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ABSTRACT
HEAD IMPACTS IN THE A7FL
by
Stephen McGeever

The American 7s Football League (A7FL) is a semi professional football league that does not use helmets or pads. The theory is that the game is safer without helmets and pads because players feel more vulnerable and use a different tackling technique to protect themselves. Rather than lowering and leading with their head when the players tackle, as many helmeted football players do, A7FL players primarily use their arms to wrap the opponent up. A7FL players were given Vector mouth guards designed by Athlete Intelligence to wear. These mouth guards have built in tri-axial accelerometers to record impact data, which can be extracted as linear acceleration, rotational acceleration, and rotational velocity. Data was collected from the 2016 and 2017 A7FL seasons. Data was also gathered from subjects performing daily activities such as heading a soccer ball, sitting down, and getting hit in the head with a pillow in order to compare the A7FL data to a baseline. Additional data was gathered using a drop tower to check the consistency of the mouth guard. All data was analyzed using MATLAB. Results show that A7FL impacts were similar to that of a high school football team, and the average peak accelerations were similar to the daily activities recorded.
HEAD IMPACTS IN THE A7FL

by
Stephen McGeever

A Dissertation
Submitted to the Faculty of
New Jersey Institute of Technology
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering

Department of Biomedical Engineering

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</tr>
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<td>And</td>
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<td>*</td>
<td>Peak measured was higher than peak reported</td>
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<td>Impact</td>
<td>A force or movement that causes the accelerometer in the mouth guard to accelerate over 10G.</td>
</tr>
<tr>
<td>Impacter</td>
<td>The part of the drop tower that falls and is used to hit whatever is at the bottom of the tower.</td>
</tr>
<tr>
<td>G Force</td>
<td>The linear acceleration that is equal to or a multiple of the force of earth’s gravity (9.8m/s).</td>
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<td>Valid</td>
<td>The impact data is transferred to the Athlete Intelligence website if the impact occurs while the mouth guard is in the mouth and the software does not filter it out because of mouth guard movement.</td>
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CHAPTER 1
INTRODUCTION

1.1 Objective
The objective of this dissertation is to present and analyze impacts that occurred in the A7FL, and to test accuracy and consistency of the Vector mouth guard. Data was collected from the A7FL season in 2016 and 2017 from 13 and 9 players respectively. Data was acquired from a high school football team that used Vector mouth guards. Other data was acquired for comparison such as doing daily activities; getting hit with a pillow, sitting down as fast as possible, and heading a soccer ball. These tasks were performed by 5 subjects that were using a Vector smart mouth guard. More data collection involved using a 3-D printed skull with a smart mouth guard, and using a drop tower to drop a soccer ball with added weight onto it. This data was analyzed to assure consistency with the mouth guards and to juxtapose the A7FL impacts with other activities.

1.2 Background Information
1.2.1 Chronic Traumatic Encephalopathy (CTE)
CTE is a degenerative brain disorder caused by repetitive head trauma. Symptoms of CTE include; impulse control problems, aggression, depression, and paranoia. Symptoms may be stable or worsen as time passes. As the disease progresses, symptoms can include problems with thinking and memory; including memory loss, confusion, impaired judgment, and eventually progressive dementia. Currently, CTE can only be diagnosed
postmortem, so it is important to look at preventative measures. Because the disease is due to repetitive head impacts, it is most commonly found in athletes, specifically football players, as well as military veterans [5].

Figure 1.1 A shows a picture of two brains, the top of a healthy brain, and the bottom of college football player’s brain who had stage IV CTE [2].

1.2.2 Football Concussions

An estimated 300,000 sport-related traumatic brain injuries, predominantly concussions, occur annually in the United States. Sports are second only to motor vehicle crashes as the leading cause of traumatic brain injury among people aged 15 to 24 years [1]. In a study on 25 public high schools, including 10,926,892 athlete exposures, it was found that football had the highest rate of concussions [3]. It has also been found that college football has the second highest rate of concussions in men’s college sports, second to wrestling, but has by far the most total concussions in number [4].
1.2.3 A7FL

The A7FL is a semi professional football league that doesn’t use helmets or pads. The game is slightly modified from traditional football, where teams play 7 on 7. The offense includes 3 lineman and 4 skilled positions and the defense does not have limitations. The field is thinner than a full size football field because there are fewer players. There are no kickoffs, so instead a player throws the ball down field, where a receiver catches the ball and returns it. The defense has two other players that join the thrower to tackle the receiver and the receiver does not have any blockers. There are also no field goals so teams can opt to go for a one point, 5 yards out, or a two point, 10 yards out, conversion after a touchdown. The ideology is that the game is safer with no pads or helmets because when players don’t have the security of the pads and helmet they feel more vulnerable and change their style of tackling, leading to a more of a wrapping technique. With no helmet, players are not inclined to lower and lead with their head. This should mean less head impacts, and therefore, fewer concussions.

1.2.4 Vector Mouth Guard

Athlete Intelligence is a company that makes smart Vector mouth guards. The mouth guard has a tri axial accelerometer built into the front of the mouth guard that sticks slightly out of the mouth as seen in figure 1.2.
Figure 1.2 A picture of the smart mouth guard used in this study. The curved back part is the normal mouth guard piece. While the bridge to the Vector part is what sticks out of the mouth and contains the tri-axial accelerometer.

[12].

The mouth guards are fitted for each player. This is done by first putting the mouth guard in boiling water for a minute to soften the mold. The mouth guard is then removed and placed in cold water for two to three seconds to cool it off. The mouth guard is then placed in the subject’s mouth and pushed up against the upper teeth. The subject then sucks on the mouth guard, while pushing up with his or her tongue to ensure a good mold. The subject does not bite down on the mouth guard as this can damage the device. After about five minutes the mouth guard should be cooled and molded. The tight mold enables mouth guards to “click” into the subject’s mouth ensuring a secure position of the mouth guard. This is important because if the mouth guard moves within the player’s mouth, it can affect the impact data. Football players usually wear mouth guards so the smart mouth guards are not intrusive, and are easily and comfortably worn by the players.
The Vector mouth guards are able to record and store impact data. The mouth guards collect the linear acceleration, rotational velocity, and rotational acceleration in the X, Y, and Z direction as well as the direction of the impact. The Athlete intelligence company uses the raw data from each impact to calculate and report the peak G-force for each hit which can be accessed through Athlete intelligence’s website. Impact direction can also be seen on the website for each impact and is shown as a 3-D head form with a colored dot depicting where the hit occurred as seen in figure 1.3.

![3-D head form](image)

**Figure 1.3** The 3-D head form can be rotated and zoomed in or out of to see precisely where the impact occurred according to the mouth guard sensors. [12].

The Vector mouth guards store impact data until they are connected wirelessly to an antenna (Figure 1.4) that is plugged into a computer or laptop that has Wi-Fi.
Figure 1.4 The vector Antenna pictured positioned upright (left) and the bottom of it (right).

The information is then sent to the Athlete intelligence website within seconds, so live impacts can be seen with very little delay. The mouth guards have a battery in them and can be charged by inserting them into its case (Figure 1.5).

Figure 1.5 The mouth guard is positioned in the case and the light is flashing, indicating that it is charging. The green light shows that it has sufficient battery. The picture on the right shows the port for charging the case.
The case is portable, and acts as a portable charger that also needs to be charged occasionally. The case is charged by plugging it into an outlet or computer through a USB cable. Data for impacts can remain saved on the mouth guard until the next time it is connected to the antenna. All hits are time stamped and have a hit ID that corresponds with the ID from the respective mouth guard. The mouth guards filter out hits under 10G as well as hits over 200G. The mouth guards have a capacitor sensor that senses when the mouth guard is in a person’s mouth in order to validate hits. Therefore, if the mouth guard is dropped, kicked, stepped on etc. an impact will not be valid and will not register. Athlete intelligence also validates impacts using their software that analyzes the impact to see if it is realistic or not.
CHAPTER 2
METHODS AND MATERIALS

2.1 Collecting Data

Data is collected by having the mouth guard in the mouth of a person as their head accelerates over 10Gs from either an impact or movement. A specialized antenna is hooked up to a computer, and then using Wi-Fi, the data is automatically transferred from the mouth guard to an online cloud if the mouth guard is in range of the antenna. Data was extracted from the website giving peak linear acceleration and peak rotational acceleration for each impact. To look at the impact in depth such as acceleration over time, the data was requested and received from Athlete Intelligence. All data was received in Excel spreadsheets and analyzed using MATLAB.

2.1.1 A7FL

Data from the 2016 and 2017 A7FL seasons was recorded. 1124 Impacts were recorded from 13 players in 2016 and 601 impacts from 8 players in 2017. Data was recorded by going to the A7FL game, plugging the antenna into a laptop, and connecting the laptop to Wi-Fi. The impact data would then be transferred from the mouth guard to antennae in real time with a time delay of less than 30 seconds. When the mouths guards are first connected, any impact data that had been stored on them from a previous game or day are uploaded. Mouth guards were then collected at the end of the season to recover any data that remained on the mouth guards. Athletes were told to only use the mouth guard during the A7FL games to ensure that impacts from other sports or activities were not recorded. To make sure the impacts only happened during the A7FL games, the time
stamps of all the hits were checked to see if they occurred on a game day during a reasonable time.

2.1.2 High School

Data from a high school team was received from the Athlete intelligence company. The company provides teams all over the country with smart mouth guards and was able to send the raw data from one specific high school that included 986 impacts. Privacy was maintained as the name of the high school, or any player information was not received. The data did include impacts from 11 different mouth guards.

2.1.3 Daily Activities

In order to provide a baseline to compare these impacts, data from daily activities were also recorded. 5 new mouth guards were personally molded to 5 subjects. All of the subjects were 22-23 year old males with experience heading a soccer ball. The subjects signed written consent forms before participating in the study. The subjects then performed three tasks; getting hit in the head with a pillow, sitting down as fast as one could, and heading a soccer ball. For the pillow impact, each subject was hit in the side, back, and top of the head, three times in each direction. Occasionally an impact would not load right, so additional impacts occurred as a precaution, which is why there are 50 rather than 45 impacts. For the soccer impacts, the subjects headed a soccer ball under three normal play conditions: thrown into the air approximately 50 feet, a two handed throw from a sideline into play, and from a corner kick. A total of 40 impacts were recorded from heading a soccer ball. The sitting impacts involved the subject plopping himself down as fast as possible. Each subject sat down as fast as they could three times.
2.1.4 Drop Tower

Another test was done using a PVC skull from anatomy warehouse and a drop tower. The skull was filled with 20% ballistics gelatin from Clear Ballistics to mimic a brain. A small neck was 3-D printed and epoxied to the skull. The skull and brain weighed about 7 pounds. An average male head is about 8.26% of a male’s body weight [6]. An average American adult male weighs about 196 pounds [7]. A soccer ball was attached as securely as possible to the impact arm of the drop tower. A steel plate was added to increase the weight and better represent a kicked soccer ball. An average adult soccer player can kick a .45kg soccer ball at a speed of 25m/s [8]. The drop tower’s speed was 3m/s so a weight of about 5kg was desired. A mouth guard was placed into the PVC skull’s mouth and the mouth was taped shut as best as possible to keep the mouth guard from moving. The skull was positioned at the bottom of the drop tower and screwed into a custom made base through the holes in the 3-D printed neck. The frame was adjustable so that the skull could be positioned in various orientations. The Drop tower set up can be seen in figure 2.1. The drop tower had a built in accelerometer that was able to report the acceleration of the impactor through software. With the help of an Athlete Intelligence Employee, the software setting on the mouth guard was changed, turning off the capacitor sensor. This enabled the software to record impacts as if the mouth guard was in a human’s mouth. The skull was positioned so the ball would hit the forehead of the skull, the crown of the skull, and the mouth or directly onto the mouth guard, 10 times each. Data was collected for the 10 forehead impacts, 5 of the crown impacts, and 5 of the mouth impacts with the drop tower having an acceleration of 22G. The remaining 5 crown and mouth impacts were tested with the drop tower having an acceleration of 13G.
Figure 2.1 The drop tower configuration. The jaw was duct tape shut for extra stability of the mouth guard. The PVC skull came in two parts and was duct taped to ensure it did not detach during the impact. The soccer ball was attached with a net to the impacter and duct taped to try to limit the movement of the ball post initial contact. The black custom made base can be seen, which is the spring like attachment that bends when the skull is hit.

2.1.5 Anomalies

Additional impacts were recorded by using ones hand to directly hit the portion of the Vector mouth guard that is sticking out of a subject’s mouth. The mouth guard was in a clenched mouth so the capacitor sensor requirement was met and the mouth guard did not move much. The athlete intelligence software was not able to detect these as invalid impacts either so all these impacts were recorded as valid. There were a total of 8 impacts from this data set.
2.2 Analyzing Data

2.2.1 Tables
MATLAB R2017 was used for analyzing all of the data. The mean and standard deviation of the peak linear and peak rotational acceleration of each hit for each of the four categories was reported, as well as: the linear median and mode, and the max peak linear and peak rotational acceleration.

2.2.2 Graphs
Box plots were created to display the distribution of the peak linear and peak rotational accelerations. The box plot displayed the median as well as the lower quartile and upper quartile values. The box plots displayed outliers as any value more than one and a half times the value of the inner quartile range. Histograms were also created as another means of displaying the distribution of the impacts. Graphs were created that display data individual hits including the linear or rotational acceleration was plotted over time. Each impact included data over 489 time samples. The time samples are 0.0002 seconds apart, giving data over 0.0978 seconds or about one tenth of a second. The magnitude of the linear acceleration and rotational acceleration was found by squaring the acceleration in each direction, adding them together, and then taking the square root to find the resultant.

For the drop tower data, multiple trials were displayed on the same graph to display consistency.
2.2.3 Moderate and Severe Impacts

An article “MEASUREMENT OF HEAD IMPACTS IN COLLEGIATE FOOTBALL PLAYERS: CLINICAL MEASURES OF CONCUSSION AFTER HIGH- AND LOW-MAGNITUDE IMPACTS” classified impacts as low-impact, below 60G, or high-impact, above 90G [8]. These parameters were used to classify impacts as moderate, above 60G and below 90G, or severe, above 90G.

2.2.4 Combined Concussion Probability

Many papers quantify the possibility of concussion differently. Many base their prediction off of linear acceleration or G force. The equation below was used to calculate combined concussion probability, and factors in the linear acceleration as well as rotational acceleration [2].

\[
CP = \frac{1}{1 + e^{(-10.2 + 0.0433 \cdot a + 0.000873 \cdot \alpha - 0.000000920 \cdot a\alpha)}}
\]
CHAPTER 3
RESULTS

The results show that the A7FL 2017 season had slightly higher averages than the 2016 season. Both seasons represent data that appears to be very similar to the high school football data, in terms of mean, median, and mode peak G force, as well as having a similar amount of outliers and max forces. The daily activities showed that getting hit with a pillow or heading a soccer ball usually resulted in an impact of about 15G, giving a good baseline to compare the football impacts to. The drop tower data proved the mouth guard to be consistent for the forehead, mouth, and the second set of crown impacts.

Table 3.1 Data Summary

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Number of Impacts</th>
<th>Mean Peak G-Force &amp; Standard Deviation</th>
<th>Median (G)</th>
<th>Mode (G) [Frequency]</th>
<th>Max G- Force (G)</th>
<th>Moderate Impacts &gt; 30G (%)</th>
<th>Severe Impacts &gt; 90G (%)</th>
<th>Mean Peak Rotational Acceleration &amp; Standard Deviation</th>
<th>Max Rotational Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7FL 2017 (n=9)</td>
<td>601</td>
<td>26.8 ± 22.9</td>
<td>19</td>
<td>12 [50]</td>
<td>224</td>
<td>34 (5.7)</td>
<td>17 (2.6)</td>
<td>2270.9 ± 1626</td>
<td>13021</td>
</tr>
<tr>
<td>A7FL 2016 (n=13)</td>
<td>1124</td>
<td>18.2 ± 17.4</td>
<td>14</td>
<td>12 [179]</td>
<td>277</td>
<td>33 (2.9)</td>
<td>11 (1.0)</td>
<td>1184.8 ± 1055</td>
<td>9293.5</td>
</tr>
<tr>
<td>HS Football (n=11)</td>
<td>986</td>
<td>23.1 ± 16.1</td>
<td>18</td>
<td>16 [81]</td>
<td>222</td>
<td>30 (3.0)</td>
<td>6 (0.6)</td>
<td>2281.0 ± 1306</td>
<td>9633.5</td>
</tr>
<tr>
<td>Daily Activities (n=5)</td>
<td>92</td>
<td>21.4 ± 12.7</td>
<td>18</td>
<td>14 [9]</td>
<td>67</td>
<td>3 (3.0)</td>
<td>0</td>
<td>2104.2 ± 1710</td>
<td>9047.3</td>
</tr>
</tbody>
</table>

This is a table outlying the important values for each of the four data sets. Under each data set, “n” represents the amount of subjects that participated. Although it was stated before that all hits over 200G are filtered out, some impacts over 200G make it past the filters and register as valid impacts. One of the most important things in this table
is how the medians are all very similar and although the A7FL 2017 data is right skewed it still has a very low mode of 12G.

**Table 3.2 Daily Activities Summary**

<table>
<thead>
<tr>
<th>Daily Activity</th>
<th>Number of Impacts (Attempts)</th>
<th>Mean Peak G-Force &amp; Standard Deviation</th>
<th>Max G-Force</th>
<th>Impacts &gt; 60g (%)</th>
<th>Impacts &gt;90G (%)</th>
<th>Mean Peak Rotational Acceleration &amp; Standard Deviation</th>
<th>Max Rotational Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit With A Pillow*</td>
<td>50</td>
<td>25.9 +- 14.9</td>
<td>67</td>
<td>3 (6)</td>
<td>0</td>
<td>2620.3 +- 2084</td>
<td>9047.3</td>
</tr>
<tr>
<td>Sitting Down</td>
<td>2 (2/15)</td>
<td>17.0 +- 8.5</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>942.6 +- 280</td>
<td>1140.9</td>
</tr>
<tr>
<td>Heading a soccer ball</td>
<td>40</td>
<td>15.8 +- 5.7</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>1517.2-838</td>
<td>3704.3</td>
</tr>
</tbody>
</table>

Daily Activities was split into three categories, and this table shows the important values coming from each individual task. Only 2 impacts were recorded for sitting down out of the 15 trials. This is most likely because the other impacts were less than 10Gs and therefore filtered out. One thing to note was that there were 3 impacts recorded above 60G, and these were significantly higher than the rest of the impacts. These three impacts occurred during the pillow impacts to the side of the face and most likely have higher readings from the pillow making direct contact with the mouth guard.
Figure 3.1 Box plots of the peak G force for each category was made. The red crosses represent outliers which are any G forces greater than 1.5* the inner quartile range. We can see that all three football categories contain many outliers and several huge outliers. A7FL 2016 season is the most condensed with the smallest inner quartile range and lowest median. The A7FL 2017 season and the high school football have similar ranges, and have a similar median as well with the daily activities.
Figure 3.2 Box plots of the peak rotational acceleration for each category was made. The red crosses represent outliers which are any G forces greater than 1.5* the inner quartile range. All three football categories contain many outliers and several huge outliers. A7FL 2016 season is the most condensed with the smallest inner quartile range and lowest median. The A7FL 2017 season, the high school football, and the daily activities all share similar ranges and median.
Figure 3.3 The histogram represents the moderate (>60G) and severe (>90G) impact percentages for each category. The yellow represents severe and blue represents moderate. The 3% of moderate impacts for daily activities come from the three impacts that were mentioned to have directly hit the mouth guard. Again the A7FL 2017 season has the highest impact accelerations and therefore the most severe impacts but the variation between the three football categories is very small; only about 2%.
Figure 3.4 This histogram shows the distribution of all the individual hits. An important thing to note is that the Daily Activities has a different Y-axis. This was changed from the others to better visually show the distribution of the category that had far less total hits. All graphs have a gap from 0 to 10G as these impacts were filtered out. A7FL 2017 season is much more right skewed than the 2016 season. The high school data shows more impacts from 20 to 30G than the 10 to 20G range.
Figure 3.5 This table displays the rotational acceleration in each of the 3 directions for the top 17 impacts from the A7FL 2017 season. The direction of rotational acceleration could potentially be much more important than the overall magnitude of rotational acceleration, so the directions were looked at independently to determine if there were any outliers. The table shows the rotational acceleration was greatest in the X direction 4/17 times, in the Y direction 6/17 times, and in the Z direction 7/17 times. All three impacts had rotational accelerations above 6000 radians per second squared, showing that all rotational directions experienced about the same values, with no one direction having extremely higher or extremely lower values than the others.
Figure 3.6 This scatter plot displays each impact’s peak G force and peak rotational acceleration as an open circle. The combined concussion probability equation (2.2) was used to plot the dotted lines. The dotted lines represent a combined concussion probability of 25% (red), 50% (magenta), 75% (blue), and 90% (green). The peak G force and peak rotational acceleration vary almost linearly for each category. Some impacts do have either a higher peak G force or higher peak rotational acceleration with respect to the other and either of these high values can greatly increase the combined concussion probability.
Figure 3.7 The histogram also uses equation 2.2 to look at the combined concussion probability. 0 to 10% probability was left out of the graphs because this is where the vast majority of the impacts fell and would have made it more difficult to display the few impacts that had percentages over 10%. The A7FL 2017 season had the highest probabilities, but all three football categories were fairly similar with none standing out with exceptionally higher or lower probabilities.
To validate the mouth guard measurement, we ran a set of controlled impacts using a drop tower system. A soccer ball was used to compare to the soccer heading data. Table 3.3 shows the 10 trials that were recorded for the impacts on the forehead of the skull. The drop tower recorded the impacts at 22G while the mouth guard sensor recorded the impact from 14 to 20G. Three hits did register as invalid impacts for this location of impact.

Table 3.3 Drop Tower Impacts on Forehead

<table>
<thead>
<tr>
<th>Impact On Forehead</th>
<th>Valid impact G</th>
<th>Invalid impact G</th>
<th>Drop Tower Accelerometer (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>
Figure 3.8 Equation 2.1 was used to find the magnitude of the linear acceleration magnitude (G) and rotational acceleration magnitude (radians/s²) which was then plotted over time. The 10 forehead impacts were plotted over time for both linear acceleration magnitude in G force and rotational acceleration magnitude. The 10 trials were very consistent as there is very little variation between the plots on the graph. The Athlete intelligence software reports the first peak which is why all the impacts had reported peak linear acceleration of 14-20G and not the actual peak of around 30G. The first peak seems to better represent the impact as it coincides with the accelerometer in the drop tower.
The 10 impact trials for the mouth are separated by a row to emphasize the change in accelerometer speed between the sets of 5 impacts. All 10 of these impacts were reported as invalid impacts due to Athlete Intelligence’s software. This is because the mouth guard was hit directly causing it to move with the mouth of the skull and therefore record an invalid hit. The mouth guard being hit directly is also the cause of the huge G forces recorded, that are much higher, and more sporadic than the drop tower acceleration reported.

### Table 3.4 Drop Tower Impacts on the Mouth

<table>
<thead>
<tr>
<th>Impact On Mouth</th>
<th>Valid impact G</th>
<th>Invalid impact G</th>
<th>Drop Tower Accelerometer (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>117</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>90</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>52</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>65</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>95</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>46</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>35</td>
<td>13</td>
</tr>
</tbody>
</table>
Figure 3.9 Equation 2.1 was used to find the magnitude of the linear acceleration magnitude \((G)\) and rotational acceleration magnitude \((\text{radians/s}^2)\) which was then plotted over time. All 10 impacts on the mouth were graphed on the same axis. There was absolutely no consistency between the trials in linear or rotational acceleration as expected. This graph also shows larger initial peaks in rotational acceleration than in linear representing the mouth guard bending or moving due to the direct contact.
Table 3.5 Drop Tower Impact on Crown

<table>
<thead>
<tr>
<th>Impact On Crown</th>
<th>Valid impact G</th>
<th>Invalid impact G</th>
<th>Drop Tower Accelerometer (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td></td>
<td>22</td>
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<tr>
<td>5</td>
<td></td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td></td>
<td>13</td>
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<tr>
<td>9</td>
<td>10</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

The 10 impact trials for the crown are also separated by a row to emphasize the change in accelerometer speed between the sets of 5 impacts. This data set had 3 invalid impacts reported in the first set all valid impacts in the second set. It can be seen in Figure 3.9 that these invalid impacts have slightly different wave forms. This could have been from slight movement of the mouth guard. Although the ball was hitting the back of the head, the mouth guard is not as securely positioned in the skull's mouth as it would be when fitted and placed in a human’s mouth. This could have caused some discrepancies in the
data, however, the second set of 5 impacts are extremely consistent.

**Figure 3.10** Equation 2.1 was used to find the magnitude of the linear acceleration magnitude (G) and rotational acceleration magnitude (radians/s²) which was then plotted over time. Trial 1 and 5 (blue and green) stand out as the only two wave forms inconsistent with the others. These are two of the three impacts that registered as invalid.

**Figure 3.11** Equation 2.1 was used to find the magnitude of the linear acceleration magnitude (G) and rotational acceleration magnitude (radians/s²) which was then plotted over time. These 5 impacts were incredibly consistent. Again, the software reports the first linear acceleration peak which also matches up the best with the drop tower accelerometer.
CHAPTER 4
DISCUSSION

4.1 Results Analysis

4.1.1 Summary Analysis
The data was chosen to be represented in box plots and histograms because it is not normally distributed. Bar graphs of the mean and standard deviation were made but did not represent the data well, as all had very similar means with very large standard deviations due to the skewedness.

4.1.2 Outliers
The three high impacts seen in daily activities could possibly be removed from the data as it is know these impacts occurred when the pillow hit the side of the face following through into the mouth guard. As it was seen, although invalid, the impacts from the drop tower that occurred on the mouth had significantly higher peak G forces. However, for this thesis, all data was included and no impacts were removed, even if their individual impact graphs stood out. All severe impacts for the 2017 and 2016 season were graphed for their individual linear and rotational acceleration over time. There were no noticeable trends between individual impacts, so no conclusion could be made about what valid impact should look like. A few impacts did stand out where the first peak did not occur at the usual .012 second mark, or other impacts which had very sharp peaks. These impacts were still included in the data as it could not be said for sure that they were invalid.

4.1.3 Drop Tower Analysis
When the mouth guard’s capacitor sensor was turned off the Athlete Intelligence’s software did a good job at reporting all of the impacts on the mouth guard as invalid.
However, it was found during testing that it is possible to get around this additional filter. When subjects had the mouth guard securely clenched in their mouth, and a hand would hit the part of the mouth guard that was sticking out, the software would report a valid impact. The difference between this and the skull is that the human subject is able to bite down on the mouth guard keeping it from moving as much and therefore registering as valid. The drop tower was not exactly representative of a person heading a soccer ball. Firstly, the ball did not bounce off the head but instead followed through the head and stayed there. Secondly, the head was mounted on a spring like base. When the ball would hit the skull this would cause the base to bend and the skull to move away from the ball. This could have been the cause of the multiple peaks in the individual impacts for the drop tower. The mouth guard was positioned between the teeth of the skull and the jaw was taped shut to try to minimize movement, but the mouth guard still had slight room for movement which could have aided in the hits registering as invalid and or the few inconsistencies in the individual impact graphs.

4.1.4 High School Impacts

A study using helmet sensors for 40 college division I football players and 16 high school football players showed that the top 1, 2, 5% of all impacts were higher for the college level players. It also states college players sustained high level impacts greater than 98G more frequently than high school players [10]. Another study using helmet sensors reported the average peak head acceleration of 3312 college football impacts to be 32G, much higher than the 23.1 average reported by the Vector mouth guards for high school players [13]. This can lead to the speculation that the A7FL is comparable to high school football which has less high impacts than college football.
4.1.5 Rotational Direction

For most of the results displayed, the rotational acceleration was the magnitude of the rotational acceleration in the X, Y, and Z directions. However, due to the anatomy of the human body, rotating the head in the sagittal plane (Y axis), coronal plane (X axis), and horizontal plane (Z) are all very different movements and can affect the brain differently. One article that researched diffuse axonal injury (DAI) tested different accelerations in the three planes on monkeys. The article showed that the injuries were very different in each direction and statistically significant for between each plane. The article also mentioned that lateral head motions are more injurious than horizontal or sagittal [14]. The largest impacts from the A7FL 2017 season produced the largest rotational acceleration in all three planes for different impact. This data showed that the rotational acceleration varied, did not always peak in the same direction for each impact, and that large rotational accelerations could occur in any of the three planes. If all the impacts were examined, it could possibly provide insight on the overall proportion for which plane the highest rotational acceleration would occur.

4.2 Limitations

4.2.1 Helmet Sensors

When comparing data sets to other studies, most of the time a helmet sensor is used instead of a mouth guard sensor. This can lead to differences in data and make it hard to compare across media. The data from the Vector mouth guards was limited to the data that was collected for this study and data from a high school team. Helmet sensors can
vary largely from mouth guard sensors as the position of the sensors are located different
distances and directions from the center of gravity of the head.

4.2.2 Validating Impacts

An anomaly was noticed during the recording of the impacts with the pillows and the extra data gathered. When a subject was hit directly in the mouth (mouth guard), either from the front or the side, the impacts recorded significantly higher G-forces. Although Athlete intelligence’s software does its best to filter these impacts out, it can be very difficult and complex enabling some of the impacts to register as valid. Ideally the most severe impacts were going to be video validated through A7FL video of the games. The time stamps of the impacts and the time stamps on the football games did not match up making it too difficult to validate the impacts. When this didn’t work, each individual impact was examined to try to detect trends between valid impacts and invalid impacts, however all the individual impacts varied greatly in size and shape making it inconclusive whether impacts were invalid or not.

4.2.3 Outside Software

While analyzing individual hits from 2016 it was noticed that the software the company used would often use the first major peak in linear acceleration as the maximum or peak linear acceleration. Some hits when analyzed showed to have multiple peaks, in which some cases the second or third peak was actually the true maximum or peak linear acceleration. The algorithm used by Athlete Intelligence to decide whether an impact is valid or not is unknown. The mouth guards are supposed to filter out impacts over 200G as these impacts are highly implausible for a person to endure during football or other activities. In the data from the A7FL for both 2016 and 2017 as well as the high school
football data all had registered valid impacts over 200G. This issue is being worked on by
the company. The 3-D head form that represents where the impact occurred is only
available for 30 days following the impact. This made it not possible to evaluate data
from the direction of the impacts.

4.2.4 Compliance

Compliance was another large issue. About 20 mouth guards were available for the 2017
A7FL season. Impacts were only received from 9 players. It was difficult for the league
commissioner to distribute all the mouth guards before the season started. They players
that did obtain the mouth guards were still responsible for charging them on their own, as
well as remembering to bring them to every game. Some players that did have the mouth
guards dealt with injuries and/or received less playing time than expected. It was not
clear whether players would be wearing the charged vector mouth guards and happen to
not receive any impacts, or if they had forgot to charge or even wear the mouth guard
during the game. Because of the smaller sample size of only 9 players, and not enough
consistency of the players wearing them every week, impacts per player or position was
not a significant statistic.
CHAPTER 5

CONCLUSION

In conclusion the impacts from A7FL 2017 season were slightly higher than the high school impacts but the 2016 A7FL impacts were slightly lower. So overall the A7FL impacts were comparable to high school football impact data. The majority of these impacts had ranges of acceleration that one could experience in daily activities such as getting hit with a pillow or heading a soccer ball. Although one problem was found with the mouth guard sensor, and a slight artifact in the software, it was found to be rather consistent and accurate in the drop tower data.
Appendix A

INDIVIDUAL IMPACTS 2017 A7FL

Figure A.1 to A.17 show individual impacts linear and rotational acceleration plotted over time. The impacts are numbered 1 through 17 in order from greatest reported linear acceleration to least for all of the severe impacts.

Figure A.1 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right. This is one of the few outliers, as the first peak occurs around .07 seconds and not .012 seconds.

Figure A.2 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.3 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.4 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.5 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.6 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.7 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.8 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.9 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.10 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.11 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.12 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.13 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.14 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.15 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure A.16 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure A.17 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
APPENDIX B

INDIVIDUAL IMPACTS DAILY ACTIVITIES

Figure B.1 to B.3 show individual impacts linear and rotational acceleration plotted over time for the moderate impacts for daily activities. The impacts are numbered 1 through 3 in order from greatest linear acceleration reported to lowest. These 3 impacts occurred when the pillow hit location was on the side, and made direct contact with the mouth guard.

Figure B.1 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right. This is another extreme outlier as the peak happens at 0 seconds so the curve does not match the others.
Figure B.2 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure B.2 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
APPENDIX C

INDIVIDUAL IMPACTS ANOMALIES

Figure C.1 to C.8 show individual impact’s linear and rotational acceleration plotted over time for the moderate impacts for the anomalies collected. All of these impacts are from hitting the mouth guard directly with a hand while in the subject’s mouth. The impacts are numbered 1 through 8 in order from greatest linear acceleration reported to lowest.

**Figure C.1** Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

**Figure C.2** Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
**Figure C.3** Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

**Figure C.4** Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure C.5 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure C.6 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
Figure C.7 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.

Figure C.8 Linear acceleration magnitude on the left and rotational acceleration magnitude on the right.
APPENDIX D

IRB Request Form

Date 10/15/2017

HUMAN SUBJECT RESEARCH REVIEW FORM
NEW JERSEY INSTITUTE OF TECHNOLOGY
INSTITUTIONAL REVIEW BOARD APPLICATION

Name of Principal Investigator(s)  Bryan Pfister, PhD, Stephen McGeeve, BS

Faculty members and/or staff must be principal investigators. Students can serve as co-principal investigators under faculty/staff supervision for expedited projects.

NJIT Address: 323 Martin Luther King blvd. Newark, NJ 07102

Department: Biomedical Engineering
E-mail Address: Sjm39@njit.edu

NJIT Affiliation of Principal Investigators (Check all that apply):

☑ Faculty ☐ Student ☐ Other - Describe:

*Note students and doctoral candidates applying for IRB approval must submit written documentation from their faculty advisors (via e-mail) stating that research is being conducted under their supervision.

Project Title: A7FL Head Impacts – Comparison to Normal Daily Activities

This project will be conducted:

☐ On Campus ☑ Off Campus: Location: A local soccer field ☑ Both

Is this research funded by outside source(s)? ☐ Yes ☑ No

If yes, indicate name(s) and type of funding source(s):

Name of Funding Source(s):

Type:

☐ Government (County, State or Federal)
☐ Foundation
IRB Request Form (Continued)

Corporation

Other

Anticipated Starting Date of Project: 11/2/17
Anticipated Closing Date of Project: 5/10/18
Number of Subjects: 10

NOTE: All principal investigators, faculty, and students who will be interfacing with human subjects in this study must complete an online training course in the protection of human subjects. This course can be accessed by going to the US Department of Health and Human Services’ Office for Human Research Protection website (http://ohrp-ed.od.nih.gov/CBTs/Assurance/login.asp). There are three modules you must complete. All certificates indicating course completion must be submitted with this application. For NIH investigator training, please see the following URL: http://viapub.nimh.nih.gov/users/login.php.

To Principal Investigator: In addition to the questions below, please furnish copies of any questionnaires, interview formats, testing instruments or other documents necessary to carry out the research. Any advertising materials used to recruit subjects must also be submitted.

The completed forms should be sent electronically to: irb@njit.edu

1. Project Title:
   A7FL Head Impacts – Comparison to Normal Daily Activities

2. List the names and status (faculty, student, etc.) of the persons conducting the research:
   a. Principal Investigator(s):
      Bryan Pfister, PhD and Stephen McGeever, BS (Student)

   b. Other Members of Research Team:

   c. NJIT Faculty Advisor(s) if Student Project:
      Dr. Pfister (faculty)
3. Describe the objectives, methods and procedures of the research project. This summary will used to describe your project to the IRB. Use up to 2 pages, if necessary. You may also attach a copy of an abstract or full research proposal describing this work.

The objective of this research project is to examine and analyze impacts recorded from the A7FL football league where players do not wear helmets or pads. We have been provided by the A7FL impacts recorded using the Athlete Intelligence Vector mouth guards that have built in accelerometers. The accelerometers provide linear and rotational velocity and acceleration in the X, Y and Z axis. This raw data will then be analyzed and quantified.

In order to provide a baseline to compare these impacts, other tasks will be performed on students while wearing the mouth guard under normal activities. This new data will be analyzed the same way as the A7FL impacts and then compared side by side. This study will include the following normal activities:
- A swing of a pillow to the top, front, back, and side of the head.
- Heading a soccer ball under three normal play conditions: (1) thrown into the air approximately 50 feet into the goal, (2) two handed throw from sideline into play, and (3) a corner kick into the goal.
- Plopping into a chair or couch as fast as possible.

4. List name and institutional affiliation of any research assistants, workers student that will be working on this project.

   Stephen McGeeve, MS Student, New Jersey Institute of Technology

5. If research assistants, workers, students will be working on the project describe their qualifications, special training and how they will be supervised.

   Stephen has been trained to use the Vector mouth Guard system and was involved with the use
6. What is the age of the subjects and how will they be recruited?
The age of the subjects will be over 18 (about 22-23), and will be recruited from old teammates Stephen used to play soccer with.

7. Attendant risks: Indicate any physical, psychological, social or privacy risk or pain, which may be incurred by human subjects, or any drugs medical procedures that will be used. (This includes any request for the subjects to reveal any embarrassing, sensitive, or confidential information about themselves or others.) Also, indicate if any deception will be used, and if so, describe it in detail. Include your plans for debriefing.

Two tasks involve typical impacts to the head so the participant may experience the typical discomfort associated with a pillow or soccer ball to the head.

8. Evaluate the risks presented in 7.
a. Is it more that would normally be encountered in daily life? ______ No, X Yes ______

b. Do your procedures follow established and accepted methods in your field? ______ Yes ______

9. How will the risk be kept at a minimum? (e.g. describe how the procedures reflect respect for privacy, feeling, and dignity of subject and avoid unwanted invasion of privacy or disregard anonymity in any way.) Also, if subjects will be asked to reveal any embarrassing, sensitive, or confidential information, how will confidentiality of the data be insured? Also include your plans for debriefing. If subjects will be placed under any physical risk, describe the appropriate medical support procedures.
IRB Request Form (Continued)

No names or private information will be needed as the impacts will be assigned and recorded to the mouthguard only. In addition to the data collected by the mouthguards, we will collect weight and height of each participant. Participants will be asked to be (1) hit by a pillow, (2) head a soccer ball, and (3) plop into a chair as described above. Since the participants will be ex-soccer players, there will not be a need to teach proper technique to head a soccer ball. If any participant shows or mentions signs of head discomfort (i.e. headache) the experiment will be terminated and the participant will be advised to see their doctor. The participants can withdraw from the study at any time for any reason.

10. Describe the benefits to be derived from this research, both by the subject and by the scientific community (this is especially important if research involves children).

The benefits to be derived from this research are to quantify the impacts football players receive, who do not wear helmets or mouth guards. The subject will not personally benefit but will help provide data for making comparisons in the research.

11. Describe the means through which human subjects will be informed of their right to participate, not to participate, or withdraw at any time. Indicate whether subjects will be adequately informed about the procedures of the experiment so that they can make an informed decision on whether or not to participate.

The human subjects will be debriefed verbally before each task and can withdraw at any time. There will be brief breaks in between each impact to give the subject time to analyze themselves and decide if they would like to continue. The subject can also choose to participate in any or all of the tasks mentioned.
12. Complete the attached copy of the Consent Form and the Institutional Review Board will make a determination if your subjects will be at risk. This Consent Form must include the following five pieces of information: (1) The purpose of the research, (2) the procedures involved in the work, (3) the potential risk of participating, (4) the benefits of the research, (5) that the subjects are free to withdraw from the research at any time with no adverse consequences.

13. Furnish copies of questionnaires, interview formats, testing instruments or other documents to carry out the research. If questionnaires are not complete please submit an outline of the questions to be used. You will have to submit the completed questionnaire to the Committee before the research can begin.

14. If the subjects will be minor children, complete Consent Form as prescribed in paragraph 12 for signature by parent or guardian. If the project is approved (regardless of the Board's determination concerning risk), it will be necessary that a Consent Form be secured for every minor child.

15. Attach copy of permission of facility to conduct the proposed research (if other than NJIT).
APPENDIX E

Informed Consent Form

NEW JERSEY INSTITUTE OF TECHNOLOGY
323 MARTIN LUTHER KING BLVD.
NEWARK, NJ 07102

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

TITLE OF STUDY: A7FL Head Impacts – Comparison to Normal Daily Activities

RESEARCH STUDY:
I, ____________________________, have been asked to participate in a research study under the direction of Dr. (Pfister).

. Other professional persons who work with them as study staff may assist to act for them.

PURPOSE:
To record impacts using a mouth guard with a built in accelerometer.

DURATION:
My participation in this study will last for ____________________.

PROCEDURES:
I have been told that, during the course of this study, the following will occur:
I will be hit in the head with a pillow at least 3 times each to the front, back, top, and side of the head.
I will head a soccer ball at least 3 times each of: ball thrown 50 feet in the air, thrown two handed from sideline, and from a corner kick.
I will sit down into a chair as fast as I can up to 5 times.

PARTICIPANTS:
I will be one of about _____10____ participants in this study.

EXCLUSIONS:
I will inform the researcher if any of the following apply to me:
You have had a concussion within the past two weeks. You have frequent headaches. Any pre-existing discomfort in the head or neck that might be irritated further from the described activities.

RISKS/DISCOMFORTS:
I have been told that the study described above may involve the following risks and/or discomforts such as a headache, dizziness, light headedness or a sore neck. I acknowledge that if injury does occur, it is my responsibility, and not NJIT’s, to treat the injury and pay the possible medical bills.
Informed Consent Form

There also may be risks and discomforts that are not yet known.

I fully recognize that there are risks that I may be exposed to by volunteering in this study which are inherent in participating in any study; I understand that I am not covered by NJIT’s insurance policy for any injury or loss I might sustain in the course of participating in the study.

CONFIDENTIALITY:
I understand confidential is not the same as anonymous. Confidential means that my name will not be disclosed if there exists a documented linkage between my identity and my responses as recorded in the research records. Every effort will be made to maintain the confidentiality of my study records. If the findings from the study are published, I will not be identified by name. My identity will remain confidential unless disclosure is required by law.

RIGHT TO REFUSE OR WITHDRAW:
I understand that my participation is voluntary and I may refuse to participate, or may discontinue my participation at any time with no adverse consequence. I also understand that the investigator has the right to withdraw me from the study at any time.

INDIVIDUAL TO CONTACT:
If I have any questions about my treatment or research procedures, I understand that I should contact the principal investigator at
Bryan.j.pfister@njit.edu
Sjm39@njit.edu

If I have any additional questions about my rights as a research subject, I may contact:

Farzan Nadim, IRB Chair
New Jersey Institute of Technology
323 Martin Luther King Boulevard
Newark, NJ 07102
(973) 596-5825
irb@njit.edu/ farzan@njit.edu

SIGNATURE OF PARTICIPANT
I have read this entire form, or it has been read to me, and I understand it completely. All of my questions regarding this form or this study have been answered to my complete satisfaction. I agree to participate in this research study.

Participant Name

Signature

Date
APPENDIX F

NIH Training Certificate

Certificate of Completion

The National Institutes of Health (NIH) Office of Extramural Research certifies that Stephen McGeever successfully completed the NIH Web-based training course “Protecting Human Research Participants”.

Date of completion: 10/17/2017.

Certification Number: 2534399.
REFERENCES


