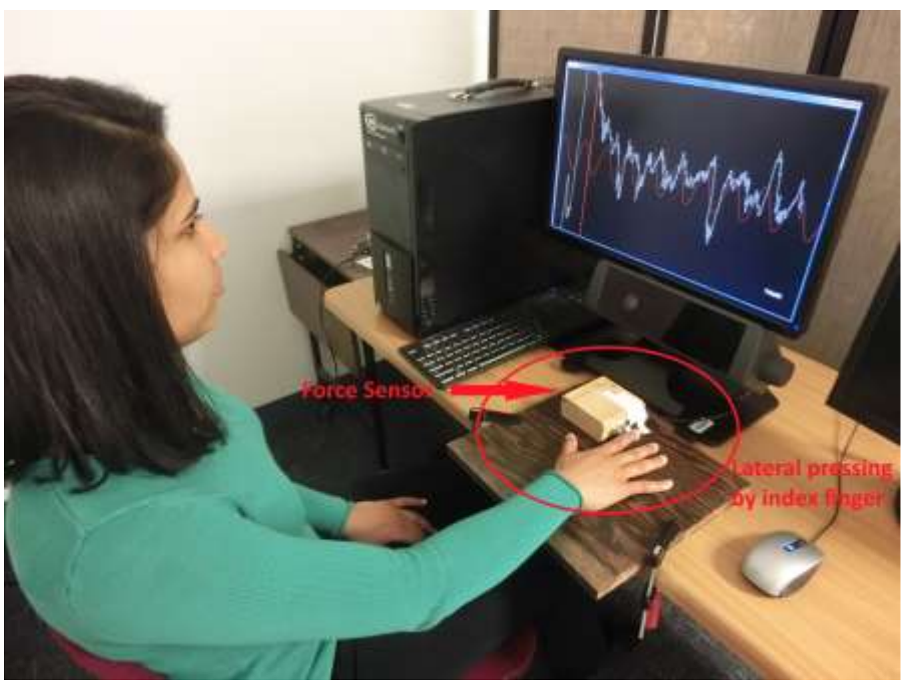

Figure 13: Participant Performing a Trial on Desktop Machine with Force Sensor

The MotionScan tablet application on the other hand requires a twisting motion of the hands while holding the tablet with elbows fixed at the torso. It collects motor data from more anterior and posterior muscle groups in coordination with visual cognition. While performing the test and trying to balance a freely falling object on the tablet screen, the motor response along with visual performance feedback is projected on the screen of the device.

1.10.3 ***Posture during Trials***

We use MotionScan to collect the user's data in a standing and sitting posture. The standing posture takes more muscle groups to control the ball, including the muscle group below the torso as well. Thus the standing posture trials are more difficult to perform because the attention of the brain is distributed between more muscle groups than the sitting posture trials. In the sitting posture, the user rests his/her lower body and back on the chair and therefore fewer muscle groups are used.

1.10.4 ***Number of Trials for Improvement***

For the MotionScan tests, each posture has 1 practice trial and 5 recorded trials for tracing both the straight line and the curved line. Each user has 4 practice trials and 20 recorded trials to perform in total. In the initial phase, we wanted to collect the data in all different settings and analyze what setting gives best results to distinguish between concussion and non-concussion cases.

1.10.5 Fixed Number of Trials

Every user is given exactly the same number of trials to perform. This is done to give an equal number of opportunities to every participant to improve their performance during the process. No user is given more than one practice trial for each setting. We have noticed users performing better with each trial. If a participant performs a test improperly because they did not use the device properly, the interviewer makes sure the user understands how to use the device before giving another test. Only one more test trial is provided in such a case with proper documentation of the extra practice trial. More accidental trials disqualify the user's data to be considered for analysis.

1.11 Summary

In this chapter, we discussed the test protocol used to conduct the data collection trials. The test protocol was strictly followed because any deviance in the protocol could disqualify or invalidate the trails for analysis. The following chapters report on the usability of the MotionScan application and analyze the data collected during the user trials.

CHAPTER 5

USER STUDY INTERVIEW RESULTS

During the user study, we interviewed the participants before and after the data collection process. This chapter reports on the background of the tested population and their feedback on the usability of the MotionScan application through information collected during participant interviews.

1.12 Participant Background

We invited students from USU to participate in the test trials by using a research participation platform for students called USU SONA. This platform is hosted by psychology department of USU to help students enroll as participants in ongoing research studies. We also posted flyers seeking volunteers and invited people we knew who fit the participation criteria to volunteer for the research. The only requirement for participation was that the participant must be in the age group of 18-35. We performed the data collection and feedback interview task with 20 participants. The background information for the participants is reported below:

- *Age:* Participants all fell within the age range of 18-30. We had eleven participants in the age group of 21-23, three participants in the age group of 24-26 and four participants in the age group of 27-29. We had one participant of age 18 and one participant of age 30.
- *Gender:* Twelve males and eight females participated in our study.
- *Handedness:* All participants were right handed.

- *Sports Participation:* The sports that the tested population reported playing were Table Tennis (5), Badminton (3), Soccer (3), Basketball (3), Tennis (2) and Volleyball (2). Other sports played by the population (but only reported by one person) were Wrestling, Skiing, Baseball, Football, Jujitsu, and Zumba. Four participants stated that they currently were not involved in any sports.
- *Conditions Affecting Testing*: No participant reported a physical or neurological condition that would alter the testing process.

1.13 Participant Concussion History

We asked participants about their history of concussion. If they reported having a concussion before, we asked when the concussion happened, what age they were, and what caused the concussion.

- *Number of Concussions:* Twelve out of twenty participants reported a history of concussion. Two participants in the population reported more than one concussion incident.
- *Timing of Concussion Events*: Of the twelve participants who reported a concussion, 41% had the concussion event when they were in the age range of 5-10 years old, 33% had the event when they were in the age range of 10-15 years old and 25% participants had the event when they were in the age range of 15-20 years old. None of the participants reported a concussion event in the age range of 20-25 or 25-30 years old**.**
- *Concussion Diagnosis:* We asked the participants about their concussion events, the diagnosis, and the effects of the concussion. The general categorization of a head injury into a concussion was based on loss of consciousness, amnesia,

convulsions and other symptoms like headache, nausea and blurred vision. Fifty percent of the tested population who had events resulting in symptoms of concussion were never formally diagnosed with a concussion while the other fifty percent of the concussed participants reported proper diagnosis by a doctor or an athletic trainer. This lack of a formal diagnosis, demonstrates a need for an accessible and easy-to-use application like MotionScan to assist in concussion detection.

1.14 Technology Use

We asked participants about the mobile devices that they use and found that all the participants had a smartphone. 40% of the participants tested had IPhones or IPads, while 50% of the participants reported their current phone to be an Android phone. 10% of the participants used a Windows phone.

Most of the participants also had experience playing motion games on their phones or other related gaming technologies. Motion gaming experience improves the performance on the tablet application because of related motor movements involved while playing a motion game. We defined motion gaming as “playing a game on a device where you move or tilt the device or where to you move your body to make a corresponding effect on the console screen.” 84% of the population reported having motion gaming experience. In our tested population with motion gaming experience, 20% had experience playing motion games on tablet devices, 40% had experience playing motion games on their smartphones and 40% of the population had experience playing motion games on the Nintendo Wii.

1.15 User Experience Feedback

We collected feedback on the interface and handling of the tablet application and the force sensor device from all the participants. We categorized the different suggestions into two sections: feedback on the interface and feedback on the testing process.

*1.15.1 **Feedback on the Interface***

The following suggestions were given by the participants in our study on the interface of the application:

- *Remove the Start Over Button:* Most of the participants reported that the start over button was distracting and if it can be removed from the test screen, it might help them to perform better on a trial.
- *Swiping Down Start Issues:* Many participants reported that after a few trials, the swiping down feature on the test screen to start a test, does not always work. They had to swipe multiple times to start the test. Some of the participants suggested replacing it with a button.
- *Automatic Navigation:* Testing on the force sensor device does not require the participant to select posture and line settings for each trail. Instead the trial process is automated on the force sensor device. Many participants stated that they would like to have the same trial automation on the tablet application. Conversely, a few participants felt that selecting parameters by themselves made them more aware of the process and they liked it.
- *Timer of 3 and "Go":* One suggestion was to start each test trial by giving a timer for a count of 3 and then display the text "Go." Especially on the force sensor device, participants reported they needed time to get ready. Similarly, on the

tablet application, instead of just starting the test by sliding down on the screen, a timer of 3 and “Go” would help the user get ready.

- *Use the Whole Screen:* A few participants suggested that the actual testing area on the screen could be expanded to fill the whole screen. There is a boundary gap between the test surface edges and the screen edges, which creates confusion and needs to be eliminated.
- *Increase Font Size:* A few participants reported that the font size on the screen to select parameters was too small. While selecting options, they were accidentally selecting the option above or below. Large font sizes and bigger controls could help eliminate this problem.
- *Color Contrast on the Screen:* We received suggestions to change the color contrast on the test screen. Like the testing with the force sensor device, a black screen with a green or yellow line might help the participant focus more on the test.
- *Trial Number on the Test Screen:* A few participants reported that it would be nice to have the trial number on the screen so the participant would know which trial he/she is currently working on. This suggestion could be combined with the suggestion to automate the trial progression. If automatic navigation was implemented, the trial number could be incremented automatically and displayed on the trial test screen so the user would know what trial they were on.
- *Utilize the Space on the Data Screen:* One suggestion on the interface was to utilize the screen size by using different controls that would automatically fill up the screen and increase the font size to accommodate the available space.

- *Disable Practice Trial Selection:* The testing protocol for performing data collection trials on the tablet stated that the user is given limited trials and strictly one practice trial on each test setting. One participant suggested disabling the practice trial option once the practice trial has been performed. This would reduce accidental practice trial selection.
- *Increase the Size of the Ball*: The size of the ball could be increased according to one participant. The participant felt that a bigger ball would draw more eye attention, especially for people with vision problems.

1.15.2 ***Feedback on Testing Process***

We categorized the feedback related to handling of the device, testing methodology and any user-experience suggestions into feedback on the testing process. We collected the following feedback:

- *Users become Self-Conscious of Their Performance:* Many participants reported that when their performance on a trial was out of control (i.e., they were performing poorly) they felt self-conscious of their performance. They felt this behavior tended to make their performance even worse.
- *Add More Practice Trials:* A few participants reported that they would have liked more practice to understand how to perform a trial. We discarded the data of two users because they were unable to follow the instructions with the allotted one practice trial. We may want to increase the number of practice trials. However, we would need to analyze the effect of practice trials on the overall performance in the test before we would increase the number of practice trials.

- *Wrist Fatigue*: A few participants reported wrist fatigue after performing the many required trials on the tablet. They had to hold the tablet still for a long time which resulted in fatigue in the forearms and wrist.
- *Sensitivity of the Tablet:* Most participants (80%) found performing the balancing tests on the tablet more difficult than using the force sensor device. We deliberately magnified the effect of motion on the tablet application to make it comparably difficult to the tracing task on the force sensor device. We may have made the application too sensitive. Some participants reported that they lost enthusiasm to perform tracing tasks on tablet after a while and after a few trials they were less focused on performing the task well and more focused on hitting the required number of trials. We also discovered that the performance of the tablet is affected by irregular breathing. Of the two testing postures for the tablet application, performing trials in the standing posture was ranked more difficult than performing trials in the sitting posture. We need to analyze the tradeoffs of reducing the sensitivity on capturing more informative data.
- *Sine Wave was Easier to Trace:* Many users reported that tracing a sine wave on the screen seemed very difficult but once they started performing the trials, it was easier than tracing a straight line. Tracing the sine wave involved tilting the device in a pattern and required less stiffness in holding the device compared to tracing the straight line.
- *Preferred Testing in Future:* Finally, we asked users which testing method would be their preference as a concussion detection tool and the reason for their preference. 60% of the participants preferred the tablet application. Also, the

majority of the users preferred the sitting posture to the standing posture in tablet tasks. Participants found the tablet application more interactive. 40% of the participants stated that the force sensor device would be their preferred way of testing. These participants found the force sensor device more comfortable and easy to use. Many of these participants became self-conscious of their performance on the tablet, which eventually disrupted their performance. A few of these participants also reported wrist fatigue after using the tablet application. More work is needed to analyze the sensitivity of the tablet application against the effectiveness of the testing process for a more user-friendly and effective concussion detection tool.

1.16 Summary

This chapter reported on the user feedback for MotionScan and the testing process. The next chapter covers the results of analyzing the motor-sensitivity data that we collected from participants during the user testing.

CHAPTER 6

TIME SERIES DATA ANALYSIS

The main aim of this study is to validate the reliability of a tablet application for non-linear assessment of motor sensitivity after concussion. To accomplish this aim, we collected data from similar balancing tasks using the force sensor device and the MotionScan tablet application and we analyzed this time-series data for correlations. Studenka [6] has already demonstrated that the force sensor device can collect time-series data from a user that can then be analyzed for non-linear variations that could indicate concussion in a user. Approximate Entropy or Sample Entropy is a measure of irregularity in the data. Approximate Entropy of a motor task plotted on a time-series curve is found to be significantly reduced post-concussion [6]. If the motor sensitivity data collected by the tablet application has a good correlation with the data collected by the force sensor device on similar tasks, Approximate Entropy should stand valid for concussion detection on tablet tasks as well. We also measured Root Mean Square Error and the power of data on different frequency ranges on data collected using the tablet application to see if it would correlate with the same performance measures on data collected using the force sensor device.

We collected data from 20 participants. However, we discarded the data from 2 participants because they were unable to follow the instructions properly. We calculated a Pearson Correlation coefficient on the18 participants with a p-value <= 0.478 to validate significance of the overall data. We found significant correlation between the data collected by the tablet application and the force sensor device on the following parameters:

1.17 Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) measures the sample standard deviation of the differences between predicted values and observed values. This measure is used in our analysis to compare the performance of similar task on the tablet application and the force sensor device.

We calculated the mean RMSE of the 18 valid participants for the two tablet posture tasks and the force sensor tasks. Then we calculated the correlations between the different tasks. The calculated Pearson Correlations are shown in Table 1:

Table 1: Correlations between Tasks for Root Mean Square Error (RMSE)

		Computer	Tablet Sit		Tablet Stand	
		Sine Wave	Line	Sine Wave	Line	Sine Wave
Computer	Line	**0.49**	0.33	0.26	0.33	0.36
	Sine Wave		0.29	0.32	0.31	0.41
Tablet Sit	Line			**0.60**	**0.48**	0.33
	Sine Wave				0.43	**0.64**
Tablet Stand	Line					**0.70**

Table 1 shows that participant performance on the Computer (the force sensor task) has a good correlation with participant performance on the Tablet sitting and Tablet standing tasks. RMSE measures in our data show how well a person performs on a task and with the high correlation, we can predict that the performance of a person on a tablet task will be similar to the performance on the computer task.

We also plotted the absolute collective RMSE on the performance of the 18 valid participants (see Figure 14) and found that the standing posture for the tablet tracking task was more difficult to perform than the sitting posture for the table tracking task. The RMSE of the data for the tablet in standing posture is considerably higher than the data for the tablet in sitting posture. Tracing the sine wave in the computer, tablet standing and tablet sitting tasks produced a higher absolute RMSE in the data than the tasks that traced a straight line. Relatively, tablet tasks showed significantly higher RMSE on all the posture and curve settings. This was also backed by the feedback of the participants that the tracing tasks on the tablet were very sensitive to motor movements, and the least comfortable to perform.

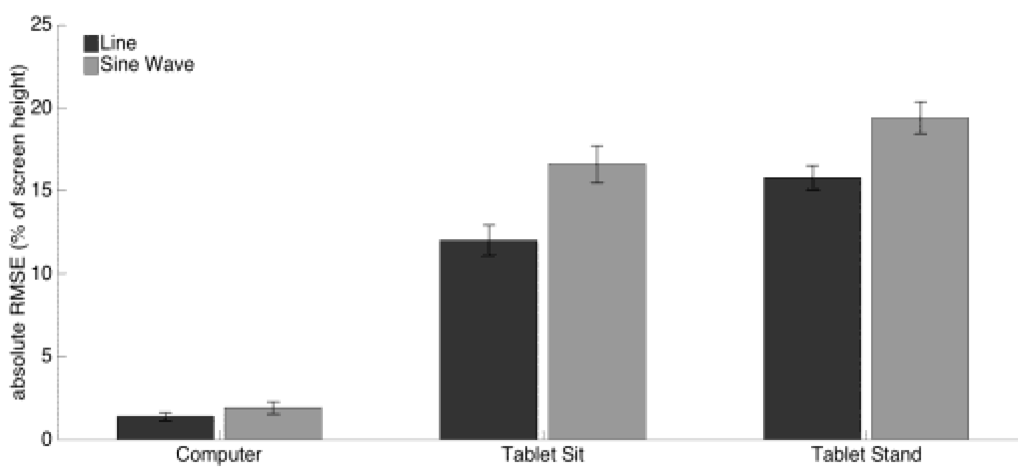

Figure 14: Absolute RMSE

1.18 Sample Entropy (SampEn)

Sample Entropy and Approximate Entropy are mathematical algorithms to measure repeatability and predictability within a time-series. Both algorithms are extremely sensitive to input parameters and can finely measure the irregularity of data. Approximate Entropy can distinguish between noisy and chaotic data only with a short number of data samples (up to 100 data points) while Sample Entropy is independent of the number of data samples and produces effective measure of irregularity [9].

A person's ability to perform complex motor-movements declines with concussion. A person who is concussed experiences changes in his or her response to different visual-motor tasks, especially where conscious control of movement is required. More conscious controlling of motor-movements in a concussed person presents less automaticity in motor-movements control and less adaptation to complex motor tasks. Initial investigation by the SMB Lab on measuring this irregularity was done by calculating Approximate Entropy on the motor sensitivity data collected by the force sensor device [6]. Approximate Entropy in a person's response post-concussion decreases when compared to responses from non-concussed persons (see Figure 15 and Figure 16). Over time, the Approximate Entropy increases back to normal. Thus, Approximate Entropy is best at predicting concussion directly after the concussion occurs, and is less reliable over time. Approximate Entropy and Sample Entropy measure irregularity in data similarly but Sample Entropy is independent of sample size while Approximate Entropy can only be used for very short sample sizes. So, we switched to Sample Entropy for versatility in current and future data analysis.

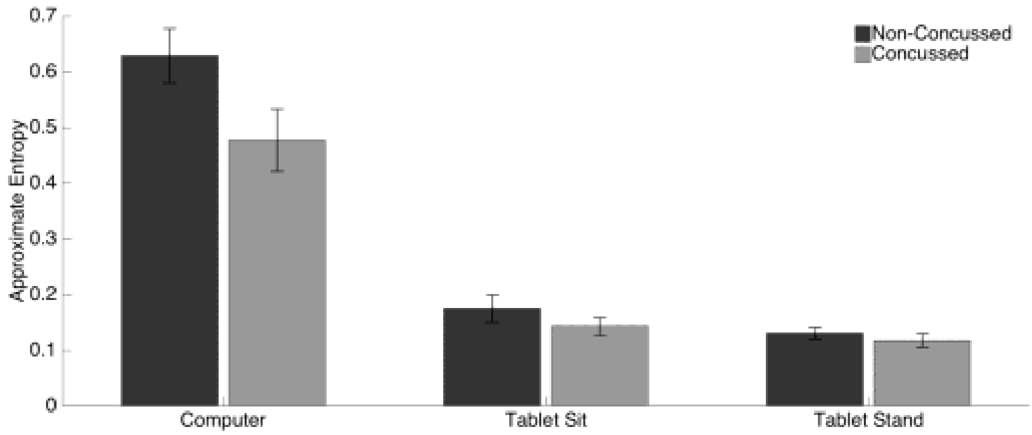

Figure 15: Comparison of Approximate Entropy for Non-Concussed and Concussed Persons for the Computer, Tablet Sitting and Table Standing Tasks When Tracing a Straight Line

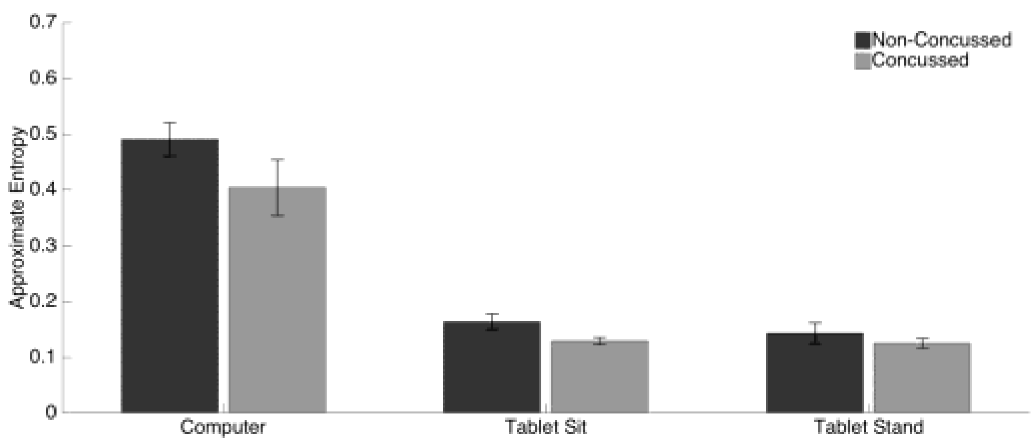

Figure 16: Comparison of Approximate Entropy for Non-Concussed and Concussed Persons for the Computer, Tablet Sitting and Table Standing Tasks When Tracing a Sine Wave Line

We found significant correlation in Sample Entropy from data collected using the tablet application and the force sensor device (see Table 2). Tracing a straight line on the tablet shows correlation of more than 0.50 with tracing a straight line with the force sensor device. This conclusion is also backed up by better correlation in terms of RMSE, discussed above. Based on this data, we can conclude that the tablet device, especially with the tracing task on a straight line, measures a similar level of irregularity in motor movement as the force sensor device and can be a potential way to detect concussion.

Table 2: Correlations between Tasks on Computer, Tablet Sitting Posture, Tablet Standing Posture for Sample Entropy (SampEn)

		Computer	Tablet Sit		Tablet Stand	
		Sine Wave	Line	Sine Wave	Line	Sine Wave
Computer	Line	**0.78**	**0.50**	**0.47**	**0.49**	0.24
	Sine Wave		0.24	0.10	**0.51**	0.16
Tablet Sit	Line			**0.72**	**0.71**	0.36
	Sine Wave				**0.50**	**0.65**
Tablet Stand	Line					**0.63**

1.19 Power in Different Frequency Ranges

We did a spectral density analysis on the mean data of participants over the two line types in different posture settings to validate how much sensitivity the device is capturing. Power Spectral Density function (PSD) shows the strength of the variations of a time-series data as a function of frequency, where power signifies signal strength at different frequencies. In other words, it shows at which frequencies variations are strong and at which frequencies variations are weak. We found that power of the data is concentrated in the 0-4Hz frequency range for the tablet while the computer was able to capture power in the 4-8Hz and 8-12Hz frequency range as well. These results demonstrate that the tablet is not sensitive to higher frequency fluctuations despite the sampling frequency of 100Hz for the accelerometer. We need to measure the higher frequency motor fluctuations to study other kinds of motor responses like physiological tremors and that's why this issue needs future attention. A possible reason for this limitation is that the calculation of displacement using linear acceleration acquired by the accelerometer has been greatly magnified and the power of the data in higher frequencies is lost. As we are analyzing the change in screen coordinates of the free-moving ball, the effect of the magnification factor in calculating displacement to reflect ball movement needs to be analyzed for its effect on the data. We might need to reduce the magnification factor or use a completely different approach to make the tablet application more sensitive to device movement. The plots for Average Power on different frequency ranges are shown in Figure 17, Figure 18 and Figure 19.

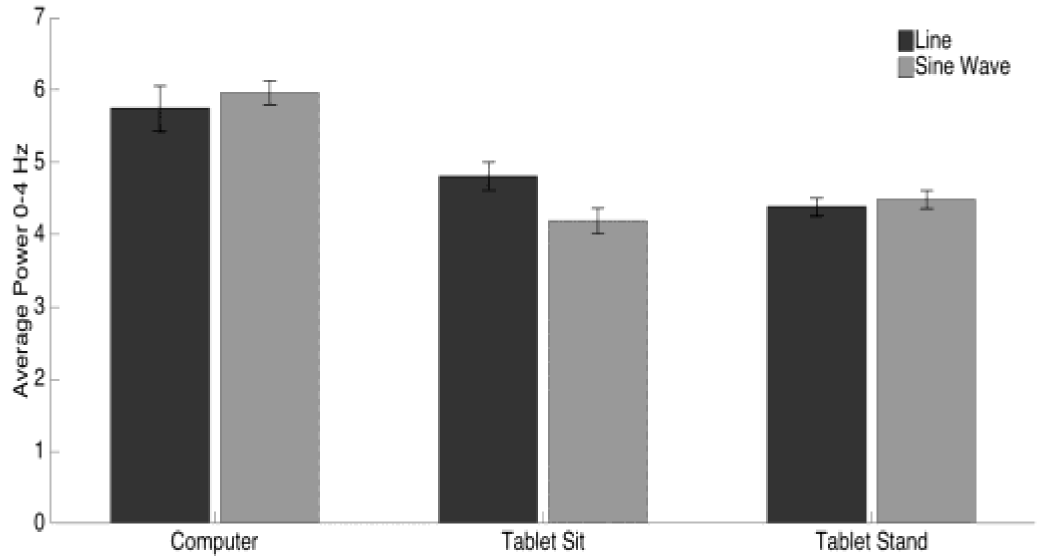

Figure 17: Comparison of Average Power in Frequency Range 0-4Hz for Computer, Tablet Sitting and Tablet Standing on Sine Wave and Straight Line tracing tasks

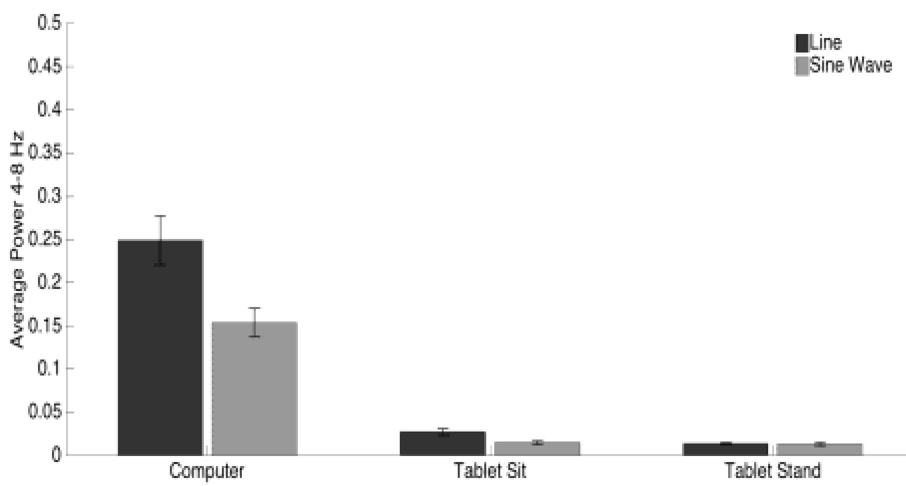

Figure 18: Comparison of Average Power in Frequency Range 0-8Hz for Computer, Tablet Sitting and Tablet Standing on Sine Wave and Straight Line tracing tasks

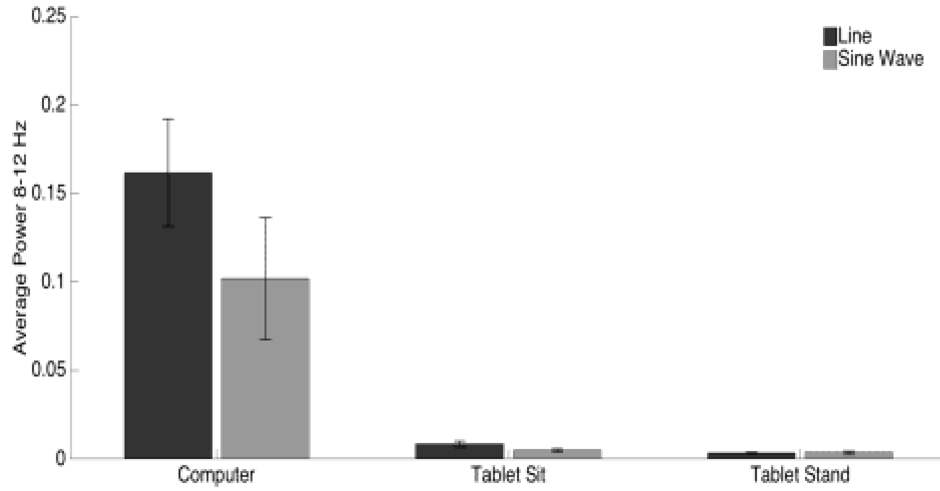

Figure 19: Comparison of Average Power in Frequency Range 8-12Hz for Computer, Tablet Sitting and Tablet Standing on Sine Wave and Straight Line tracing tasks

In the Figure s above, the average power of a frequency domain on the tablet data is mostly visible in the 0-4Hz range. The frequency range of 0-4Hz in motor fluctuation cover improved and conscious motor responses but not the physiological tremor (>5Hz) [10] which needs to be studied for post-concussion effects.

We validated the correlation of power plots between the frequency range 0-4Hz for different tasks (see Table 3) because the tablet can capture fluctuations only in this frequency range. We found that tracing a straight line on the computer has a good correlation factor with tracing a straight line on the tablet in different postures. Backed with the findings from the other non-linear parameters discussed above, we find that tracing a straight line on the tablet is a comparable way of detecting concussion to that of values (from all 3 axis) to calculate displacement of the ball on the screen is different than plotting linear force change on the force sensor device (only in one axis) on the display screen. Also, the power of fluctuations captured by the tablet is limited to the 0-4Hz frequency range possibly due to the manipulation of raw sensor values. So, we need to analyze the manipulations involved to display visual clue from raw sensor values to conclude accurate results.

Table 3: Correlation between tasks on Computer, Tablet Sitting Posture and Tablet Standing Posture for Average Power in 0-4Hz

		Computer	Tablet Sit		Tablet Stand	
		Sine Wave	Line	Sine Wave	Line	Sine Wave
Computer	Line	**0.57**	**0.56**	0.08	**0.65**	0.30
	Sine Wave		-0.04	-0.03	0.19	0.39
Tablet Sit	Line			0.14	**0.76**	0.08
	Sine Wave				0.26	**0.54**
Tablet Stand	Line					0.45

1.20 Summary

In this chapter, we interpreted the data plots provided by the SMB Lab on the data collected by 20 participants for tracing tasks on the tablet and the force sensor devices. We validated correlations in the data using RMSE, Sample Entropy and Power in different frequency ranges, and found that both the tablet application and the force sensor device report similar performance outcomes. The next and final chapter concludes with the findings of this thesis research and next research steps.

CHAPTER 7

CONCLUSION

This thesis investigates the viability of using a tablet device as a concussion detection tool. This study is based on the findings of the SMB Lab that Sample Entropy of motor performance of a person reduces after concussion. We developed an Android application (MotionScan) that uses the accelerometer of a tablet device to measure motor movement while a user tries to trace a line with a free-moving ball. We tested this application with 20 participants and calculated the mean values from all the data collected in the test trials using different test settings. We compared the Root Mean Square Error, Sample Entropy and Average Power in different frequency ranges on the data collected by the tablet application in both a sitting and standing posture and the force sensor device (a similar device developed by the SMB Lab that collects motor sensitivity data). Finally, we calculated the Pearson's correlation between different settings to validate how well the performance outcome matches in the two collection methods on similar tasks. We found a significant correlation between the data collected by the tablet in sitting posture as well as standing posture and the data collected by the force sensor device. We found the most correlation in tracing a straight line compared to tracing a sine wave line in the data across the methods of data collection. Also, the power captured by the tracing straight line tasks was more than the power captured by tracing the sine wave line. Overall, tracing a straight line using the force sensor device produces similar performance outcomes as tracing a straight line on the tablet application.

During the user testing, we also collected feedback from the participants around the usability of MotionScan and the testing process. The minor issues reported by users that were hindering the testing process were fixed while the rest are left for future work. Another iteration of the MotionScan application can address the feedback reported in this thesis document to improve it. However, care should be taken because some of the suggestions may affect the accuracy of the MotionScan application. For example, a lot of test participants reported that the tablet is highly sensitive to motor movement and the sensitivity should be reduced for a better user experience. We will need to analyze the effect of reducing sensitivity on the tablet before making any changes because making the application less sensitive could invalidate the motor sensitivity data the application collects.

The MotionScan application does not currently detect or diagnose concussion; instead, it serves as a data collection tool that enables easy collection of time-series motion data for later analysis. We have found strong correlations in the data collected by the tablet and the force sensor device, which shows that the use of a tablet device to record motor sensitivity could be used as a concussion detection tool. After studying the process of recording motor movement via a tablet in detail and further testing with more concussed and non-concussed users, the tablet application could be modified to detect concussion.

1.21 Future Work

We developed the tablet application to collect motor data from users and to validate the viability of a tablet device as a concussion detection tool. In this section, we describe future directions for this research.

*1.21.1 **Adjusting the Sensitivity of the Tablet Application***

The majority of participants found the tablet application very sensitive. Some participants also reported wrist fatigue after performing the trials on the tablet. We magnified the motion captured by the tablet device to reflect the movement of the ball on the tablet screen using a Magnification Factor. We also noticed the loss of signal power in the data for frequencies higher than 4Hz even when the device has a sampling rate of 100Hz. We attribute this anomaly to the manipulation of accelerometer values to reflect movement of ball on the screen. The value of the Magnification Factor was calibrated to make the tablet tasks equivalently hard as the tasks on the force sensor device. The Magnification Factor needs to be tested with different values on more subjects to acquire better results. The SMB Lab will be analyzing the effect of different sensitivity levels on the device for better accuracy in capturing motor data.

*1.21.2 **Improving the User Experience***

We collected feedback from the test participants regarding their user experience with MotionScan. Here are the issues identified by the participants that will need to be addressed in future versions of MotionScan:

- Swiping down on the test screen to start the test does not always work.
- The Android Canvas on the testing screen does not completely fill the tablet screen. We can address this issue by using background bitmaps to replace the Canvas after calculating background line coordinate points.
- The navigation from one trial to another can be automated so the trial participants do not have to manually select trial settings.

- The screen to select test settings can be modified to be more intuitive. The layout of the screen can utilize the empty space with a larger font for the text and reorganization of the controls.
- The starting of the test can have a timer displaying a count of 3 to let the user get ready for the test.
- The Start Over button was not used during any of the test trials and only served to clutter the test screen. This button can likely be removed.
- The test screen should have the current trial number on the testing screen to inform the user about what trial is in progress.

1.21.3 ***Determining Optimal Line and Posture Settings***

With the interpretation of the data collected by tablet tracking tasks, we know that the data from the tablet application is correlated with data from the force sensor device. The strongest correlations between the data from both methods of data collection were found in tracing straight lines along the screen. Even though tracing a straight line was comparatively easy compared to tracing a sine wave curve, the change in Sample Entropy was reflected better in the tracing a straight line task. Therefore, further iterations of the application can consider using straight line tracing tasks to produce necessary data. Also, the posture settings need to be analyzed for better results. The standing posture invokes most of the posterior and anterior muscle groups but results in a lack of attention in task performance. The sitting posture on the other hand, makes the task easier and more comfortable to perform. More users need to be tested to Figure out what posture produces the best results.

1.21.4 ***Investigating Technology Platforms***

This version of MotionScan was developed specifically for high-end tablet devices. Different sampling frequencies (of accelerometer) for different mobile devices need to be tested to develop the application along a range of tablet devices. A future research direction would be to develop the MotionScan application for the mobile phone platform provided that the phone has a high enough sampling frequency for the accelerometer.

1.21.5 ***Establishing a Baseline***

In this study, we found that a tablet can be used to record motor movements of a person on line tracing tasks. We collected the motor data from 20 participants on designated tracing tasks via tablet and found strong correlation with the performance of tracing via the force sensor device. Now, the application needs to be tested on larger samples of concussed and non-concussed people. We know that Approximate Entropy on motor performance decreases post-concussion but a baseline for a person pre-concussion will be needed for better diagnosis.

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APPENDICES

Appendix A IRB Consent Form

UtahState University
Department of Computer Science
4205 Old Main Hill
Logan UT 84322
Telephone: (435) 797-3671

IRB Approval Date: 11/13/2015
IRB Approval Expires: 11/12/2016
Protocol #6941
IRB Password Protected per IRB Director

INFORMED CONSENT
Towards Brain Concussion Detection with a mobile device

Introduction/ Purpose Professor Amanda Hughes and student researcher Shantanu Saxena from the Department of Computer Science at Utah State University, and Professor Breanna Studenka from the Department of Health, Physical Education and Recreation (HPER), are conducting a research study to discover how the motion-sensors of a mobile phone can be used to assess visual-motor coordination and potentially detect concussion. You have been asked to take part in this research because you are between the ages of 18 and 35, able to use a tablet device, and can perform simple balancing tasks without any physical hindrance. There will be approximately 20 total participants for this user study.

Procedures If you agree to be in this research study, you will first be asked a series of question about your level of physical activity and whether you have any past experience with concussion. You will then perform 30 trials of force tracking on a computer and 30 trials of force tracking using a tablet device. Both will assess your visual-motor coordination. Using the tablet you will trace a freely falling object on a line or a curve as it moves across the screen of the tablet. For the computer task, you will sit in front of a computer screen with your right index finger pressed against a force transducer (a sensor that picks up the force that your finger produces). A white line representative of the force you produce will move across the screen from the left to the right and will go up and down as you press harder and softer on the force transducer. You will attempt to trace a red line with the force you produce. Finally, we will ask a set of follow-up questions about your experience and your assessment of the tablet application's interface. The entirety of your participation should take about 1 hour. With your permission, we will audio record this testing session.

Risks You may experience finger fatigue or discomfort with sitting at a computer or using a tablet device. To alleviate this fatigue or discomfort, you may take a break at any time during the testing. There is a small risk of loss of confidentiality but we will take steps to reduce this risk, detailed in the "Confidentiality" section, below.

Benefits There are no measurable benefits to you for participation in this study, however, this work may help advance knowledge in the fields of motor control related to vision and tracking. If you are interested we can share with you the results of this study.

Explanation & offer to answer questions Professor Amanda Hughes or student researcher Shantanu Saxena has explained this research study to you and answered your questions. If you have other questions or research-related problems, you may reach Professor Hughes (PI) at (435) 797-3671 or amanda.hughes@usu.edu.

Voluntary nature of participation and right to withdraw without consequence Participation in research is entirely voluntary. You may refuse to participate or withdraw at any time without consequence.

Confidentiality Research records will be kept confidential, consistent with federal and state regulations. Only the principal investigator, co-investigator, and student researcher will have access to the data which will be kept in a locked file cabinet or on a password protected computer in a locked room. All audio

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INFORMED CONSENT
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recordings will be destroyed after transcription. To protect your privacy, personal identifiable information will be removed from study documents and be replaced with a study identifier. Identifying information will be stored separately from the data and will be kept in a different locked file cabinet in a locked room. Identifying information will be destroyed by July 2016.

IRB Approval Statement The Institutional Review Board for the protection of human participants at Utah State University has approved this research study. If you have any questions or concerns about your rights or a research-related injury and would like to contact someone other than the research team, you may contact the IRB Director at (435) 797-0567 or irb@usu.edu to obtain information or to offer input.

Investigator Statement "I certify that the research study has been explained to the individual, by me or my research staff, and that the individual understands the nature and purpose, the possible risks and benefits associated with taking part in this research study. Any questions that have been raised have been answered."

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Signature of Participant By signing below, I agree to participate.

Participant's Signature	Participant's Name (Printed)	Date

Appendix B Instructions for Data Collection Session

Before a subject arrives:

1. Set up the equipment
2. Make sure two consent forms are set out and ready
3. Get out an intake form and the subject collection sheet
4. Make sure you have a pen handy
5. Open up Matlab
6. Turn on the force sensor box
7. Type in Tablet_Tracking_Spring2016 and hit <Enter>

Once a subject arrives:

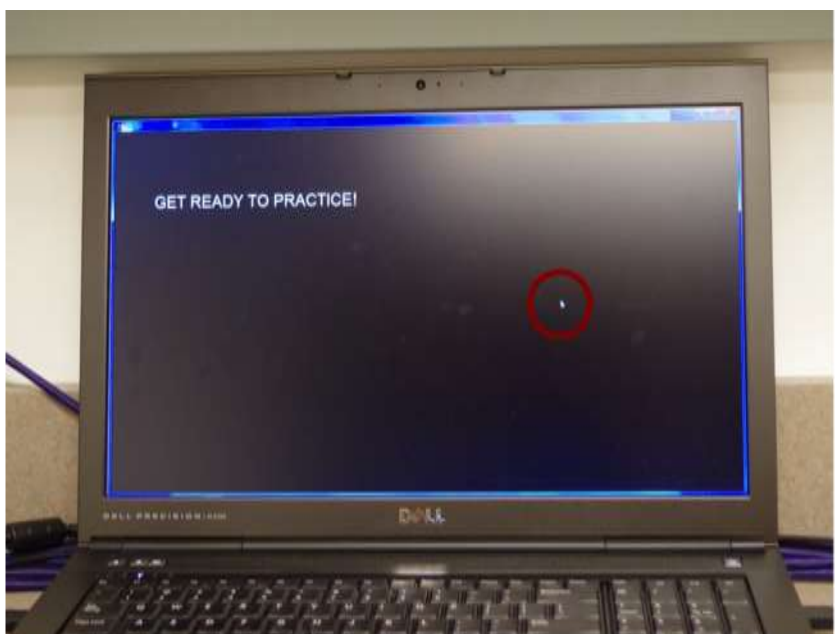
1. Greet the subject, tell them your name
2. Explain the force and table track tasks briefly
3. Have the subject sign the consent form
4. Once the subject has signed the consent form, record subject's age, gender, handedness, the date, etc…

Tasks:

<u>Computer force tracking</u>

1. Once subject is ready have them sit in front of the computer and force transducer
    a. Make sure they are comfortable, and make sure the clamps aren't in the way of their legs
2. Explain how the subject should place his or her index finger (of the dominant hand) centered on the force transducer (see below)
    a. "center your distal knuckle on the center of the sensor"
    b. "lift the index finger off of the table"
    c. "make sure to press inward with only your index finger"


3. Hit <Enter> to begin the acclimation trial
4. Make sure the mouse cursor is not visible on the screen



5. On the first trial, have the subject practice pushing in and out on the force transducer. Have him/her press as hard as he/she can to make sure the force trajectory goes up. This is how he/she will perform the MVC (maximal voluntary contraction) trials.

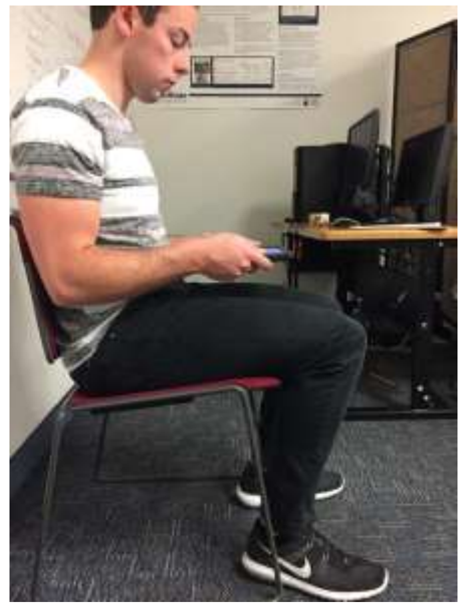
   a. ***"You can control the line by pressing inward with your finger, with more or less force".***

6. Also make sure that the subject is pushing only with one finger and that the finger is in the proper position.
7. Have the subject perform the three MVC trials making sure that, on each trial, the white line goes upward.
   a. If the subject does not press correctly, and the MVC does not go up or does not go up much, type <control c> and re-start the program. Re-start the program, enter the subject number, enter <n> for 'is this the start of the experiment', then enter starting task <0>, trial <1>.
8. Once the subject has completed the three MVC trials, he or she will practice each of the trial types.
   a. Make sure each of these practice trials, you explain what he/she needs to do, especially on the trial where he/she does not get any feedback.
      i. The constant force red line: "*Please trace the red line as well as you can*".
      ii. The sine wave: "*Please trace the red line as well as you can*".
9. Once the subject has practiced each trial type, the experiment will begin.
10. Tell the subject ***"You can take a break whenever you need to. Start the next trial at your own pace by pressing any key on the keyboard once".***
11. Keep an eye on the subject to make sure he or she is performing the task and understands what to do.
12. Make sure to be quiet and to make sure that the testing room is quiet.

Tablet tracking

1. Once the subject is ready have them either sit on the chair or stand with their toes at the tape.
   a. Make sure they are comfortable, and sitting with their back to the back of the chair, and their feet planted firmly on the ground.
   b. Make sure the table is on full brightness.

2. Explain how the subject should hold the tablet:
   - ***a.*** ***“please hold the tablet with each thumb centered on the short edge of the tablet”***
   - ***b.*** ***“please also hold the tablet above your lap with your feet squarely on the ground”***
   - ***c.*** ***“please hold the tablet parallel to the ground”***



3. Instruct the subject on how to open the program, and which trial to select.
   - ***a.*** ***“For this task you will try to trace the line on the screen with the ball”.***
   - ***b.*** ***“You can control the ball on the screen by tilting the tablet away from and toward you”.***
   - **c.** **“*Please select the straight line/sine wave, then the sitting task/standing task, and the practice trial/trial 1/trial2…..*”.**
   - d. Make sure the subject is on task, and maintains the appropriate grasp and position of the tablet.
   - e. For the standing trials make sure the subject isn’t swaying back and forth or moving.
   - ***f.*** When the trial is over, say, ***“Please hit the triangle on the left bottom of the screen to go back. Now select the straight line/sine wave….”***
   - ***g.*** ***“please let us know when you are starting the next trial”***

4. Tell the subject **"*You can take a break whenever you need to. Start the next trial at your own pace by selecting the next trial*".**
5. Keep an eye on the subject to make sure he or she is performing the task and understands what to do.
6. Make sure the subject takes a small break between tasks.
7. Make sure to be quiet and to make sure that the testing room is quiet.

Once the tracking tasks are completed:

1. Have the subject sit comfortably at the table, across from you and administer the questionnaire.

Once the experiment is over:

1. Thank the participant for his/her time.
2. Give the participant a card with our lab information and ask them to put this into their phone or keep it handy in case they do ever experience a concussion, or know of anyone who has.
3. If the participant was concussed in the past 6 months, ask the participant if he/she would mind if we gathered his/her contact information so that we can schedule follow up visits.

Once the participant leaves:

4. Make sure the force sensor is turned off
5. Make sure the tablet is plugged back in to charge.

Appendix C Pre-Trial Interview Sheet for Subject#1

Subject: 1 Date: __________

Age:_____ Hand Preference: R L Gender: M F

History of stroke or neurologic or motor impairment due to disease or injury? ____

Block 1: **COMPUTER**

Task 1: CONSTANT LINE

Practice	1	2	3	4	5	6

Task 2: SINE WAVE

Practice	1	2	3	4	5	6

Block 2: **TABLET SIT**

Task 1: CONSTANT LINE

Practice	1	2	3	4	5	6

Task 2: SINE WAVE

Practice	1	2	3	4	5	6

Block 3:**TABLET STAND**

Task 1: CONSTANT LINE

Practice	1	2	3	4	5	6

Task 2: SINE WAVE

Practice	1	2	3	4	5	6

Appendix D Post-Trial Interview Guide

Interview guide:

Section 1: Background Information

Do you currently play sports? YES NO
Which sports?

How often do you play these sports?

Section 2: Concussion Questions:

Have you had a concussion in the past? YES NO How many? ______
When?__________

If yes, briefly describe the event(s).

Did you lose consciousness? YES NO For how long? ______________
Did you have concussive convulsions? YES NO
Did you experience amnesia? YES NO For how long? ______________
Did a **Doctor** diagnose you with your concussion? YES NO
Did an **Athletic Trainer** diagnose you with your concussion? YES NO

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)

For how long did you experience symptoms of your concussion?

Were symptoms recurring particularly with exertion? YES NO

Are you still experiencing any effects from the concussion? YES NO
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* YES NO
Which device?
How often?

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

COMPUTER:

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

COMPUTER:

Was there anything that the tablet had that the computer didn't have or vice versa?

Was one device easier or harder to control?

Which way of testing (tablet or computer) would you prefer in the future?
Why?

Do you have any conditions that might alter your visual or motor responses to this application?

Appendix E User Testing Interview Sheets

Interview guide

Subject- **1**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports?
Volleyball, Baseball

How often do you play these sports? **Few times a month**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **2005**

If yes, briefly describe the event(s).
Bike accident, slammed forehead.

Did you lose consciousness? **Yes** For how long? **1 hour**
Did you have concussive convulsions? **No**
Did you experience amnesia? **No** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **Yes**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
Symptoms

For how long did you experience symptoms of your concussion?
1 day

Were symptoms recurring particularly with exertion? **No**

Are you still experiencing any effects from the concussion? **No**
If so, which ones? **NA**

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
IPhone

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Phone, Wii**
How often? **Very little, few times a year**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **To sensitive to control**

COMPUTER: **No**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **No**

COMPUTER: **No**

Was there anything that the tablet had that the computer didn't have or vice versa?
No

Was one device easier or harder to control?
Tablet was harder

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Tablet standing was harder, more control on computer using just a finger

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **2**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports?
Wrestling, one and a half year ago.

How often do you play these sports?
Everyday for 3-4 months

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 16**

If yes, briefly describe the event(s).
During a wrestling game, head slammed to floor.

Did you lose consciousness? **No** For how long? **NA**
Did you have concussive convulsions? **No**
Did you experience amnesia? **Yes** For how long? **20 seconds**
Did a **Doctor** diagnose you with your concussion? **No**
Did an **Athletic Trainer** diagnose you with your concussion? **Yes**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
Symptoms

For how long did you experience symptoms of your concussion?
1 day, couple of hours

Were symptoms recurring particularly with exertion?
No

Are you still experiencing any effects from the concussion? **No**
If so, which ones? **Na**

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
IPhone 5s

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Wii, IPhone**
How often? **Few times a month**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Like the navigation, go back, select trial and start (cleaner).**

COMPUTER:

- **A blank screen is displayed and then movement of force line out of a sudden. (Had to restart trial)**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **Standing trials were harder than sitting trials. Liked tracing sine wave, easy to perform like a pattern.**

COMPUTER:

- **Trials on force sensor were easiest.**

Was there anything that the tablet had that the computer didn't have or vice versa?
No

Was one device easier or harder to control?
Tablet is easy

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Performing trials on tablet was cleaner.

Do you have any conditions that might alter your visual or motor responses to this application?

No

Interview guide

Subject- **3**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Tennis, 3-4 months back.**

How often do you play these sports? **Used to play a few times a week.**

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? When?

If yes, briefly describe the event(s).

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**
Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion? **NA**

Were symptoms recurring particularly with exertion? **NA**

Are you still experiencing any effects from the concussion? **NA**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Samsung S5

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **No**
Which device? **NA**
How often? **NA**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Straight forward, lists options that are needed. Navigation to next trial can be automated.**

COMPUTER:

- **Liked the black background and white line.**
- **Want the line to move right and left instead of up and down, can relate to the force sensor more in that way.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Trial-5 seemed harder. User became self-conscious on both the device. Tablet requires more focus.**

COMPUTER:

- **Finger pressing was uncomfortable.**

Was there anything that the tablet had that the computer didn't have or vice versa? **No**

Was one device easier or harder to control?
Tablet standing –Force Sensor – Tablet sitting

Which way of testing (tablet or computer) would you prefer in the future? Why?
Tablet in sitting posture or computer standing.

Do you have any conditions that might alter your visual or motor responses to this application?

No

Interview guide

Subject- **4**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Ping Pong**

How often do you play these sports?
Nearly everyday

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **At the age of 7**

If yes, briefly describe the event(s).
Slipped on snow, slammed the back of head on surface.

Did you lose consciousness? **No** For how long? **15 minutes not unconscious, impaired memory.**

Did you have concussive convulsions? **No**
Did you experience amnesia? **Yes** For how long? **15 minute**
Did a **Doctor** diagnose you with your concussion? **No**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion?
NA

Were symptoms recurring particularly with exertion?
NA

Are you still experiencing any effects from the concussion? **NA**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
HTC- One

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Wii**
How often? **Few times a week**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Swiping down to start the test does not work sometimes.**
- **A button on the test screen to go to next trial will be better.**

COMPUTER:

- **Automatic Navigation between trials is good.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **No**

COMPUTER: **No**

Was there anything that the tablet had that the computer didn't have or vice versa?
Computer Interface was convenient.

Was one device easier or harder to control?
Tablet standing - Tablet sitting – Force sensor (Hard -> Easy)

Which way of testing (tablet or computer) would you prefer in the future? **Tablet**
Why? **Easy to use, handy.**

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- 5

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Ping Pong**

How often do you play these sports? **Few times a week**

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? **NA** When? **NA**

If yes, briefly describe the event(s).
NA

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**

Did a **Doctor** diagnose you with your concussion? **NA**

Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion? **NA**

Were symptoms recurring particularly with exertion? **NA**

Are you still experiencing any effects from the concussion? **NA**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android, Windows

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **No**
Which device? **NA**
How often? **NA**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Color contrast on the testing screen can be different, like black background, red trace.**
- **There must be an indication when the test is about to start.**

COMPUTER:

- **An object (like ball on the screen) can make visual clue better.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **If I can know the tablet is parallel to the ground, it will help me start well and perform well.**

COMPUTER:

- **Sideways pressing is very uncomfortable to perform the tracing task.**

Was there anything that the tablet had that the computer didn't have or vice versa?
No

Was one device easier or harder to control?
Tablet standing - Force sensor – Tablet standing (Hard -> Easy)

Which way of testing (tablet or computer) would you prefer in the future? **Tablet**
Why? **Easy and handy, more control.**

Do you have any conditions that might alter your visual or motor responses to this application? **No**

Interview guide

Subject- **6**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Ping Pong**

How often do you play these sports?
Few times a month

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? **NA** When? **NA**

If yes, briefly describe the event(s).
NA

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**

Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion? **NA**

Were symptoms recurring particularly with exertion? **NA**

Are you still experiencing any effects from the concussion? **NA**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Samsung Galaxy S6 (Android)

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Phone**
How often? **Few times a year**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Font size can be bigger, selecting settings on the screen has small font, difficult to select.**
- **Sliding down to start test does not work sometimes.**

COMPUTER:

- **An object to signify movement will make it more intuitive. Right now, there is no clue what to do when a test initializes.**
- **Color contrast on the screen can be changed. Black screen is hard to look on for long time.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **No**

COMPUTER: **Lateral pressing the force sensor is uncomfortable.**

Was there anything that the tablet had that the computer didn't have or vice versa?
Tablet gives flexibility to choose settings, gives better experience. Sideways pressure makes force sensor tasks difficult.

Was one device easier or harder to control?
Force Sensor – Tablet standing – Tablet sitting (Hard -> Easy)

Which way of testing (tablet or computer) would you prefer in the future? **Tablet**
Why? **More intuitive, handy and comfortable**

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **7**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Jujitsu**

How often do you play these sports? **Few times a week**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **3** When? **Age of 12(I), 17(II), 19(III)**

If yes, briefly describe the event(s).

I. **Roller blades, slammed back of head-**
II. **Slipped from rope swing, slammed forehead - age 12**
III. **Snowboarding, slammed face – age 19**

Did you lose consciousness? **II, III** For how long? **II- 5 minutes, III – 2 minutes**
Did you have concussive convulsions? **No**
Did you experience amnesia? **No** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **II**
Did an **Athletic Trainer** diagnose you with your concussion? **III**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
By symptoms for III, brain imaging for II.

For how long did you experience symptoms of your concussion? **One day(I, II, III)**

Were symptoms recurring particularly with exertion? **No**

Are you still experiencing any effects from the concussion? **No**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android, Windows

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Wii**
How often? **Few times a year**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET: **No**

COMPUTER: **Was not able to figure out when the test initializes. Activity on the screen is only displayed when force sensor is pressed.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **No**

COMPUTER: **No**

Was there anything that the tablet had that the computer didn't have or vice versa?
Computer can have the same test interface as tablet.

Was one device easier or harder to control?
Tablet stand – Force Sensor – Tablet sitting

Which way of testing (tablet or computer) would you prefer in the future? **Tablet**
Why? **Handy, natural position.**

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **8**

Section 1: Background Information

Do you currently play sports? **No**
Which sports? **NA**

How often do you play these sports? **NA**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 10**

If yes, briefly describe the event(s).
Hit by a slow moving truck, slammed the back of the head (wearing helmet)

Did you lose consciousness? **Yes** For how long? **5-6 minutes**
Did you have concussive convulsions? **No**
Did you experience amnesia? **Yes** For how long? **5-10 minutes**
Did a **Doctor** diagnose you with your concussion? **No**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)

For how long did you experience symptoms of your concussion?
1 day

Were symptoms recurring particularly with exertion?
No

Are you still experiencing any effects from the concussion? **No**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone, iPad

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* ***Yes***
Which device? **Mobile**
How often? **Everyday**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Add more practice trials**
- **Take the start-over button off the screen, distracts the user**
- **Test screen can fill up the full tablet screen**

COMPUTER:

- **Trial number on the test screen distracts, display a screen before trial to convey that info**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Very sensitive**

COMPUTER:

- **Force Sensor is good to perform test on**

Was there anything that the tablet had that the computer didn't have or vice versa?
Strict guidelines on any posture makes the user conscious.

Was one device easier or harder to control?
Tablet standing - Tablet Standing – Force Sensor (Hard -> Easy)

Which way of testing (tablet or computer) would you prefer in the future? **Force Sensor**
Why? **Felt more control**

Do you have any conditions that might alter your visual or motor responses to this application?

No

Interview guide

Subject- **9**

Section 1: Background Information

Do you currently play sports? **No**
Which sports? **Volleyball**

How often do you play these sports? **A few times a month**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 17**

If yes, briefly describe the event(s).
Slipped out of a moving car, slammed the back of head on pavement.

Did you lose consciousness? **Yes** For how long? **5 minutes**
Did you have concussive convulsions? **No, but involuntary laughing**
Did you experience amnesia? **Yes** For how long? **5-10 seconds**
Did a **Doctor** diagnose you with your concussion? **No**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion?
1 day

Were symptoms recurring particularly with exertion?
No

Are you still experiencing any effects from the concussion? **No**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android phone

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Phone, Wii**
How often? **Every day on phone, few times a month on Wii**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Sliding down does not work sometimes**

COMPUTER:

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

COMPUTER:

- **Force sensor is uncomfortable to perform**

Was there anything that the tablet had that the computer didn't have or vice versa?
No

Was one device easier or harder to control?
Tablet standing - Force Sensor - Tablet Sitting (Hard -> Easy)

Which way of testing (tablet or computer) would you prefer in the future? **Tablet**
Why? **Easy and handy**

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **10**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Badminton, Ping Pong**

How often do you play these sports? **Few times a week**

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? **NA** When? **NA**

If yes, briefly describe the event(s). **NA**

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**
Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…) **NA**

For how long did you experience symptoms of your concussion? **NA**

Were symptoms recurring particularly with exertion? **NA**

Are you still experiencing any effects from the concussion?
If so, which ones? **NA**

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android Phone

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.*
Which device? **Phone, 2 years back**
How often? **Few times a year**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

COMPUTER:

- **Red color for curve, not a good idea.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **It is way too sensitive, the user lost enthusiasm to perform good after few trials.**

COMPUTER:

Was there anything that the tablet had that the computer didn't have or vice versa?
Computer can be more intuitive.

Was one device easier or harder to control?
Tablet Standing – Force Sensor – Tablet Sitting

Which way of testing (tablet or computer) would you prefer in the future? **Tablet**
Why? **Easy, handy and intuitive**

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **11**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Badminton, Zumba**

How often do you play these sports?
Few times a month

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? **NA** When? **NA**

If yes, briefly describe the event(s).
NA

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**
Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion? **NA**

Were symptoms recurring particularly with exertion? **NA**

Are you still experiencing any effects from the concussion? **NA**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Xbox (motion stick)**
How often? **Few times a month**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Start-over button can be received**

COMPUTER:
No

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Very sensitive, sensitive to breathing as well**

COMPUTER:

- **Comfortable, more control**

Was there anything that the tablet had that the computer didn't have or vice versa?
Computer is not very intuitive, can have the options to select postures and curves like tablet. Helps in comprehending the task

Was one device easier or harder to control?
Tablet standing – Tablet sitting – Force Sensor

Which way of testing (tablet or computer) would you prefer in the future? **Force Sensor**
Why? **More control**

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **12**

Section 1: Background Information

Do you currently play sports? **No**
Which sports? **NA**

How often do you play these sports? **NA**

Section 2: Concussion Questions:

Have you had a concussion in the past? **NA** How many? **NA** When? **NA**

If yes, briefly describe the event(s).
NA

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions?
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**
Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion?
NA

Were symptoms recurring particularly with exertion?
NA

Are you still experiencing any effects from the concussion? **NA**
If so, which ones?

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone
Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Phone**
How often? **Everyday**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Sliding down to start the trial does not work sometimes.**

COMPUTER:

- **All good.**
- **Calibration period helps a lot.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Instructions on feet movement can help.**
- **Instruction on tucking elbow helped a lot.**

COMPUTER:

- **Instructions on not using wrist and forearm support were helpful.**

Was there anything that the tablet had that the computer didn't have or vice versa?
More options on tablet device made me aware of the testing process, its good. While in force sensor, I was just doing something.

Was one device easier or harder to control?
Computer-Tablet Sitting- Tablet Standing

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Tablet, I am used to motion gaming, and it was more comfortable.

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **13**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Soccer**

How often do you play these sports? **Few times a week**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 10**

If yes, briefly describe the event(s).
Slammed the front of head on a water slide crash.

Did you lose consciousness? **Yes** For how long? **4-5 seconds**
Did you have concussive convulsions? **No**
Did you experience amnesia? **No** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **No**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA
For how long did you experience symptoms of your concussion?
NA
Were symptoms recurring particularly with exertion?
No
Are you still experiencing any effects from the concussion?
If so, which ones? **No**

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Tablet**
How often? **3 times in school**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Sliding was hard sometimes**

COMPUTER:

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Uncomfortably sensitive**

COMPUTER:

- **Takes some time after pressing space bar, is confusing**

Was there anything that the tablet had that the computer didn't have or vice versa?
Tablet can have a next button on the test scree to go to next setting.

Was one device easier or harder to control?
Tablet Standing (Hardest) – Tablet Sitting – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Computer, it's easy to perform and more comfortable

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **14**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Football, Soccer, Basketball, Skiing**

How often do you play these sports? **Few times a week**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1+1** When? **Age of 13 & 17**

If yes, briefly describe the event(s).

- **Slammed the front of head playing football.**
- **Hit the back of head by a golf ball.**

Did you lose consciousness? **Yes** For how long? **30 seconds (1st Concus.), 5 min (2nd Concus.)**
Did you have concussive convulsions? **No**
Did you experience amnesia? **Yes** For how long? **Sick most of the day, don't remember much.**
Did a **Doctor** diagnose you with your concussion? **Yes**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
Brain Imaging
For how long did you experience symptoms of your concussion?
A few days
Were symptoms recurring particularly with exertion?
No

Are you still experiencing any effects from the concussion?
If so, which ones?
No

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone, iPad

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Nintendo Wii**
How often? **A few times a year**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Sliding down to begin a trial can be replaced by button**

COMPUTER:

- **Test start out of a sudden, did knew the test has begun.**
- **An object to signify the force line on display will help a lot.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **No**

COMPUTER: **Force sensor is way too sensitive.**

Was there anything that the tablet had that the computer didn't have or vice versa?
Options to select different settings in computer will help understand the testing.

Was one device easier or harder to control?
Tablet Standing (Hardest) – Tablet Sitting – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future?
Why?

Computer, force sensor is easy and comfortable

Do you have any conditions that might alter your visual or motor responses to this application?

No

Interview guide

Subject- **15**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Soccer, Ping Pong**

How often do you play these sports?
A few times a month

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 12**

If yes, briefly describe the event(s).
Slammed the front of head

Did you lose consciousness? **Yes** For how long? **10-15**
Did you have concussive convulsions? **No**
Did you experience amnesia? **Yes** For how long? **30 min**
Did a **Doctor** diagnose you with your concussion? **Yes**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
Symptoms
For how long did you experience symptoms of your concussion?
1 day
Were symptoms recurring particularly with exertion?
No
Are you still experiencing any effects from the concussion?
If so, which ones?
No

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Phone**
How often? **A few times a month**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Trial numbers on the test screen can be helpful.**

COMPUTER:

- **Need to have a timer before a trial starts, helps getting prepared for it.**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **More sensitive than expected, very hard.**

COMPUTER:

- **Very sensitive to perform.**

Was there anything that the tablet had that the computer didn't have or vice versa?
It's difficult to figure out when a test starts on computer, need to have a timer to know when it's starting or use an object in force line like in ball in tablet.

Was one device easier or harder to control?
Tablet Standing (Hard) – Tablet Sitting – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future? Why?
Tablet, more options to select, makes the user aware of the testing.

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **16**

Section 1: Background Information

Do you currently play sports? **No**
Which sports? **NA**

How often do you play these sports? **NA**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 11**

If yes, briefly describe the event(s). **Slammed left front head in a car accident**

Did you lose consciousness? **No** For how long? **NA**
Did you have concussive convulsions? **No**
Did you experience amnesia? **No** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **Yes**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
Symptoms
For how long did you experience symptoms of your concussion?
1-3 months
Were symptoms recurring particularly with exertion?
No
Are you still experiencing any effects from the concussion?
If so, which ones?
No

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
Android

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.*
Which device? **No**
How often? **NA**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET: **No**

COMPUTER: **No**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET: **Super sensitive, frustrating, made muscles tense, felt tired (muscle fatigue)**

COMPUTER: **Fine**

Was there anything that the tablet had that the computer didn't have or vice versa?
Easy to navigate in automated settings, can have that in tablet too.

Was one device easier or harder to control?
Tablet Standing (Hardest) – Tablet Sitting – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Computer, controlling force sensor is easier

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **17**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Badminton**

How often do you play these sports? **A few times a week**

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 13**

If yes, briefly describe the event(s).
Hit by a door, sudden jerk on head

Did you lose consciousness? **No** For how long? **NA**
Did you have concussive convulsions? **No**
Did you experience amnesia? **Yes** For how long? **15-20 seconds**
Did a **Doctor** diagnose you with your concussion? **No**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion?
No

Were symptoms recurring particularly with exertion?
No

Are you still experiencing any effects from the concussion?
If so, which ones?
No

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Android phone**
How often? **Everyday**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **When user has performed a practice trial on a setting, just disable it**
- **Remove the start over button**
- **Need a button to proceed to the next trial**

COMPUTER:

- **Cannot figure out when a trial starts**
- **Automated and comfortable to perform**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Discomforting on wrist**

COMPUTER:

- **Hooks down the table hitting the knee distracts the participant**

Was there anything that the tablet had that the computer didn't have or vice versa?
Automated navigation in tablet can be helpful

Was one device easier or harder to control?
Tablet Standing (Hardest) – Tablet Sitting – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future?
Why?

Computer, it is easy to do the trials on it. For kids, tablet can be very user-friendly

Do you have any conditions that might alter your visual or motor responses to this application?

No

Interview guide

Subject- **18**

Section 1: Background Information

Do you currently play sports? **No**
Which sports? **NA**

How often do you play these sports?
NA

Section 2: Concussion Questions:

Have you had a concussion in the past? **Yes** How many? **1** When? **Age of 7**

If yes, briefly describe the event(s).
Slammed the back of head on cement floor, crashed with a person.

Did you lose consciousness? **Yes** For how long? **2-3 minutes**
Did you have concussive convulsions? **No**
Did you experience amnesia? **No** For how long?
Did a **Doctor** diagnose you with your concussion? **Yes**
Did an **Athletic Trainer** diagnose you with your concussion? **No**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
Symptoms and imaging

For how long did you experience symptoms of your concussion?
1 day

Were symptoms recurring particularly with exertion?
No

Are you still experiencing any effects from the concussion?
If so, which ones?
No

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone, iPad

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Tablet, Wii**
How often? **A few times a week**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **1 test stopped in the middle**
- **A next button on the test screen to navigate to the next trial will be good**

COMPUTER:

- **Cannot figure out when a test initializes, no clue on the screen**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Start over button was distracting**

COMPUTER:

- **A little difficult to understand how to control the fluctuation**

Was there anything that the tablet had that the computer didn't have or vice versa?
No

Was one device easier or harder to control?
Tablet Standing (Hardest) – Tablet Sitting – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Computer, better settings, only one motor movement involved, easy and comfortable

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **19**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Basketball**

How often do you play these sports?
A few times a week

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? **NA** When? **NA**

If yes, briefly describe the event(s). **NA**

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**
Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion?
NA

Were symptoms recurring particularly with exertion?
NA

Are you still experiencing any effects from the concussion?
If so, which ones?
NA

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone, iPad

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Tablet, Wii**
How often? **A few times a week**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Utilize the space on the parameter selection screen**
- **Give a next button on the test screen**

COMPUTER:

- **Can make it more intuitive**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Suggest them to not to lean the body, posture affects the performance a lot**

COMPUTER:

- **All comfortable**

Was there anything that the tablet had that the computer didn't have or vice versa?
No

Was one device easier or harder to control?
Tablet Sitting (Hardest) –Tablet Standing – Computer (Easiest)

Which way of testing (tablet or computer) would you prefer in the future?
Why?
Computer, it was comfortable and easy to perform the trials on

Do you have any conditions that might alter your visual or motor responses to this application?
No

Interview guide

Subject- **20**

Section 1: Background Information

Do you currently play sports? **Yes**
Which sports? **Cross fit**

How often do you play these sports?
A few times a week

Section 2: Concussion Questions:

Have you had a concussion in the past? **No** How many? **NA** When? **NA**

If yes, briefly describe the event(s).
NA

Did you lose consciousness? **NA** For how long? **NA**
Did you have concussive convulsions? **NA**
Did you experience amnesia? **NA** For how long? **NA**
Did a **Doctor** diagnose you with your concussion? **NA**
Did an **Athletic Trainer** diagnose you with your concussion? **NA**

How was the concussion diagnosed (e.g., based on your symptoms, brain imaging etc…)
NA

For how long did you experience symptoms of your concussion?
NA

Were symptoms recurring particularly with exertion?
NA

Are you still experiencing any effects from the concussion?
If so, which ones?
NA

Section 3: Technology Awareness:

Do you use a smartphone and/or tablet device? If yes, what device(s)?
iPhone, iPad

Do you have experience with motion gaming on any device? *Motion gaming is any game where you move the actual device, such as the Nintendo Wii, where you move your body, or the task you just performed where you tilt the device.* **Yes**
Which device? **Tablet**
How often? **A few times a year**

Section 4: Feedback Questions:

What do you like about the interface of the application? Do you have any suggestions for improvement?
TABLET:

- **Bigger size ball on the test screen will draw better focus on trials**
- **Sometimes tapping in place of touching the screen starts the trial**

COMPUTER:

- **Like the black screen, had more focus for line**

Do you have any feedback on the controls of the application or the handling of the device during the test? If yes, please describe.
TABLET:

- **Had to hold very stiff, started having cramps in wrist.**

COMPUTER:

- **Noticeable finger fatigue**

Was there anything that the tablet had that the computer didn't have or vice versa?
Any movement on tablet had major impact while force sensor was more forgiving.

Was one device easier or harder to control?
Tablet Standing (Hardest) – Tablet Sitting – Computer (Hardest)

Which way of testing (tablet or computer) would you prefer in the future? Why?
Computer, easy to perform, more control with finger movement

Do you have any conditions that might alter your visual or motor responses to this application?
No