MEASUREMENT OF HEAD IMPACT BIOMECHANICS: A COMPARISON OF THE HEAD IMPACT TELEMETRY SYSTEM AND X2 BIOSYSTEMS xPATCH

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ABSTRACT

ALESSA RAE LENNON: Measurement of Head Impact Biomechanics: A Comparison of the Head Impact Telemetry System and X2 Biosystems xPatch
(Under the direction of Jason P. Mihalik)

The purpose of this study was to capture on-field head impact data from the HIT System and xPatch concurrently in order to gain a broader understanding of their ability to appropriately measure head impact biomechanics. Nine collegiate football players participated in this study. We used video analysis to record head impacts during three game sessions. Our findings reveal a moderate correlation between the HIT System and xPatch in measuring linear acceleration and HITsp, and low correlation in measuring rotational acceleration. Our findings also reveal poor agreement in impact location between the recorded impact location of the HIT System and xPatch, and the actual impact location verified by video analysis. Additional analyses revealed the number of false positive head impacts recorded and allowed us to estimate total head impact exposure. Future research should investigate head impact biomechanics in non-helmeted sports and test the xPatch in a laboratory setting.

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CHAPTER I

INTRODUCTION

Approximately 3.8 million sport-related traumatic brain injuries (concussions) occur each year in the United States, with football annually accounting for the most concussions.[1] It is reported that each year 5-10 concussions occur per college football team,[2] and that a single collegiate football athlete may sustain as many as 1,400 head impacts in a single season.[3] Furthermore, athletes sustain a greater number of head impacts as well as impacts of a higher severity on days of a diagnosed concussion.[4] Concussion research is continually evolving and expanding, including injury management, and the study of long-term effects and deficits believed to be associated with concussion. One supplementary tool to study and help develop concussion injury risk curves includes head impact biomechanics.[5]

Early investigation of head impact biomechanics consisted of laboratory methods utilizing the Hybrid III Headform to reconstruct on-field head impacts resulting in concussions from National Football League (NFL) video footage.[6] Since 2003, the Head Impact Telemetry (HIT) System has been used in numerous studies for objectively measuring head impact biomechanics in youth, high school, and collegiate football and hockey players in on-field settings.[3,7,8] Research using the HIT System has reported head impact exposures,[9] identified positional differences in exposure and impact magnitude,[10] frequency and location of head impacts,[3] and correlated head impact biomechanics with clinical outcomes.[11] Additionally, using the HIT System has advanced our ability to track head impact trends over the course of a season, and begin to study the patterns observed in head impact biomechanical data on days of a diagnosed concussion.[4,12,13] Although extensive research has been conducted with the purpose of relating head impact biomechanics to concussion, a biomechanical concussion injury threshold for magnitude of impact remains elusive to clinical researchers.[14-16]

Although research with the HIT System has provided much insight into head impact biomechanics, in-vivo analysis has been restricted by licensing agreements limiting the study of football head impact biomechanics to those who wear Riddell helmets capable of accepting the HIT System accelerometer units. More recently, non-helmet based technologies capable of measuring head impact biomechanics have become an option to clinical researchers. These technologies are not restricted to one particular helmet brand, and introduce the potential for the widespread study of athletes in helmeted and non-helmeted sports. One of these technologies includes the xPatch (X2 Biosystems, Seattle, WA). The xPatch system is designed to measure head impact biomechanics and store the data for later downloading and post-impact processing. The xPatch possesses many benefits including, but not limited, to the following: 1) relative low cost, 2) use in helmeted and non-helmeted sports, 3) a small form factor, and 4) a long battery life. However, how these two systems compare during in-vivo data collection remains unstudied.

In exploring head impact biomechanics in-vivo, video footage has previously been used in football and ice hockey events.[17,18] However, on-field head impact location data from the HIT System have yet to be verified with video analysis and no published reports exist on the xPatch. Therefore, the purpose of this study was to capture on-field head impact data from the HIT System and xPatch concurrently in order to gain a broader understanding of their ability to appropriately measure head impact biomechanics. Specifically, our first aim was to compare the HIT System and xPatch on measures of linear acceleration, rotational acceleration, and HITsp in college football players. Our second aim was to verify system-determined head impact locations based on video-observed head impact locations.

Clinical Significance

Historically, sport-related head impact research has focused mainly on a limited group of football and ice hockey athletes due to the expensive nature and limitations of the HIT System. Newer devices, such as the xPatch, developed to objectively measure head impacts have not been extensively tested in-vivo. If the xPatch is valid for measuring linear acceleration, rotational acceleration, frequency, and location of head impacts, then researchers may be able to use these devises to gather more data from more sports, to better prevent needless head injuries, and to support interventions designed to prevent further injury. Knowledge gained from these additional data can also be used to improve future concussion management protocols.

Specific Aims & Hypothesis

Specific Aim 1: To determine system differences in linear acceleration, rotational acceleration and HITsp of head impacts in college football athletes.

Hypothesis: There will be a significant correlation between the HIT System and xPatch on measures of linear acceleration, rotational acceleration, and HITsp in college football players.

Specific Aim 2: To determine the agreement between system-determined head impact location and location based on video observation.

Hypothesis: There will be an agreement between both systems' impact location data and actual impact location as observed on video.

CHAPTER II

REVIEW OF THE LITERATURE

Overview

The Head Impact Telemetry (HIT) System has been used to better understand head impact biomechanics in American football players. Often the purpose of studies utilizing this technology is to measure and analyze head accelerations.[7] Dependent variables that have previously been measured include the magnitude of peak linear acceleration, peak rotational acceleration, impact frequency and impact location of head impacts.[3,14,18] Data collected with this technology have been used to investigate differences between head impacts sustained by player position,[3,19] session type (limited contact practice, full contact practice, game),[3] helmet type,[20] effect of play type,[18] and various helmeted sports at different levels of play.[14,19,21,22] Location of head impacts have often been characterized by whether the impact occurred in the front of the helmet, back of the helmet, side of the helmet or top of the helmet.[14,21]

The first series of studies to analyze head impact biomechanics in NFL games used video analysis of plays that resulted in concussion, aimed at determining the speed and direction of head impacts.[6,23] The reconstruction of the head impacts were conducted in a laboratory using the Hybrid III Headform.[24] Without the use of video analysis, there is no way to re-create head impacts in the laboratory using the Hybrid III Headform. Subsequent research using the same data from the NFL assessed the accuracy of the linear and rotational acceleration measures previously reported.[25] Results indicate that errors with the impact reconstructions occurred secondary to effects of noise and camera angles of the video. An estimated difference between the video reconstruction and actual linear acceleration was 17% and up to 25% for rotational acceleration. Initial studies aimed at addressing head impact biomechanics demonstrated the need for additional research and technology that could be utilized in-vivo.

Validation of the HIT System

The HIT System has been studied in both the laboratory and on the field during athletics.[7,26-29] Video analysis has been used in conjunction with the Head Impact Telemetry (HIT) System in order to link impact data collected through time synchronization, allowing researchers to ensure that the data collected is a result of an impact that occurred during play.[18] In a laboratory, the Hybrid III Headform is the gold standard for measuring linear and angular acceleration of head impacts.[30] Laboratory testing has compared impacts measured by the HIT System to those measured by the Hybrid III Headform, using data from the NFL that describe head impact locations that most frequently result in concussion.[24,31] The four primary impact sites tested were to the front of the facemask, side of the face mask, side of the helmet, and back of the helmet.[24] Impact location is defined by azimuth and elevation, measured in degrees. The angle of elevation is defined as the impact directional vector through the head center of gravity and a horizontal plane through the head center of gravity.[5,24] The azimuth angles are based on the midsagittal and coronal planes, and are used to measure impacts to the front, side and back of the head. Each site was impacted three to five times at four target speeds including 4.4, 7.4, 9.3 and 11.2 m/s based on data showing the average impact velocity for head impacts associated with and without a concussion.[24,31] Results show a high correlation for peak linear acceleration between the HIT System and Hybrid III Headform ($r^2 = 0.903$), and peak rotational acceleration was correlated for all sites tested (r^2 = 0.710–0.981), with the exception of impacts to the facemask (r^2 = 0.415). Impacts to the facemask resulted in a large difference, with 31.2 ± 46.3° noted when considering all impact locations tested, but only a 13.2 ± 6.3° difference when excluding impacts to the facemask.[24] Overall there is a high correlation between the HIT System and Hybrid III Headform, and impact location was deemed within practical reason for on-field use.[7,24]

Limitations of studies validating the HIT System is that the data have been collected in a laboratory with precision equipment that is unable to be used in-vivo, technical expertise required to use the technology, high cost, and reports that the medium helmet used in testing does not accurately depict how most football players wear their helmet.[24,30] Therefore, assumptions must also be made that the human surrogate models would act like a live participant.[24] Furthermore, as compared to the Hybrid III Headform, the HIT System in its current commercially available design is only capable of linear acceleration measures as it utilizes 3 degrees of freedom (DOF) to reduce the cost and computation time required for processing head acceleration measurements.[24] As a result, a mathematical algorithm for estimating the magnitude of rotational acceleration and impact location using single-axis accelerometers was developed and validated in the literature as an accurate estimation of rotational acceleration.[24,27,32]

Literature Involving the HIT System

Research utilizing the HIT System has focused on many variables including the number and distribution of head impacts,[3,9] differences between player position and level of competition,[10,22] differences in event and play type,[10,14,18] helmet type,[20] and magnitude of head impacts.[9] It is reported that an individual college football player can sustain as many as

1400 impacts in a single season, with player position having a role in the head impact exposure, impact location, and impact magnitudes.[3,9,21] In a study of college football players with a total of 286,636 impacts analyzed, the median number of impacts for one season ranged from quarterbacks with 149 impacts to defensive linemen sustaining 718 impacts.[9] Results from high school and college football players indicated that defensive linemen, linebackers, and offensive linemen sustained a higher frequency of impacts per season, while quarterbacks and wide receivers had the lowest impact frequency.[9,14] However, many discrepancies also exist in the literature with the degree of correlation between head impacts and player position when considering head impact magnitude. When accounting for impact magnitude in college football players, offensive backs were more likely to sustain an impact greater than 80 g than defensive linemen, defensive backs, linebackers, wide receivers and offensive linemen.[9,10] This is consistent with data from both high school and college levels that report skill position players receive a higher percentage of increased magnitude of impacts, and that linemen sustained an overall greater number of impacts, but at a lower magnitude.[21,22]

Although similar when comparing player positions, differences between youth, high school, and college athletes have been noted in the literature. College football players sustain a higher frequency of high magnitude impacts greater than 98 g, and a lower frequency of head impacts greater than 60 g compared to high school athletes.[22] In high school athletes the mean linear acceleration for both games and practices was larger than reported in college athletes with a mean linear acceleration for impacts across all session types of 24.98 g, as compared to 22.25 g and 20.9 g previously reported in college football players.[10,14,26]

Although the mean linear acceleration is slightly greater, the clinical significance of the difference is unclear.[14]

Head impact exposure also varies between levels of play, with far fewer head impacts in younger athletes. In youth football players aged 7-8 years old, an average of 107 head impacts are sustained over the course of a season. As youth football players become older, the number of head impacts increases. It is reported that youth football players aged 11-13 years old sustain a median of 252 head impacts over the course of a season, with a median of 9 impacts occurring during each practice session and 12 impacts per game.[33] One explanation for the differences in head impact exposure in varying levels of play is the increase in the total hours of contact exposure, with longer seasons and an increase in practice and games sessions as the level of play becomes more competitive.

Differences in practice and game sessions as well as play type have been investigated in high school and college football players. At both levels of play, a greater number of head impacts occur during games as compared to practices.[3,14] In college football players, the average number of impacts per game was nearly three times greater than the number of impacts per practice.[3] Although differences in impact frequency between game and practice sessions are consistent among studies, there are inconsistencies between studies when considering impact magnitudes and session type. One study has reported that game impacts have higher linear acceleration and rotational acceleration than practice impacts, while another has reported no increase in magnitude between sessions except for impacts in the 95th percentile, which increased significantly during games.[14,21] Head impacts during college football game sessions have been broken down even further to include differences between play type and the amount of closing distance players have before sustaining a head impact.[18]

Although the interaction effect between play type and closing distance is not statistically significant for linear acceleration ($P = 0.084$) or rotational acceleration ($P = 0.096$), head impacts with a greater closing distance are statistically significant for linear acceleration ($P = 0.001$) and rotational acceleration ($P < 0.001$). The most severe head impacts, as measured by linear acceleration and rotational acceleration, occurred during special teams plays with a greater closing distance defined as greater than 10 yards.

In addition to investigating differences between player position, level of competition and session type, literature involving the HIT System has included differences in impact location and the magnitude of head impacts. Of 3312 valid head impacts in college football players, the average peak head acceleration was 32g, with 89% of all impacts less than 60 g across all player positions and impact locations.[7] In both high school and college football players, the front of the helmet had the greatest frequency of head impacts, but impacts to the top of the helmet were shorter in duration and had greater linear acceleration measures.[10,14,21] When impact location was correlated with player position in college football players, wide receivers sustained more impacts in the sagittal plane and fewer lateral impacts, while fullbacks exhibited a lateral band of impacts around the equator of the helmet, and linebackers and defensive linemen had more frequent impacts to the rear of the helmet.[7]

More recently, research using the HIT System has aimed at assessing if helmet design plays a role in head impacts. Using a total of 1,281,444 head impact data collected across 8 college football teams, differences were noted in head impacts dependent upon the type of Riddell football helmet worn.[20] Players wearing Riddell VSR4 helmets sustained significantly fewer head impacts per season, but had a greater frequency of high-magnitude head impacts as compared to players wearing Riddell Revolution helmets.[20] An important—

but unknowingly accurate—assumption is that all accelerometer units behave the same way regardless of the helmet model they were designed for. Of all players wearing Revolution helmets, 2.28% sustained a concussion, as compared to 4.47% of players who wore VSR4 helmets.[20] When controlling for player exposure, a lower percentage of players wearing Revolution helmets sustained a concussion than players wearing VSR4 helmets ($P = 0.03$).[20] A number of factors may explain these findings. It is very possible that newer Revolution helmets possess better protection than their older VSR4 counterparts. Additionally, better players (starters), particularly at the high school level, are more likely to have access to newer equipment. It is possible that Revolution-wearing players were more skillful and apt to protect themselves from injury than those less experienced VSR4-wearing players. We can only speculate as to the validity of these factors in the context of the study design, but raise them to highlight the complexities that exist in on-field head impact biomechanics research.

Video analysis has previously been used both in the laboratory for re-creating head impacts and in-vivo for assessing the effect of play type and closing distance on head impact biomechanics.[6,18,34] To match head impact biomechanical data to video, video footage was time-synchronized to the HIT system sideline controller, and two angles of footage were analyzed.[18] A single investigator analyzed the video, with strong intra-rater agreement (k = 0.88) for closing distances.[18] Video analysis has also been used to investigate head impact severity in youth ice hockey players.[35] Head impacts that did not occur in the view of the video footage were excluded from the analysis, and both intra-rater and inter-rater agreement was evaluated.

Relation to Concussion

Research conducted with the HIT System has been used to investigate a possible correlation between head impact biomechanics and concussion using receiver operating characteristic (ROC) curves to determine the likelihood of sustaining a concussion for a given head impact. With previous literature published using HIT System data including 62,974 sub-concussive impacts and 37 diagnosed concussive impacts; ROC curves were generated for linear acceleration, rotational acceleration and the combined probability of concussion.[11] As impact acceleration magnitude increases, injury risk also increases. No statistically significant differences were found in the area under the curve associated with the combined probability of a concussion and linear acceleration, meaning that linear acceleration magnitude is able to predict a concussion as well as the combined probability of a concussion. Linear acceleration has consistently been reported as the best measurement for predicting a concussion, with the ability to correctly predict a concussion above 70% of the time.[5,11] However, a composite variable including aspects of linear acceleration, rotational acceleration, impact duration and impact location is even more sensitive to incidence of concussion as compared to just using linear acceleration values.

In college and high school football athletes the frequency and magnitude of head impacts sustained on days with a diagnosed concussion are reported to be higher than on days without a diagnosed concussion.[12] Head impacts associated with diagnosed concussion occurred most frequently to the front of the head, followed by the top of the head, side of the head and back of the head.[4] In a study of three college and three high school football players diagnosed with a concussion, all associated head impacts were sustained during games, and the linear acceleration for the concussive impacts was in the top 3% of all impacts sustained by each individual player.[22]

In an effort to find a "concussion threshold," Pellman et al.[6] attempted to establish a correlation between head impact magnitude and incidence of concussion. The study found that concussions in padded helmets are more likely to occur between 70-75 g of linear acceleration. However, since published, the notion of a 70-75 g threshold has been refuted through additional in-vivo research.[5,8,10,12,22] Research has since found that there are greater odds of sustaining a concussion with a head impact greater than 84.9 g, and the risk of sustaining a concussion at impacts greater than 98.9 g is 0.3%.[5,12] These findings are more consistent with an additional study reporting that less than 0.35% of impacts greater than 80 g result in concussion based on athlete self-reporting symptoms.[10] Discrepancies between studies may be contributed to the different levels of play, the differences in sample size, and the different technologies for collecting data on head impacts used. For example, the study by Pellman et al.[6] used the Hybrid III Headform and video analysis, while the study by Beckwith et al.[12] used head impact data collected with the HIT System.

Although extensive research has been done utilizing the HIT System, there remains no accepted threshold for magnitude of impact which causes concussion.[15] Using data from 43 college football players, clinical outcome measures from the NeuroCom Sensory Organization Test and the Graded Symptom Checklist were compared following high and low magnitude impacts.[16] Although differences were noted following high magnitude impacts of greater than 90 g for math processing, procedural reaction time and the total number of symptoms reported as compared to baseline scores, the finding do not support a 70-75 g magnitude that is previously described as more likely to result in a concussion.[6,16]

Furthermore, the total number of impacts to the top of the helmet and the total number of head impacts greater than 90 g predicted an increase in the number of concussion-like symptoms reported from pre-season to post-season.[13]

Aims to find a "concussion threshold" using high-magnitude head impacts, are further hindered with the overall distribution of head impacts sustained is highly skewed toward the low end of the severity spectrum.[8] Therefore, additional areas of interest include assessing if there is a correlation between sub-concussive head impacts and neurocognitive changes. It has been reported that over the course of one season, college football players sustain and averaged 1177 sub-concussive head impacts.[13] A subgroup of athletes demonstrated temporary learning and memory deficits from repetitive head impacts, although it is also noted that a single season of head impacts is not known to cause widespread short-term detrimental effects.[36]

Limitations of the HIT System

Limitations for studies utilizing the HIT System include the inconsistencies in criteria for defining a head impact and the threshold to be used in the data.[8] Many studies have utilized a 10 g threshold,[7,10,28,37,38] while others only counted head impacts greater than 15 g.[3,14] Head impact location data has often been misclassified for impacts to the facemask, and head impact location has not been verified during on field competition.[24] Due to the high cost and logistical problems, a limited number of institutions have access to the HIT System. The initial cost of the HIT System is substantial, and additional encoders costing approximately $1,500 each.[39] This results in a relatively low number of football players equipped with the technology, and when broken down by player position, even fewer participants are in each group. Additionally, differences in practices between teams are difficult to control for, possibly causing some discrepancies between studies. Some argue that accelerometers placed in helmets do not accurately measure head acceleration because of helmet fit issues and greater force dispersion.[40] Furthermore, the HIT System utilizes 3 DOF for linear acceleration, and a mathematical equation in order to measure rotational acceleration.[2] As it relates to concussion, limitations in attempting to establish a correlation between head impacts and concussion may be exacerbated by the under-reporting of concussion by athletes.[20]

New Methods

Due to limitations with the HIT System, alternative technologies for measuring head impact biomechanics have been established and validated in the literature.[40] This includes the development of accelerometers attached to a mouthpiece. Research conducted in a laboratory using a mouthpiece accelerometer (DVT3, X2Impact, Inc., Seattle, WA) to assess linear acceleration, angular acceleration and angular velocity of head impacts found that on average, the mouthpiece under-predicted the peak angular acceleration by 10%, especially at higher impact velocities, and that face mask impacts measured 12-44% greater.[2] Furthermore, on average the mouthpiece was found to be most accurate for measuring impacts to the front and rear of the helmet, and less accurate in measuring impacts to the face mask. When using the National Operative Committee on Standards for Athletic Equipment (NOCSAE) test regulations of standard heights and impact sites, there was no statistical difference between the modified NOCSAE headform and the instrumented mouthpiece.[40] Limitations in studies using mouthpice accelerometers are that they are conducted under ideal laboratory settings, the instrumented mouthpiece is bolted to a headform, and using helmet testing standards consistent with linear—not rotational—mechanisms, which may not be realistic for in-vivo use.

Additional technology for measuring head impact biomechanics including linear acceleration, rotational acceleration, impact frequency and impact location is the xPatch (X2 Biosystems, Seattle, WA), which uses 6 DOF. No literature to date has validated the use of the xPatch, although the product uses similar technology as the previously described instrumented mouthpiece made by the same company, which has been validated in the literature.[2] No peer-reviewed literature to date has tested the xPatch encoder in-vivo. The xPatch is less expensive as the HIT System, and may be used by any athlete for any sport. The xPatch has software to analyze head impact data that may be interpreted for clinical use.

Rationale for Study

The HIT System is currently the gold standard for measuring head impacts in-vivo and has previously been validated in the literature. Although extensive research has been conducted utilizing the HIT System, few institutions have access to the technology in addition to being limited in the sports it is compatible with. The purpose of this study is to compare the xPatch to the HIT System in measuring linear acceleration, rotational acceleration, frequency, and impact location of head impacts in college football players. If the xPatch accurately assess linear acceleration, rotational acceleration, frequency and impact location then it may be more widely used for a variety of sports and researchers. Furthermore it may be a more cost effective way to gain knowledge of head impact biomechanics and allow for possible advances in research of concussion mechanisms of injury.

CHAPTER III

METHODOLOGY

Participants

Nine NCAA Division I college football players were recruited (age = 20.8±0.3 years; height = 188.2±5.4 cm; mass = 109.6±20.9 kg) during the Fall 2014 season. Participants were selected to represent a variety of player positions including 1 running back, 2 offensive linemen, 1 wide receiver, 1 defensive lineman, 2 linebackers, and 2 defensive backs. Each participant signed an informed consent approved by the university's Institutional Review Board. Inclusion criteria required that each participant be a Division I college football player during the Fall 2014 season who wore a helmet equipped with the HIT System.

Instrumentation

Head Impact Telemetry System

The HIT System (Riddell Corp., Elyria, OH) was used to collect linear acceleration, rotational acceleration, Head Impact Technology severity profile (HITsp), impact frequency, and impact location during all practice and game sessions. Use of the HIT System has been widely used in the literature to measure our variables of interest.[7,26-29] It is comprised of six single-axis accelerometers and a Sideline Response System (Riddell Corp., Elyria, OH). The Sideline Response System includes a laptop with the Head Impact Telemetry Impact Analyzer software, allowing the user to access the head impact data. The model-specific encoders are compatible with Riddell Revolution (M, L, or XL), or Revolution Speed (M, L, or XL) helmet types. The HIT System collected data at 1 kHz for a period of 40 ms (8 ms recorded pre-threshold, and 32 ms after the impact). The data are time-stamped and processed through a proprietary algorithm to determine impact location and magnitude.

X2 Biosystems xPatch

The xPatch is a six degree-of-freedom system, and measures linear acceleration, rotational velocity, HITsp, impact location, and impact frequency of head impacts. Rotational acceleration is computed through a proprietary post-processing procedure. The xPatch device has yet to be widely used in the literature owing to its recent commercial available, although similar mouthpiece-instrumented technology has been documented.[2,40] To remain consistent with the HIT System, the impact threshold was set at 10 g. The xPatch stores data for up to 1600 head impacts, which were manually transferred via computer using the xPatch software to a cloud database. X2 Biosystems uses a proprietary algorithm to determine if data recorded by the xPatch were actual head impacts or not. This algorithm is based on the waveform parameters associated with known head impacts measured in laboratory conditions. Although the exact matching criteria are unknown, the algorithm uses characteristics from the recorded waveform such as area under the curve, points above threshold, and ratio of filtered to unfiltered resultant linear acceleration to determine real head impacts. Data were manually transferred to the cloud database after each game session and the battery charged after each use. The xPatch has a six-hour battery life, and must be activated prior to each use.

Video Analysis

A standard high-definition digital video camera (Model: PV-GS35; Panasonic Corporation of North America; Secaucus, NJ) was time-synchronized to the sideline controller and was used to record the game clock and time of day during competition. This was necessary to synchronize head impact location data captured by the HIT System and xPatch with video observations of these collisions during regular play. To verify head impact location data from games, video footage from an end zone angle using two Panasonic P2 cameras at 60 frames per second were used and recorded onto 16 GB P2 cards.

Procedures

A professional equipment manager fit all participants with a Riddell helmet, which our research team then instrumented with the model-specific accelerometer (encoder) prior to the Fall 2014 season. The xPatch encoder was activated and affixed using Omnifix tape superficial to the right mastoid process prior to each event. Head impact data were collected during three games of the regular 2014 football season. Prior to each game session, a single investigator was responsible for time synchronization across the data collection devices to ensure that video footage could be accurately linked to head impact biomechanical data. Video personnel filmed each game session from two positions on the field: sideline view of the entire field and view from the end zone. Video analyses were conducted to link actual head impact location to the recorded head impact location of the HIT System and the xPatch. Based on the observed impact utilizing the video, impacts were assigned a location (back, front, side, or top), or as one of the following: no impact visible on video; impact location unclear based on video; or multiple impacts concurrently sustained and unable to assign a specific location. A single investigator determined head impact location on video and was blinded to what system recorded each impact and the biomechanical data. Every impact recorded by either system was analyzed a minimum of two times, once from each camera angle. If impact location was unclear after the initial angles were observed, the investigator watched the impact until an appropriate location could be determined. We randomly selected a subset of head impacts (n = 50) to re-evaluate head impact location no less than 30 days following the initial evaluation. There was a strong intrarater agreement for impact location ($\kappa = 0.91$).

Data Reduction

Only data captured by both the HIT System and xPatch were retained for our data analyses. Reasons for exclusion included if one of the systems did not capture the impact event, had a battery failure, or was otherwise not functioning properly. In order to appropriately address our study aims, we identified impact events where each system recorded head impact information. Figure 4.1 details the number and reason for excluding impacts associated with each study aim.

Head impact data from three game sessions in the Fall 2014 season were exported from the Sideline Response System using the Riddell Export Utility and the X2Net wireless Windows Azure cloud database, and subsequently reduced in SAS (SAS Institute, Inc., Cary, NC). Linear acceleration (g), rotational acceleration (rad/s^2), HITsp, and impact location were the outcome measures of interest. Because raw impact data for linear acceleration, rotational acceleration, and HITsp are heavily skewed to low-magnitude head impacts, logarithmic base 10 transformations were employed to normalize the impact data and to allow for parametric statistical analyses.

Statistical Analysis

All data were analyzed using SAS 9.3 statistical software. An a priori alpha level of 0.05 was used. All statistical analyses were performed on the log base 10 transformed values. Pearson correlations (r) and the coefficient of determination (r^2) were calculated for each of the following variables between systems; rotational acceleration, linear acceleration, and

HITsp. Pearson correlations defined as high ($r > 0.6$), moderate ($r = 0.3 – 0.6$) or low ($r < 0.3$). Random intercepts general linear mixed models were performed to compare means between systems. A weighted Kappa analysis was used to analyze frequency differences between the recorded impact location for each system and the actual impact location verified on video. Weighted Kappa allowed us to apply a greater level of disagreement to situations where the video location was front and the data location was back, or vice versa. To further explore the ability of each head impact system to properly record real on-field impacts, we performed a capture-recapture analysis as previously described. This allowed us to estimate the number of real on-field head impacts not recorded by each system based on the data we collected.

Table 3.1. Data Analysis Plan

Aim	Objective	Variables		Statistical Method
		Dependent:	*Independent:*	
1	Is there a difference between the HIT System and xPatch in measuring linear acceleration, rotational acceleration, and HITsp	Linear acceleration Rotational acceleration HITsp	System (HIT System and xPatch)	Correlation
1	Is there a difference in means between the HIT System and xPatch in measuring linear acceleration, rotational acceleration and HITsp	Linear acceleration Rotational acceleration HITsp	System (HIT System and xPatch)	Random Intercepts General Linear Mixed Model
2	Is there agreement between the HIT System impact location data and actual impact location	Impact location	HIT System and video	Kappa
2	Is there agreement between the xPatch impact location data and actual impact location	Impact location	xPatch and video	Kappa

CHAPTER IV

MANUSCRIPT

Introduction

Approximately 3.8 million sport-related traumatic brain injuries (concussions) occur each year in the United States, with football annually accounting for the most concussions.[1] It is reported that each year 5-10 concussions occur per college football team,[2] and that a single collegiate football athlete may sustain as many as 1,400 head impacts in a single season.[3] Furthermore, athletes sustain a greater number of head impacts as well as impacts of a higher severity on days of a diagnosed concussion.[4] Concussion research is continually evolving and expanding, including injury management and the study of long-term effects and deficits believed to be associated with concussion. The study of head impact biomechanics can aid in the development of concussion injury risk curves.[5]

Early investigation of head impact biomechanics consisted of laboratory methods utilizing the Hybrid III Headform to reconstruct on-field head impacts resulting in concussions from National Football League (NFL) video footage.[6] Since 2003, the Head Impact Telemetry (HIT) System has been used in numerous studies for objectively measuring head impact biomechanics in youth,[41] high school,[14] and collegiate football and ice hockey players in on-field settings.[3,19,42] Research using the HIT System has reported head impact exposures,[9] identified positional differences in exposure and impact magnitude,[10] frequency and location of head impacts,[3] and correlated head impact biomechanics with clinical outcomes.[11] Additionally, using the HIT System has advanced our ability to track head impact trends over the course of a season, and begin to study the patterns observed in head impact biomechanical data on days of a diagnosed concussion.[4,12,13]Although extensive research has been conducted with the purpose of relating head impact biomechanics to concussion, a biomechanical concussion injury threshold for magnitude of impact remains elusive to clinical researchers.[14-16]

Although research with the HIT System has provided much insight into head impact biomechanics, in-vivo analysis has been restricted by licensing agreements limiting the study of football head impact biomechanics to those who wear Riddell helmets capable of accepting the HIT System accelerometer units. More recently, non-helmet based technologies capable of measuring head impact biomechanics have become an option to clinical researchers. These technologies are not restricted to one particular helmet brand, and introduce the potential for the widespread study of athletes in helmeted and non-helmeted sports. One of these technologies includes the xPatch (X2 Biosystems, Seattle, WA). The xPatch system is designed to measure head impact biomechanics and store the data for later downloading and post-impact processing. The xPatch possesses many benefits including, but not limited, to the following: 1) relative low cost, 2) use in helmeted and non-helmeted sports, 3) a small form factor, and 4) a long battery life. However, how the HIT System and xPatch compare during in-vivo data collection remains unstudied.

In exploring head impact biomechanics in-vivo, video footage has previously been used in football and ice hockey events.[17,18] However, on-field head impact location data from the HIT System have yet to be verified with video analysis and no published reports exist on the xPatch. Therefore, the purpose of this study was to capture on-field head impact data from the HIT System and xPatch concurrently in order to gain a broader understanding of their ability to appropriately measure head impact biomechanics. Specifically, our first aim was to compare the HIT System and xPatch on measures of linear acceleration, rotational acceleration, and Head Impact Technology severity profile (HITsp) in college football players. Our second aim was to verify system-determined head impact locations based on video-observed head impact locations.

Methods

Participants

Nine NCAA Division I college football players were recruited (age = 20.8 ± 0.3 yrs; height = 188.2 ± 5.4 cm; mass = 109.6 ± 20.9 kg) during the Fall 2014 season. Participants were selected to represent a variety of player positions including 1 running back, 2 offensive linemen, 1 wide receiver, 1 defensive lineman, 2 linebackers, and 2 defensive backs. Each participant signed an informed consent approved by the university's Institutional Review Board. Inclusion criteria required that each participant be a Division I college football player during the Fall 2014 season who wore a helmet equipped with the HIT System.

Instrumentation

Head Impact Telemetry System

The HIT System (Riddell Corp., Elyria, OH) was used to collect linear acceleration, rotational acceleration, HITsp, impact frequency, and impact location during all practice and game sessions. Use of the HIT System has been widely used in the literature to measure our variables of interest.[7,26-29] It is comprised of six single-axis accelerometers and a Sideline Response System (Riddell Corp., Elyria, OH). The Sideline Response System includes a laptop computer with the Head Impact Telemetry Impact Analyzer software, allowing the user to access the head impact data. The model-specific encoders are compatible with Riddell

Revolution (M, L, or XL), or Revolution Speed (M, L, or XL) helmet types. The HIT System collected data at 1 kHz for a period of 40 ms (8 ms recorded pre-threshold, and 32 ms after the impact). The data are time-stamped and processed through a proprietary algorithm to determine impact location and magnitude.

X2 Biosystems xPatch

The xPatch is a six degree-of-freedom system, and measures linear acceleration, rotational velocity, HITsp, impact location, and impact frequency of head impacts. Rotational acceleration is computed through a proprietary post-processing procedure. The xPatch device has yet to be widely used in the literature owing to its recent commercial availability, although similar mouthpiece-instrumented technology has been documented.[2,40] To remain consistent with the HIT System, the impact threshold was set at 10 g. The xPatch stores data for up to 1600 head impacts, which were manually transferred via computer using the xPatch software to a cloud database. X2 Biosystems uses a proprietary algorithm to determine if data recorded by the xPatch were actual head impacts or not. This algorithm is based on the waveform parameters associated with known head impacts measured in laboratory conditions. Although the exact matching criteria are unknown, the algorithm uses characteristics from the recorded waveform such as area under the curve, points above threshold, and ratio of filtered to unfiltered resultant linear acceleration to determine real head impacts. Data were manually transferred to the cloud database after each game session and the battery charged after each use. The xPatch has a six-hour battery life, and must be activated prior to each use.

Video Analysis

A standard high-definition digital video camera (Model: PV-GS35; Panasonic Corporation of North America; Secaucus, NJ) was time-synchronized to the sideline controller and was used to record the game clock and time of day during competition. This was necessary to synchronize head impact location data captured by the HIT System and xPatch with video observations of collisions during regular play. To verify head impact location data from games, video footage from an end zone angle and wide angle of the field, using two Panasonic P2 cameras at 60 frames per second, were used and recorded onto 16 GB P2 cards.

Procedures

A certified equipment manager fit all participants with a Riddell helmet, which our research team then instrumented with the model-specific accelerometer (encoder) prior to the Fall 2014 season. The xPatch encoder was activated and affixed using Omnifix tape superficial to the right mastoid process prior to each event. Head impact data were collected during three games of the regular 2014 football season. Prior to each game session, a single investigator was responsible for time synchronization across the data collection devices to ensure that video footage could be accurately linked to head impact biomechanical data. This time synchronization occurred within 4 hours of game time. Video personnel filmed each game session from two positions on the field: sideline view of the entire field and view from the end zone. Video analyses were conducted to link actual head impact location to the recorded head impact location of the HIT System and the xPatch. Based on the observed impact utilizing the video, impacts were assigned a location (back, front, side, or top), or as one of the following: no impact visible on video; impact location unclear based on video; or multiple impacts concurrently sustained and unable to assign a specific location. A single investigator determined head impact location on video and was blinded to which system recorded each impact. Every impact recorded by either system was analyzed a minimum of two times, once from each camera angle. If impact location was unclear after the initial angles were observed, the investigator watched the impact until an appropriate location could be determined. We randomly selected a subset of head impacts ($n = 50$) to re-evaluate head impact location no less than 30 days following the initial evaluation. There was a strong intrarater agreement for impact location ($\kappa = 0.91$).

Data Reduction

Only data captured by both the HIT System and xPatch were retained for our data analyses. Reasons for exclusion included if one of the systems did not capture the impact event, had a battery failure, or were otherwise not functioning properly. In order to appropriately address our study aims, we identified impact events where each system recorded head impact information. Figure 4.1 details the number and reason for excluding impacts associated with each study aim.

Head impact data from three game sessions in the Fall 2014 season were exported from the Sideline Response System using the Riddell Export Utility and the X2Net wireless Windows Azure cloud database, and subsequently reduced in SAS (SAS Institute, Inc., Cary, NC). Linear acceleration (g), rotational acceleration (rad/s^2), HITsp, and impact location were the outcome measures of interest. Because raw impact data for linear acceleration, rotational acceleration, and HITsp are heavily skewed to low-magnitude head impacts, logarithmic base 10 transformations were employed to normalize the impact data and to allow for parametric statistical analyses.

Statistical Analysis

All data were analyzed using SAS 9.3 statistical software. An a priori alpha level of 0.05 was used. All statistical analyses were performed on the log base 10 transformed values. Pearson correlations ® and the coefficient of determination (r^2) were calculated for each of the following variables between systems; rotational acceleration, linear acceleration, and HITsp. Pearson correlations were defined as high ($r > 0.6$), moderate ($r = 0.3 – 0.6$) or low ($r < 0.3$). Random intercepts general linear mixed models were performed to compare means between systems. A weighted Kappa analysis was used to analyze frequency differences between the recorded impact location for each system and the actual impact location verified on video. Weighted Kappa allowed us to apply a greater level of disagreement to situations where the video location was front and the data location was back, or vice versa. To further explore the ability of each head impact system to properly record real on-field impacts, we performed a capture-recapture analysis as previously described.[43] This allowed us to estimate the number of real on-field head impacts not recorded by each system based on the data we collected.

Results

We captured 1251 total head impacts with both systems (HIT System n= 554; xPatch n= 697). We observed statistically significant correlations between the HIT System and xPatch for linear acceleration (r = 0.44; r^2 = 0.19; P <0.001), rotational acceleration (r = 0.15; r^2 = 0.02; P = 0.017), and HITsp (r = 0.34; r^2 = 0.12; P <0.001) (Figure 4.2). We observed significant differences in mean rotational acceleration ($F_{1,8}$ = 832.19; P <.001) and HITsp ($F_{1,8}$ = 8.95; P = 0.017) between systems, but no difference in linear acceleration ($F_{1,8}$ = 0.10; P = 0.754; Table 4.1). We observed low agreement between video-observed impact location and: 1) HIT System impact location (weighted $\kappa = 0.17$); 2) xPatch impact location (weighed $\kappa = 0.12$). Likewise, a low agreement was observed between xPatch impact location and HIT System impact location (weight $\kappa = 0.04$). Additionally, Table 4.2 details the number of impacts recorded by each system that were verified using video analysis, and Table 4.3 presents the capture-recapture analysis.

Discussion

From our study it appears data from the HIT System and xPatch should not be used in conjunction in order to draw conclusions about head impact biomechanics. The HIT System and xPatch do not appear to be measuring similarly for rotational acceleration and head impact location. Video analysis revealed poor agreement in recorded impact location and observed impact location for both systems, in addition to providing insight into estimated head impact exposure and the number of head impacts recorded that did not occur during competition.

Although our hypothesis was confirmed, and we had significant correlations, our results show a moderate correlation between the HIT System and xPatch in measuring linear acceleration and HITsp, and a low correlation in measuring rotational acceleration. While a moderate correlation between the two systems in measuring linear acceleration was found, there was not a significant difference in the means. In addition to having a low correlation, the mean rotational acceleration of the xPatch was significantly greater than the HIT System. The mean HITsp for the xPatch was also significantly greater than the mean for the HIT System. A possible explanation for this difference is that HITsp is a derivative of linear acceleration, rotational acceleration, impact location, Gadd Severity Index, and Head Injury

Criterion. Therefore, significantly greater rotational acceleration values for the xPatch may also have an effect on the HITsp.

One potential explanation for the difference in rotational acceleration of head impacts between the HIT System and xPatch is that both systems must estimate the rotational acceleration. Because the HIT System only measures linear acceleration, a mathematical algorithm for estimating the magnitude of rotational acceleration was developed and has been previously reported in the literature.[24,27] It is important to note the HIT System is unable to estimate rotational acceleration about the transverse plane. This may cause an underestimation of rotational acceleration measurements. In contrast, the xPatch is able to measure rotational velocity, but not rotational acceleration directly. This may cause an overestimation of rotational acceleration values, but we are unable say this for certain from our data. Our findings do not demonstrate that rotational acceleration measurements should be excluded in head impact biomechanics, but that the data are relative to the measurement device. Further investigation is needed to ascertain the reliability of each system's reported rotational acceleration values. Beyond reliability, laboratory study is needed to continue to develop methods to properly measure, derive, and report rotational acceleration. Additionally, our data only included 264 matched head impacts. A larger data set may be able to account for some of the variability in rotational acceleration between the HIT System and xPatch. While this may be possible, we believe it is unlikely due to the very large mean difference we noted between systems. The results of our data are consistent with other studies reporting linear acceleration measurements may be more consistent between devices.[5,11]

Head impact location has previously been reported in both football and ice hockey players.[3,19] However, no study to date has verified head impact location with video analysis in-vivo. Impact location for both the HIT System and xPatch was not as accurate as we hypothesized. A Kappa of 1.0 means that the impact location recorded by the system and the actual impact location verified by video analysis is in complete agreement whereas a Kappa of 0 indicates purely chance agreement. Our data found poor agreement for both the HIT System ($\kappa = 0.17$) and xPatch ($\kappa = 0.12$). One initial explanation was investigator error; however, after further video analysis of 50 randomly selected impacts, our intra-rater reliability was $\kappa = 0.91$. Furthermore, we found poor agreement in impact location for the same impact event between the HIT System and the xPatch. A possible explanation for the poor agreement is that the HIT System and the xPatch use different conventions to determine impact location. Regardless of the conventions used, we analyzed the output reported by each system. Unless researchers redefine impact location using given azimuth and elevation values, the system generated impact location values would be analyzed. Therefore, we feel justified in analyzing the system generated impact location values. Future research needs to identify inter-tester reliability and investigate head impact location agreement for each head impact location (back, front, side, top). Further, researchers should determine the most appropriate conventions to use when defining head impact location. In our study we did not differentiate between right side and left side head impacts, future research should differentiate between side impacts. Furthermore, in our study the xPatch was only placed behind each subject's right ear. It is unclear if this had an effect on impact location, and future research should investigate differences in head impact location based on which side of the head the xPatch was affixed to.

Although not one of our research aims, one important finding of our study is the number of head impacts recorded that were not visible on video analysis. We did not exclude head impacts in our analysis because they did not occur, but rather because they were not visible on video. On-field head impact biomechanics has previously been studied using head impact monitoring systems and documented in the literature.[3,4,9,10,12,14,18,44,45] In data sets with large numbers of head impacts, it is unlikely that each impact recorded was verified on video. By analyzing video from two angles we were able to determine if an impact recorded by either system actually occurred during competition. In our data set, approximately 23% of the total number of head impacts recorded by either system were false positives and did not occur during competition. It is interesting to note that in approximately 2% of recorded HIT System impacts and 14% of xPatch impacts, the player was clearly visible on the field, and did not sustain a head impact. A possible explanation for the xPatch recording false positives is that the device is too sensitive, recording impacts when the head is moving or rotating quickly, or movement of the arm or shoulder pads in close proximity to the placement of the xPatch. Although the HIT System had a lower rate of false positives when the player was on the field, it had a greater rate of false positives when the player was not on the field compared to the xPatch. Approximately 21% of HIT System impacts and 9% of xPatch impacts were recorded when the player was not on the field. A possible explanation for the increased number of head impacts recorded by the HIT System when the player was not on the field include celebratory head slaps, and taking the helmet on or off. It would take a tremendous effort for a researcher to take into account every time a player is off the field, as well as requiring additional camera angles to view the sideline. Thus, it is likely many datasets that have been previously analyzed and reported in the literature contained a fairly substantial number of off-field head impacts. Whether or not these off-field impacts were head slaps or head butts or where a result of the player removing, replacing, or slamming down his helmet is unknown. This is an important finding and researchers should continue to investigate the most appropriate data collecting and cleaning procedures in order to ensure appropriate impact data are analyzed.

Previous studies have reported head impact frequencies during game and practice sessions.[3,9,33,36,45] This is important as quantifying total head impact exposure may be a key component in understanding potential late life cognitive and behavioral challenges faced by former athletes. Because neither the HIT System nor the xPatch are considered the gold standard for measuring head impact biomechanics, we used the capture-recapture method to estimate the total number of head impacts that may have actually occurred but not have been recorded. This method has previously been used to estimate the number of missing recorded injuries when investigating two injury surveillance systems.[43] The capture-recapture method demonstrates that many head impacts may have occurred and not been recorded. An estimated number of 146 total head impacts were missed by both systems. The capture rate of the HIT System and xPatch for the total number of head impacts is 62.71% and 73.36%, respectively. This means that the HIT system is failing to capture approximately 35% of actual head impacts, and the xPatch is failing to capture approximately 25% of head impacts. This is concerning as researchers continue to understand a potential relationship between head impact exposure and long-term pathologies and consequences.[39]

The findings of our study reveal that both the HIT System and xPatch have poor agreement with actual head impact location, and that we are unable to accurately compare measurements from both systems. Furthermore, both the HIT System and xPatch provide false positive data that are often included in head impact biomechanics analyses when every impact is not verified by video analysis. Our study also suggests that head impact monitoring devices may not be capturing every actual head impact. Limitations of this study include the use of a single football team and low number of subjects that may not represent a larger population of football athletes and non-helmeted sports. Other limitations include the relatively low number of competitions and head impacts analyzed. Future research should include laboratory testing for measuring and comparing rotational acceleration of the xPatch and HIT System in a controlled environment, and exploring differences between the systems when broken down by head impact location and head impact severity. Future research should also investigate head impact biomechanical data in non-helmeted sports as well as head impact exposure and the potential long-term consequences.

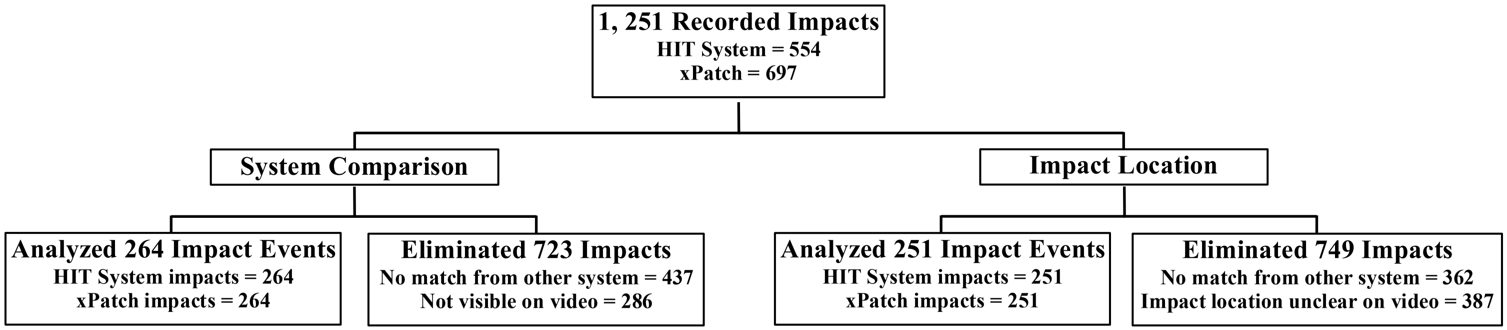

Figure 4.1. Impact selection flow chart, broken down by Aim 1 (System Comparison) and Aim 2 (Impact Location).

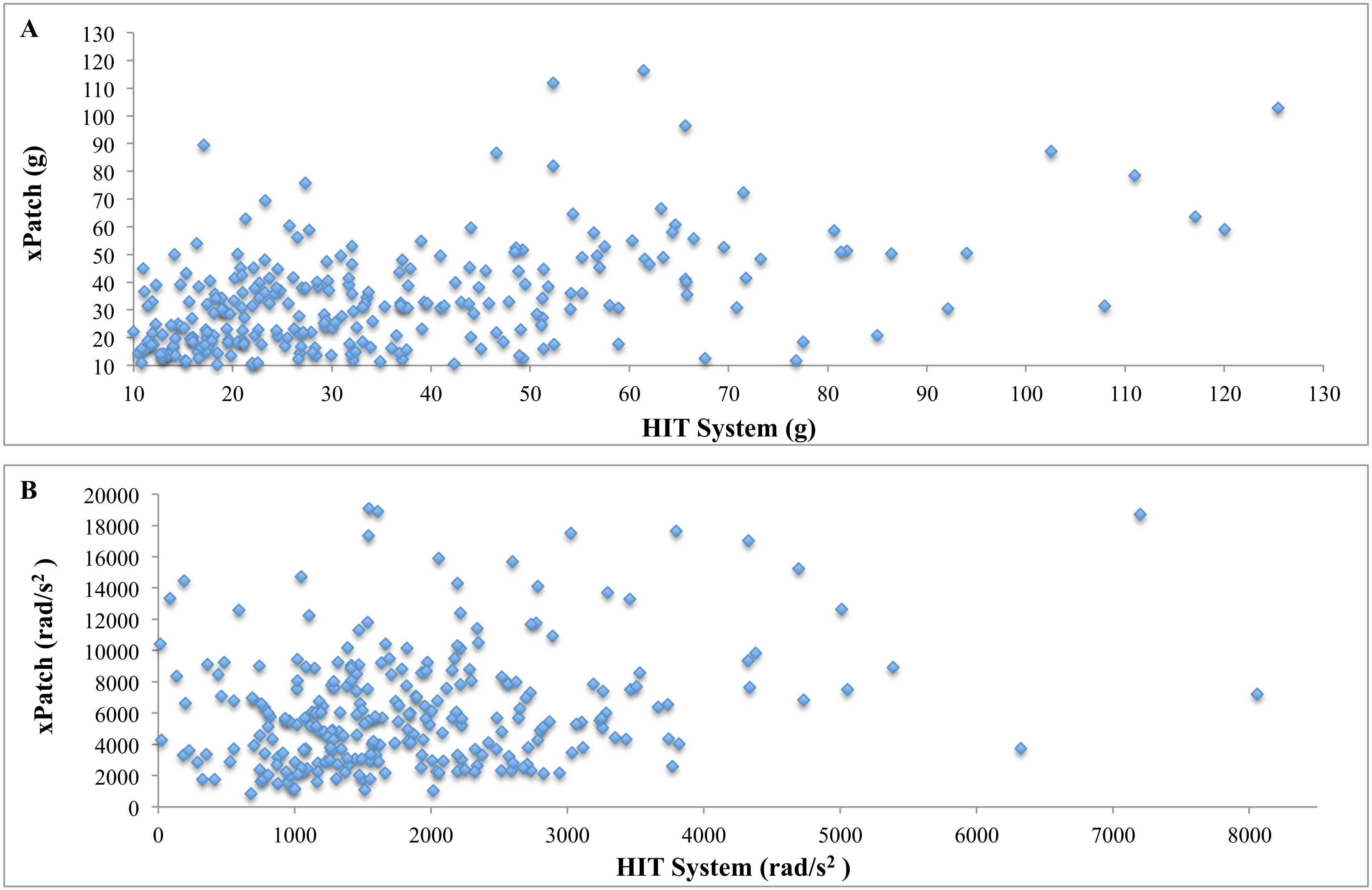

Figure 4.2. Scatter plots representing the correlation between the HIT System and xPatch in measuring linear acceleration (A) and rotational acceleration (B).

Table 4.1 Descriptive statistics and means comparisons between systems

	Linear Acceleration (g)			**Rotational Acceleration (Rad/s^2)**			**HITsp**		
	Mean	95% CI	P	Mean	95% CI	P	Mean	95% CI	P
HIT System	29.63	26.23, 33.47	0.754	1549.85	1375.96, 1745.71	<0.001	16.38	15.17, 17.69	0.017
xPatch	28.83	25.80, 32.21		5255.89	4608.75, 5993.90		19.13	16.96, 21.57	

HIT – Head Impact Telemetry, CI – Confidence Interval

Table 4.2. Impacts recorded by each system and verified by video analysis

Video Impact Verification	HIT System (%)	xPatch (%)	Total (%)
Impact clearly visible on video	425 (76.7)	540 (77.4)	965 (77.1)
Player visible on field, did not sustain head impact	11 (1.9)	96 (13.7)	286 (22.9)
Player was not on the field	118 (21.2)	61 (8.7)	
Total	554 (44.3)	697 (55.7)	1251 (100)

HIT – Head Impact Telemetry

Table 4.3. Capture-Recapture analysis for total number of head impacts

		Captured by HIT System	
		Yes	No
Captured by xPatch	Yes	639 (a)	380 (b)
	No	232 (c)	138 (x)

x = estimated number of head impacts not captured by either system
x = bc/a

N = estimated number of total head impacts
N = a + b + c +x
N = 1389

Estimated capture rate of HIT System = (a+c)/N = 62.71%
Estimated capture rate of xPatch: (a+b)/N = 73.36%
Estimated capture rate of HITS and xPatch: a/N = 46.01%

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