RELIABILITY OF THE TRIAX SMART IMPACT MONITOR-G SYSTEM ON HEAD IMPACTS IN COLLEGIATE CHEERLEADERS

by

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A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science
with a Major in Athletic Training
August 2017

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ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my committee members Dr. Karen Meaney, Dr. Darcy Downey, and my thesis chair Dr. Melissa Fraser. Your cooperation, advice, guidance, and patience were greatly appreciated. Dr. Fraser, I cannot thank you enough for the time you dedicated to me and my growth as a master's student. I appreciate all you have done for me and taking me on during the middle of the year and becoming my chair. I cannot explain how grateful I am to have you as my thesis chair. This has been a different experience for me and I am very happy I was able to have a mentor like you to guide me through this. This has been an amazing learning opportunity and I have expanded my knowledge so much about sensors and concussions because of you, and words cannot explain the feeling I have that finally, I have completed my task. You will forever be a mentor to me and I am extremely grateful for everything you have done for me at Texas State University. I also want to thank Darcy Downey for being a great athletic training mentor to me and helping me excel as an athletic trainer. Dr. Meaney thank you so much for coming onto my committee last minutes you are very appreciated by me.

To my family and friends, I want to say thank you for the continued support especially being so far away, I could not have done this without all of you and your words of encouragement throughout this process. Thanks mom and dad, I am finally done!

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LIST OF ABBREVIATIONS

Abbreviation	Description
G-Force	G
Radian per Seconds Squared	$krad/s^2$
National College Athletic Association	NCAA
International Cheer Union	ICU

I. INTRODUCTION

The early roots of cheerleading (i.e., cheer) involved a group of participants encouraging spectators to cheer in support of their sports team. However, over the years cheer has evolved from basic maneuvers such as jumps and clapping to more competitive activities with acrobatic, gymnastic-like tumbling and stunts such as pyramids and basket tosses.[1] There are a variety of cheerleading teams such as traditional school-based squads as well as All-Star squads. The primary goal of All-Star cheer is to win cheer competitions and is not associated with school or sports leagues.[1] Like most sports, participants' ages range from 4 years (mini cheerleaders) to adult squads where there is no age limit but most participants are typically 18 to 35 years old.

Cheerleading has evolved from to an entertainment sport now focused on increasing difficulty of stunts and tumbling maneuvers, ultimately increasing the risk of injury.[1-7] Cheerleading is often overlooked as a competitive sport in the athletics world, as cheerleading is considered a feminine activity. Cheer has many inherent risks as demonstrated by the number of cheer injuries increasing two fold from 10,900 injuries in 1990 to 22,900 injuries in 2002 with an average of 16,100 (95% CI: 12,848-19,352) injuries per year. [2,7,8] Stunts have been the main cause for all cheer-related injuries.[1] When looking at concussions in particular, collegiate cheerleaders and collegiate competition cheerleaders are 3.1 times more likely to sustain a concussion compared to other cheer squads at various levels (including, middle school, high school, and All-Star teams).[3]

In the last few decades, concussions have become an important issue in the athletic world with an estimated 1.6 million occurring each year, [9] and are one of the most common injuries among collegiate cheerleaders.[3] In 2012, the national center for catastrophic sport injury conducted research on all sports and compared to all female sport injuries, collegiate cheerleading had the highest rate of direct catastrophic injuries at 71.2% of all collegiate female sports injuries, during the 30 years of data collection.[8] While concussions and their associated symptoms vary across individuals, there are serious consequences such as memory loss and emotional issues that may impact individuals indefinitely.[10] Better concussion education has led to improved recognition as concussion rates have increased over the last few years.[10]

In the last 10 to 15 years research has increased using various head impact biomechanics accelerometer systems to detect the linear (g) and rotational (rad/sec^2) accelerations the head and body receive during an activity.[11-16] Accelerometers that have recently been studied include the gForce Tracker ™ (Gforcetracker Inc., Ontario),[17] Head Impact Telemetry System (HITS) (Riddell, Chicago, IL), [11,12,18-20] X2 mouthguard (X2 Biosystems, Seattle, WA),[14] X2 Xpatch (X2 Biosystems, Seattle, WA),[21] and Smart Impact Monitoring-G (SIM-G) system (Triax Technologies Inc., Norwalk, CT).[16,22-24] These accelerometer-based sensors are constantly evolving in shape, placement, capabilities, and user friendliness; however, they all detect impacts to the head and body as well as the general impact location and associated forces. A study by Siegumd et al. reported that the HITS sensors detected 861 out of the 896 impacts (96.1%) and the X2 XPatch detected 845 out of the 896 (95.4%).[18] If a sensor is detecting better than 95% that has good reliability that it is missing less than 5% of all impacts. Linear and rotational acceleration are common measurements recorded by head impact biomechanics sensors. Cheerleaders are constantly changing the direction of their body and they do not wear helmets; therefore using a helmetless sensor will be the most effective at providing accurate data.

Three previous studies have verified a level of validity of the Triax SIM-G in the laboratory environment. In a laboratory setting the SIM-G sensor was deemed reliable for measuring short (7ms) and long duration (40ms) events, with data suggesting that the SIM-G can consistently record rotational and linear accelerations of the head during movement.[23,24] The SIM-G has been compared to the gold standard headform. The peak linear acceleration between the headform and the SIM during low and medium impacts was not significantly different. The linear acceleration during high impact had a significant difference (p=0.014) between the headform (M=61.8, SD=8.4) and the SIM (M=75.0, SD=21.9).[24] These findings suggest that the SIM is more accurate at monitoring lower energy levels. In the study they found that the SIM has a tendency to overestimate higher energy levels compared to the headform, which makes is a more considerable on the field tool since it can identify high-risk head impact .[24]

Cheerleading is a high-risk sport for concussions, but there is a dearth of research investigating the biomechanics of their injuries. Competitive cheerleaders do not wear helmets and often are required to move in complex patterns (flipping, twisting) throughout their routines. Therefore, light, helmetless sensors, like the Triax SIM-G, are necessary to accurately capture their head motion. To our knowledge, there currently are no field-based reliability studies assessing the Triax SIM-G sensors. It is important to verify the ability of these sensors to consistently measure head impacts/rapid head movements during competitive cheer practices to improve our understanding of concussion risk in cheer. Therefore, the purpose of this study is to verify the reliability of the SIM-G helmetless head impact biomechanics accelerometer system during competitive cheer practices.

Overview of Study

Purpose of the Study: The primary purpose of this study was to determine the reliability and validity of the Triax SIM-G sensor.

Experimental Hypotheses: The SIM-G will yield an acceptable level of 95% reliability and validity in detecting incident impacts and impact location compared to video confirmation.

Assumptions:

- The researchers will be able to see all sensors on the video.
- The researchers will grade them all the exact same.
- The headbands will all fit properly
- The athletes will always put the headbands on correctly.
- All sensors will work properly per the manufacturer's guidelines.
- The video will capture all activities being performed.

Delimitations:

- This study is delimited by the recruitment of colligate competition cheerleaders attending Texas State University.

Limitations:

- This study is limited to a total of 8 practices and does not represent an entire season.
- This study is limited to female and male collegiate competition cheerleaders.
- This study is limited to data specific to the Triax SIM-G sensors.

Operational Definitions:

- Concussion- A brain function disturbance induced by biomechanical forces which is caused by a blow to the head or violent shaking of the head and body.[2]

Independent Research Variables:

1. Position
    a. Base- person with a least one foot on the floor who is in direct, weight bearing contact with the performing surface and who provides primary support for another person (flyer)
    b. Primary Base (main base)- holds the flyer's foot at the heel and toe, taking on most of the initial weight
    c. Secondary Base- faces the primary base, two to three feet apart, also holding onto the flyer's foot by placing one hand under the arch of the foot and the other on the primary base wrist
    d. Flyer- person who is elevated and/or tossed in the air by a base and may perform twists and/or flips before being caught by one or more bases
    e. Tumbler- a cheerleader who specialized in gymnastic passes
    f. N/A- position was not involved in stunting or tumbling
2. Activity
    a. Stunt- refers to when athletes lift other athletes and these athletes perform body positions and skills while suspended
    b. Pyramid- Two or more connected stunts
    c. Basket Toss- a stunt in which a flyer is tossed in the air by bases whose hands are interlocked
    d. Cradle- when a flyer dismounts to a face-up position caught by bases

e. Double Down Cradle- when the flyer completes two 360° twists and lands in a piked position a cradle

f. Tumbling- any gymnastic or acrobatic skill executed by a single individual on hard surfaces.

g. Not related- non-cheer related activity (e.g. nothing was happening, flicking of sensor, adjusting band)

3. Correct technique
    a. Yes- the activity was executed correctly
    b. No- the activity was not performed correctly
    c. N/A- was not applicable to the activity (i.e. non-related activities)
4. Landing
    a. Soft- cradle and/or tumbling landed in a spongy manner
    b. Hard- cradle and/or tumbling landed in a solid manner
    c. N/A- impact was not related to landing
    d. Fall- incomplete stunt and/or tumbling pass resulting in the cheerleader hitting the ground with something other than their feet.

Dependent Research Variables:

1. SIM-G Impact
    a. Yes: impact recorded by the SIM-G accelerometer.
    b. NIT: an impact that was recorded as a result of a direct impact to the sensor. These impacts are not considered to be "real" impacts by the Triax system.

    c. No: The SIM-G did not record a possible impact event. These were determined by potential impact events identified during video analysis of the eight cheer practices.

2. Video Impact
    a. Yes: the researchers were able to visually confirm a potential impact event during the specified time via video analysis.
    b. No: the researchers were able to confirm that a potential impact event did not occur at the specified time via video analysis.
    c. Unsure: the researchers were not able to confirm if a potential impact event occurred at the specified time via video analysis. Potential reasons for this included but were not limited to athletes walking out of the frame, or the researcher's view of the potential impact event was obstructed.
3. Head impact biomechanics measures
    a. Impact frequency- The total number of impacts sustained by an individual cheerleader over 8 cheer practice sessions
        i. SIM-G accelerometer: recorded impacts that were ≥16g. (n=120)
        ii. Video: the research team reviewed the video for all 8 practices. The research team listed each activity for all cheerleaders seen on the video as possible impact events (n=1048)
    b. Impact magnitude- The severity of an impact to the body or head.
        i. Linear acceleration (g): The rate of change in velocity along a straight line.
        ii. Rotational acceleration (krad/s2): The rate of change in

angular/rotational velocity per second squared.

c. Impact location:

   i. Triax SIM-G: The Triax system data determined the location of the impact to the head. The circumference is divided into eight equal sections of 22.5 degrees (front, front right, front left, left, right, back left, back right, back). There were two additional locations (crown, base) as described below:

      1. Top (Crown): elevation greater than 45 degrees
      2. Base: any impact that results in a primarily upward acceleration to the head and less than -45 degree. Includes hits on the bottom of the helmet/facemask.

   ii. Impact location as determined by video analysis:

      1. Front: impact on the front of the head before hairline from either side of anterior mid-sagittal plane
      2. Top (Crown): impact above the forehead-hairline junction and above the top of the ears
      3. Side (right and left): any anterior or posterior impact posterior to the face and anterior to the posterior angle of the head.
      4. Back: Any impact posterior to the ears
      5. Body- Any impact to the body
      6. None- no impact to the body or head occurred (e.g., athlete removed their headband, headband came off)

7. Unsure- Researchers could not visually verify impact location (i.e. athlete walked out of frame, impact was blocked by other participants, etc.)

II. REVIEW OF LITERATURE

Research in cheerleading advances is limited, especially related to injuries and injury epidemiology as some of the last studies were conducted in 2012.[7] The early roots of cheerleading (i.e., cheer) involved participants encouraging groups of spectators to cheer in support of their sports team. However, over the years cheer has evolved from basic maneuvers such as jumps and clapping to more competitive activities with acrobatic, gymnastic-like tumbling and stunts such as pyramids and basket tosses.[1] Concussions are very common in collegiate cheerleaders due to the dynamic motions required during stunting and tumbling maneuvers. Collegiate cheerleaders are 3.1 times more likely to sustain a concussion compared to other cheer squads at various levels (including, middle school, high school, and All-Star teams).[1]

With the advent of competition cheerleading, this sport has become more dangerous through the years since the stunts have increased difficulty.[4] Competition cheerleaders train and perform stunting and tumbling routines in large or small group competitions where they are scored against other teams on difficulty and precision. They must be in sync with one another and the music while performing stunts that may involve multiple flyers going 11 feet in the air simultaneously.[4]

Concussion reporting has increased in the last few decades maybe due to the improved education and recognition. A concussion is a functional disturbance in the brain induced by biomechanical forces, which is caused by a blow to the head or violent shaking of the head or body.[25, 26] Typically collision sports incur more concussions due to the contact and nature of the sport. Head impact biomechanical accelerometers have been used in sports like football and ice hockey to look at head impacts and impacts forces since 1999.[33]

There are various factors currently being employed that can help reduce concussion risk, including rule changes in sports,[26,27] the CDC Heads Up program,[26] player education, and awareness of possible concussion consequences.[26, 28] For example, in football a player can no longer purposefully hit another player in the helmet with their helmet (targeting), because this activity has been shown to increase the risk of a concussion.[26] The National Football League (NFL) and National Collegiate Athletic Association (NCAA) have also changed the kick-off rules to reduce the risk of a concussion, due to the research indicating that the impact magnitudes that occurred during kick-offs with the ball at the 30-yard line increased concussion risk. Coaches in football also teach athletes to not lead with their heads when tackling to help reduce concussion and cervical spine injuries. A widely used program that helps coaches teach and enforce this head-up contact theory is the CDC Heads Up program.[29] It is important to note that while helmets are worn in sports to protect the skull, they do not prevent concussions.[30] Cheerleaders do not wear helmets due to the nature of their bodies in the air and the contact with another cheerleader without pads. Cheer coaches also have rules and techniques that they are supposed to teach their cheerleaders so that they perform the stunts properly.

Cheerleaders are in constant contact with other cheerleaders when cradling; cradling occurs when a cheerleader is thrown in the air and caught in another cheerleader's arms during a stunt. Cheerleaders' injuries can potentially be prevented or mitigated by modifying the method of catching a flyer and deciding which stunts are safe to perform.[2] A flyer should be caught in a soft cradle by the base in such a way that the base is able to absorbed the shock of the impact safely. There are certain circumstances that can change a base's ability to absorb the impact safely such as when the stunt was not performed correctly causing the flyer to fall erratically. In these instances the bases are simply trying to prevent the flyer from hitting the ground. Pyramid stunts and basket-tosses are some of the most advanced stunts, and they are also the more dangerous due to the height of the stunts. During collegiate football games these are typically performed to get the crowd involved and if done correctly are relatively safe. However, when a pyramid is performed incorrectly, the cheerleaders, especially those on the top, can be seriously injured if they fall because of the height of these stunts. Cheer competitions include a variety of stunts including, basket-tosses, single leg stunts, extensions, pyramids, single based stunts, preps, stunt cradle combinations, transitions, and group stunts.

In 2006, a cheerleader fell from a 15-foot pyramid backwards onto a wooden gym floor during a basketball game onto her neck and head. She sustained a concussion and a chipped cervical vertebra.[2] Her injury raised concern about the dangers of cheerleading. All cheer teams that compete or are run in a school are required to have a certified coach because of the high injury risk associated with this sport. Coaches must have completed the safety certification for stunting to be certified.

Many studies have investigated sport-related concussion and the most commonly associated sports.[25,28,31,32] Surprisingly, previous research has found the practice rate (11.32 per 100,000 exposures) for incident concussions in cheerleading is higher than the game rate (3.38 per 100,000 exposures) which is dissimilar to other most sports, like football, where the game rate (148.84 per 100,000 exposures) exceeds the practice rates

(8.47 per 100,000 exposures).[32] This may be due to the cause of trying new stunts and harder passes during practices, where as in football most full contact is only during games.

To our knowledge, no study exists that specifically analyzes rotational and linear acceleration with the use of sensors in cheerleading. Current research is lacking in the study of the forces produced to the head during cheerleading stunts, cradles, and falls. Accelerometers have been used in other sports such as football and ice hockey. The research for football has grown throughout the years where as cheerleading research has almost subsided. The high injury-risk in cheerleading indicates that this sport still requires further investigations to help improved safety. Head impact biomechanics data as a conduit to track head-related injuries in cheerleading can help improve our understanding of the sport and what activities and positions are associated with the greatest risk.

Improved training techniques and knowledge of biomechanical-related risks can be helpful when learning a new stunt or trying to execute it properly. Preventative techniques such as using a foam pit and trampoline to practice cradles properly are currently being used by many teams. As previously mentioned, stunting is the cause of most head injuries in cheerleading;[2] however, we do not currently know the magnitude or location of these impacts, or if certain stunts are more dangerous than others leading to greater risk. Inclusion of head impact biomechanics into cheer-related research has the potential to have a positive impact on concussion in cheerleading by improving the coaches understanding of position and activity related injury risk.

Collection of head impact biomechanics data would allow researchers to determine the magnitude and location most commonly associated with various stunts during cheer activities. In 2009 Shields and Smith found that a total of 338 out of 567 cheerleaders were injured in a stunt-related activity.[4] Specifically concussions occur more frequently in collegiate cheerleaders than compared to cheerleaders at other levels and are typically due to the difficulty of the stunts they perform.[2,4,5]

Risk of Concussions in Cheerleading

Cheerleading inherently is associated with injury risk due to the height of their stunts. According to a study conducted by Jacobson et al., collegiate cheerleaders have the highest average of 1-2 days lost per injury (26.7) compared to high school cheerleaders.[1] Another study evaluated the association between landing surfaces and injury and traditional foam floors were associated with the greatest risk (39.7%), followed by spring floor (22.5%) and mat (12.7%).[2,6] Concussions in cheerleading are mostly received by collegiate cheerleading teams compared to all other cheerleading squads (RR=2.98).[5] This is a logical finding since as explained above these cheerleaders perform more difficult stunts compared to the non-competitive cheerleaders.

Contributing factors to concussive injuries have been found to include surfaces, stunts being attempted and poor communication.[7] The critical landing height of cheerleaders, which is the minimal height at which cheerleaders are susceptible to critical injury, is 11ft on a foam floor surface.[7] Cheerleaders may reach 11ft high in a pyramid and potentially higher in a basket toss. Since these stunts are so high they fall at a faster speed that may cause higher magnitudes impacts compared to other activities. Another study confirmed that basket tosses and pyramids were the most likely stunts that would result in one cheerleader colliding with another, ultimately causing injury.[3] The various forms of injuries during pyramid stunts resulted from losing balance, getting bumped, dismounting, and falling.[3] Spotters were primarily responsible for the basket toss injuries since they were sometimes unable to properly judge where the cheerleader was going to land. Spotters are primarily in a stunt as a preventive measure to catch the flyer is something goes wrong.

<u>Preventive Measures</u>

Cheerleading is one of the more dangerous sports in the world of athletics.[2] Unlike other sports that wear various forms of protective equipment (helmets, body pads, gloves), cheerleaders wear no protective devices. This is one of the many factors that can put a cheerleader in danger of sustaining an injury. Cheerleaders are more susceptible to injuries because of the various physical requirements of their sport.

Cheerleading has evolved throughout the years in regards to the growing physical demands and expectations of their sport. Cheerleaders used to just jump, perform basic stunts, and clap their hands. Collegiate cheerleaders now perform gymnastic tumbling runs, difficult human pyramids, and basket tosses involving flips in the air.[2,4] The more difficult stunts have been associated with a higher risk for injury.[4] A basic stunt such as a prep for a collegiate cheerleader is easy and the risk of injury is small, but a stunt such as a basket toss is very difficult and the risk for injury increases due to both the height at which the cheerleader is being thrown as well as the impact of the cradle. A recommendation to preventing injuries would be to practice stunts in a foam pit, on a trampoline, with more spots, and practicing in a belt harness. The certification the coaches must complete explains the correct method to determine when to progress stunts. Coaches and cheerleaders must always start with the basics such as preps before moving onto basket tosses and pyramids. This is part of the learning process of new stunts. When cheerleaders skip these steps injuries could take place and potentially have a higher risk of injury. Sensors could be used to help with this injury prevention. The data from the sensor would be able to inform the coaches about what stunts that is associated with greater risk and which cheerleaders may need more practice before attempting more difficult stunts. Cheerleaders may need more practice with cradling and making sure to absorb some of the landing impact which could reduce injury.

Wireless Head Impact Sensor Technology

There is currently no threshold at which a concussion may be sustained. A concussion can happen at various magnitudes and may occur as a result of many different mechanisms. Guskiewicz et al. reported a wide range in linear accelerations (60.51g to 168.71g) resulted in concussive impacts.[33,34] Several other studies have been conducted to determine impact thresholds but this has proven to be difficult since they have all found a wide range of magnitudes (54.9g to 168.71g) have caused incident concussions.[13,17,18,33-40] It is important to note that while incident concussions do not always occur with every impact throughout this range, there is a higher likelihood of receiving a concussion when the impact is around 80g but the lowest reported was 60.51g.[33,34]

Body position has been found to be important when evaluating head impacts in high school football. A study by Cabell et al. concluded that impacts that occur to the top of the head and impacts sustained with poor body position have a higher odds of occurring at a greater magnitude (OR=2.96).[41] Cross et al. found impacts that are coming from a greater distance with poor body position also have a higher risk of a severe head impact (OR=1.66).[42] These studies indicate that reinforcement of proper body position could limit the risk of concussions.[42] Body position and body awareness is important in cheerleading. If one does not have good body awareness in the air they may put themselves and others at risk of injury. Body awareness and correct technique can be problematic for the flyers and bases while learning new stunts. The flyers may loose their balance in the air and fall awkwardly increasing the risk of a collision with a base or being dropped by the base and hitting the floor.

Wireless sensors that have previously been studied are the gForce Tracker™, [17] (HITS), [18-21] X2 mouthguard, [18] Xpatch, [14] and Triax SIM-G.[22-24] Both the HITS system and the X2 mouthguard have been deemed reliable.[18] The HITS system is one of the most commonly used helmet sensor and has a high reliability, but is expensive and it can only be worn in two helmeted sports (football and ice hockey), which limits its ability to be used in helmetless sports such as cheer.[13,18] The X2 mouthguard has reported good validity, but if the teeth are clenched more accurate results are likely.[18] Instrumented mouthguards would be a viable option for this study, but cheerleading has a lot do with their physical appearances and annunciation when cheering and a mouth guard may pose problems when speaking.

The Xpatch is another possible accelerometer option but since they are applied using an adhesive patch behind the ear, it is more likely to become less adhesive the more they sweat and it could get caught in their hair. We were also concerned that it could also be knocked off with direct contact during a stunt, or due to the flyer's extreme accelerations when in the air. Due to these reasons we opted to not utilize the X2 Xpatch.

Finally, the SIM-G is secured in a manufacturer provided Neoprene® headband just around the nuchal line. This headband is fitted to the head and the sensor is situated posterior on the head. Due to the sensor placement and the headband application we determined that it was appropriate head impact biomechanics device for cheerleaders. The sensor is not seen as it is behind the hair, and it does not affect their speech like the mouthguard. The Triax SIM-G system does not require a helmet and will not fall off as a result of heavy perspiration. These are several of the reasons why the SIM-G is the best choice for this study.

<u>SIM-G Sensor</u>

The SIM-G minimum g-force threshold is ≥16g for this accelerometer system to record a possible impact event. Once an impact above this threshold occurs the data is collected via the cloud-based system. Rotational acceleration can be measured accurately from the 3-axis gryo in the SIM-G.[22] Therefore, with a better understanding of the biomechanics of head impacts, as well as the tolerance for human head accelerations, it may help improve safety through head biomechanics information. This information can be used by coaches to determine if particular athletes are at greater risk for injury or if certain activities are potentially unsafe.

The Triax system data includes two different types of impacts. Linear impacts ≥16g to the head or body are registered by the system as impacts. The system also records impacts that it believes were not actual impacts (NIT). The NIT filter is a set of heuristic classifiers that identify characteristics in the impact waveform that typically indicate direct contact with the sensor as opposed to a measured impact to the head. The details of the filter algorithms are proprietary. Direct impacts to the sensor are registered as a NIT impacts.

Validity

The clinical validation of a sensor is important in being able to determine a device's ability detect head impacts in non-laboratory settings. Oeur et al. conducted a study in 2016 to determine the validity of the SIM-G sensor on a Hybrid III headform at 20g's of force.[23] The head impacts included falls onto hard surfaces, helmet-to-helmet collisions, and soccer ball to the head.[23] Impacts from all these events were detected except for helmet-to-helmet collisions and the central of gravity between sides.[23] Although the sensors were only able to detect 24/30 helmet-to-helmet collisions, the SIM-G sensors used in the study were still deemed reliable based on all other detection capabilities.

Karton et al. compared a SIM-G sensor to a Hodgson-WSU headform in 2016.[24] The researchers concluded that the SIM-G was more accurate at monitoring low force level similar to the headform.[24] Karton et al. concluded that the SIM-G has a tendency to overestimate impact magnitudes which in turn makes it a more conservative on-field tool in measuring head impacts and trauma load to the head.[24] Over-estimation of an impact magnitude is more desirable than underestimation clinically because the system is typically reporting the "worst-case-scenario". If high magnitude impacts are of concern for elevated concussion risk, a higher magnitude impacts are more likely to draw the attention of clinicians and encourage them to assess those athletes. Under-estimations could result in the reverse effect and athletes who had sustained blows in the concussive ranges may go unchecked. Although accelerometer systems do not detect concussions they can increase awareness of potentially injurious impacts resulting in better healthcare for the athletes.

The Hodgson-WSU (NOCSAE) headform has a similar dimension and weight to that of a real human head. The Hodgson-WSU and the Hybrid III are the two most commonly used headforms to assess the validity and reliability of various head impact sensor systems. A study conducted by Campbell et al. placed a SIM-G on a Hodgson-WSU headform to determine its reliability and validity.[16] Internal validation of the SIM-G was performed at the Neurotrauma Impact Science Laboratory at the University of Ottawa.[22] The Hodgson-WSU headform has 9 single axis linear accelerometers that are placed at the center of gravity of the headform. A SIM-G was secured to the headformjust around the nuchal line. The headform was impacted with a pendulum system at eleven different impact locations and across three different energy levels. The peak resultant acceleration for each impact waveform was compared with that of the instrumented headform. The results determined the SIM-G accurately reports linear acceleration (r^2=0.84) and rotation acceleration (r2=0.78).[30, 31] These data suggest that SIM-G can consistently record the rotational and linear accelerations of the head during movement.[16]

Data Recording

In a rugby study conducted by McIntosh et al., they analyzed game impact kinematics using Video Home System (VHS) video.[43] The position of the video camera was 20m perpendicular to the runway and moved parallel to the runway during activity.[43] McIntosh, et al. estimated about a 10% error in the speed estimates of the VHS.[43] The video allowed them determine the validity of the SIM-G location and speed data, but also to determine the nature of the impact.[43] Inclusion of the impact nature allowed the researchers to determine how the impact occurred and the athlete's body position at the time of impact. They also used WinAnalyze software to identify the coordinates during the impact.[43] Throughout their study the researchers were able to gather data on 100 cases of concussions of which 97 resulted from direct contact with the athlete's heads from striking other athlete's bodies.[43]

Head impact biomechanical measurements have been collected in several sports to detect concussion-like forces, but they have never been used to monitor cheerleading activities.[15-24,38,39,41,42] Using these accelerometers could benefit cheerleaders and coaches by determining what cheer activities are associated with the greatest magnitudes, impact locations, and the underlying causes of these forces (i.e., specific stunts, technique). This research could potentially help the International Cheer Union determine if rule changes may improve safety and what preventive measures may help decrease injury risk, such as making sure the cheerleaders perfect their stunts and tumbling before progressing to more difficult maneuvers.

Summary

Collegiate competitive cheerleading teams are more likely to receive an injury compared to other cheerleading teams. Collegiate cheerleaders perform stunts that are more complex, on a variety of surfaces, and the tumbling passes they perform are more extreme. In particular, basket tosses and pyramids are the most common stunts associated with cheer-related injuries. In addition, routines that require more athletes to perform simultaneously are also associated with greater injury risk due to increased likelihood of collisions.

The SIM-G headbands are the most appropriate sensors when trying to measure head impact biomechanical forces during cheerleading due to their shape, weight, and being helmetless in nature (headband). Measuring the validity of this sensor in a clinical setting is important, as it has only been researched in a controlled laboratory setting. Clinical settings involve many factors that cannot be controlled (human error, body-to-body collisions) when attempting to collect head impact biomechanical data. It is important to conduct this type of research to determine the clinical feasibility, validity, and reliability of these devices overall, but also for specific sports/activities. As a result, this study is the first step in determining the feasibility, validity, and reliability of the Triax SIM-G sensor in competitive cheerleading.

III. METHODS

Design

This pilot study was a prospective cohort repeated measures design. Head and body impacts were recorded over 8 collegiate competitive cheer practices by SIM-G sensors (Triax Technologies Inc., Norwalk, CT USA) during the competitive season. The SIM-G sensors measured linear (g) and rotational (rad/sec^2) accelerations and were utilized during a 3-week time period. The researchers attended all practices. The independent variables in the study were activity, positions, location, correct, and landing. The outcome variables in the study was the clinical validity and reliability of the SIM-G sensor during cheer-related activities. Data for the SIM-G sensors and video verified potential impact events will be stored up to three years on a University password protected computer.

Participants

Members (age range: 18-24 years) of the Texas State University competitive cheer team were asked to volunteer for this research study. The Texas State University Institutional Review Board approved this study prior to participant enrollment. Inclusion criteria can be found on Table 1.

Table. 1 Inclusion Criteria

Inclusion Criteria
Collegiate competition cheerleaders
All gender
Ages 18-24
Actively participating in practice at the start of the study

The researchers explained the purpose of this study to the participants prior to data collection during a team recruitment meeting. Volunteers (n= 26) who satisfied the inclusion criteria gave written consent prior to participation in any part of this study. The data for each participant were obtained over 3 weeks of competition cheerleading practices at a university athletic gym and a cheer gym. During the first three practices, each cheerleader was assigned a different sensor for each practice. The participants were assigned the same sensor for the remaining five practices. This sensor recoded impacts that occurred during practices and video was used to confirm potential impact events.

Triax Smart Impact Monitor – G (SIM-G) System

The SIM-G sensor is designed to measure rapid head movement that is often characteristic of head impacts that are associated with sport-related concussion. Researchers use these sensors to monitor potentially injurious head impacts that athletes experience during practices and games. The Triax SIM-G uses a 3-axis accelerometer and Gyro to obtain linear and rotational impact measurements. The SIM-G minimum linear acceleration threshold for this study was 16g.[22] Linear acceleration is measured by G-force (g) where as rotational acceleration is measured in radians per seconds squared (rad/s^2). Linear acceleration is the rate of change of velocity without a change in direction. Rotational acceleration is the change in angular velocity that a spinning object undergoes per unit time.

The information from the wireless sensor is transmitted to a SKY-I sideline aggregator (Figure 1). Impact data is transmitted within 20 milliseconds to the SKY-I. If the SKY-I is connected to the internet, the data is then transmitted to a cloud-based system allowing for instant notifications of high impact events.[22] The SKY-I receives all impact data (magnitude, location, and duration) from the sensors. All recorded impacts are time and date stamped. The data from the sensors are stored securely on the Triax cloud-based system where it can be accessed, downloaded, and then analyzed by a research team.

The SIM-G is a comparatively new sensor that has yet to be verified by independent researchers for reliability in clinical settings. Without verification of measures by independent researchers, the true utility of this important wearable technology may lead to mis-interpretations of the data.

Figure 1. SKY-I

Instrumentation of the Smart Impact Monitor – G (SIM-G) System

All participants were assigned a SIM-G sensor as well as an appropriately sized headband. The SIM-G was secured in a manufacturer provided Neoprene® headband just around the nuchal line (Figure 2-5). Athletes wore the device during 8 practice sessions. None of the cheerleaders reported that the device negatively affected their performance at practice. Each SIM-G sensor was handed out to each participant at the beginning of each practice and collected by the researchers after practice. Following practices the information from the SKY-I that was downloaded from the Triax cloud-based system to an excel sheet.

The Triax system data is determined by the location of the impact to the head. The circumference is divided into eight equal sections of 22.5 degrees (front, front right, front left, left, right, back left, back right, back). There were two additional locations crown and base. Crown was determined by elevation greater than 45 degrees. Base was any impact that results in a primarily upward acceleration to the head and less than -45 degree.

Figure. 2 Front view Triax SIM-G sensor placement in custom head

Figure 3. Back view Triax SIM-G sensor placement in custom headband

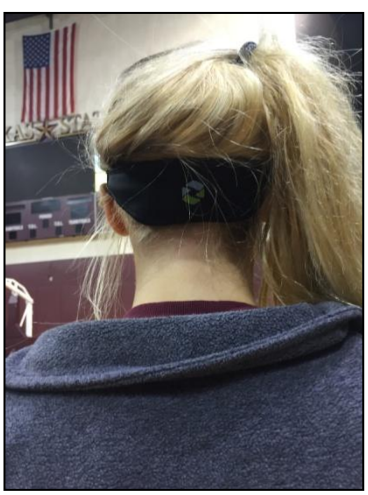

Figure. 4 Correct Triax SIM-G headband placement back view

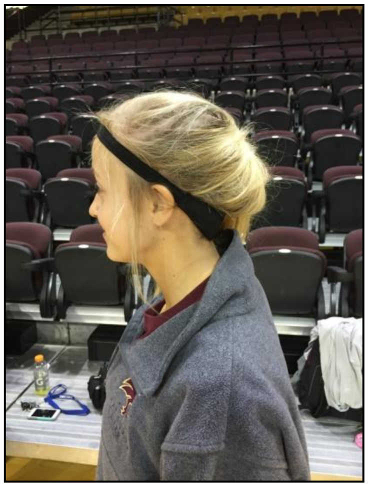

Figure 5. Correct Triax SIM-G headband placement side view

Video Analysis

Our study compared video recordings of the practices with the SIM-G data gathered during the same cheerleading practices. In order to confirm if a sensor correctly identified a head impact and the impact location we employed the use of a sideline video camera to provide recorded evidence to determine if head movement and/or head/body impacts occurred as reported by the SIM-G. The video recorder was time synced with the SIM-G. When video analyses were performed the researchers watched video and matched it with impact times to determine if a possible impact event may have occurred.

A Sony Handycam video camera (Tokyo, Japan) was used to video all cheer practices. The video camera recorded 60 frames per second. The camera was placed 20 feet in front of the practice area in the university gym (Figure 6) and 20 feet diagonal to the practice mat in the cheer gym (Figure 7). The camera was used during every practice that the cheerleaders wore the SIM-G sensors. The tripod of the video camera sat at 4 feet 1 inch tall. The tripod sat this tall and the camera is placed 20 feet away to ensure a complete view of the practice area. The video was time and date synced with the SIM-G sensors. This was important because it helped improved the researchers' ability to match the sensor data to the video data. The video did have a time stamp on the camera but when it was transferred over to a university computer it was no longer available. To correct for this, the researchers recorded what time it was when they started filming each practice and when each practice ended. They also recorded the time each sensors was registered with a hit according to the SKY-I.

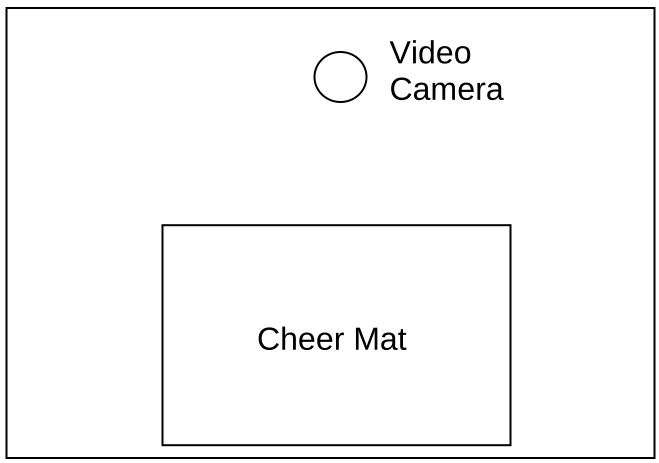

Figure. 6 Camera Placement University Athletic Gym

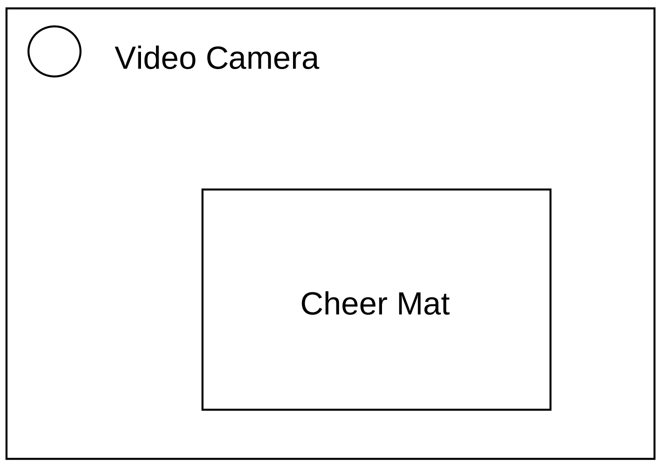

Figure. 7 Camera Placement Cheer Gym

Video footage was used to confirm the validity and reliability of the SIM-G sensors for both impact incidence and impact location. The video verified impact sites recorded by the researchers included top, front, and back of head as well as the right or left side. Researchers determined front as an impact on the front of the head before hairline from either side of anterior mid-sagittal plane. Top was determined as an impact above the forehead-hairline junction and above the top of the ears. Side was any anterior or posterior impact posterior to the face and anterior to the posterior angle of the head. Back was any impact posterior to the ears. Body was any impact to the body. None was classified as no impact to the body or the head (e.g., athlete removed their headband, headband came off). None was expected to be the most common location because even through a participant may have been included in an activity; they typically do not sustain impacts to their head or body.

One excel spreadsheet was used to record additional information during every practice time. The assignment table contained information about the sensor number, and the participants' name, position, and gender (Table 2). Initially the cheerleaders were assigned different sensors for each practice, then after three practices our procedures were altered so that the cheerleaders were assigned the same sensor for the remainder of the study to improve consistency and reduce experimenter error.

Table 2. Sensor Assignment

Name	**Position**	**M/F**	**Date** **Sensor**	**Date** **Sensor**	**Date** **Sensor**	**Date** **Sensor**

Stunting has been found to have the highest likelihood of receiving a concussion in cheerleading.[2] Figure 8-10 shows two different types of cradles, one from a basket toss and one from a double down. A double down is when the flyer completes two 360° twists and lands in a piked position in a cradle. Both stunts end in the same position. Notes were taken in real time during practices to help researchers know if and when they identified a potential impact event to assist them when reviewing the video. The video was also analyzed to verify the participant and their sex, and to determine the activity, if correct technique was used for each maneuver (good, bad), the landing force (hard, soft), and to compare the impact location identified on the film (top, front, right, left, back) to the SIM-G data.

An example of a stunt that was performed with correct technique would be a stunt where the participant did not fall short and was cradled or brought down under full control of the bases. Conversely, if a cheerleader fell and hit the ground it was classified as poor technique. This grading of performance applied to tumbling as well. If the tumbler fell half way through the tumbling pass, the SIM-G was more likely to record an impact. Landing was classified as soft, hard, fall, or not applicable meaning it was not related to stunting or tumbling and didn’t fall into one of the assigned categories. A soft landing was a cradle and/or tumbling pass that landed in a controlled manner with good absorption of the landing forces. A hard landing meant that the cradle and/or tumbling ended abruptly and with ineffective absorption of the landing forces.

Figure. 8 Basket toss pre-cradle **Figure 9. Double down pre-cradle**

Figure 10. Cradle

Statistical Analysis

Non-parametric chi-square analyses were utilized to determine the reliability and validity of the SIM-G data compared to the video verified potential impact events. The impacts collected were compared to two or more categorical data that have been arranged into nine categories. SAS 9.4 (SAS Institute Inc. Cary, NC) was used for all statistical tests.

IV. RESULTS

Twenty-six collegiate competition cheerleaders initially participated in the study (females=20). Due to attrition only 20 participated in all 8sessions. A total of 1048 possible impact events were identified over these 8 practice sessions. After exclusion of the SIM-G impacts that could not be verified through video analyses (n=89) we included 959 possible impact events in our final analyses. The two most common positions involved in possible impact events were the main bases (19.8%) and flyers (19.5%) while stunting (72.6%) was the most common activity. No concussions were reported during this study. Almost 85% (n=811) of the stunts and tumbling passes were performed using correct technique, and nearly 50% of the landings were graded as being soft (n=472). Two different methods were utilized to identify impact location: the Triax impact sensor data and video confirmation. The video locations most commonly reported were none (77.9%), followed by body (12.3%). The most common Triax impact site was the crown (36.9%) (Table 3).

Chi-Square was run on all the factors that could have had an influence on the impact data. These factors included sex, position, activity, correct technique, landing, and location (Triax and video verified). Table 8 presents the frequency and percentages for these variables.

Table 3. Video and Triax Impact Locations

Video Location	Total n (%)	Female's n (%)	Triax Location	Total n(%)	Female's n(%)
Front	7 (0.7)	6 (0.7)	Back	30 (9.4)	28 (9.2)
Back	51 (5.3)	43 (5.2)	Back Left	4 (1.3)	4 (1.3)
Top (crown)	24 (2.5)	21 (2.5)	Back Right	8 (2.5)	7 (2.3)
Left	9 (0.9)	5 (0.6)	Base	47 (14.7)	43 (14.1)
Right	3 (0.3)	3 (0.4)	Crown	118 (36.9)	114 (37.3)
Body	118(12.3)	118 (14.2)	Front	54 (16.9)	52 (17.0)
None	747 (77.9)	638 (76.6)	Front Left	16 (5.0)	16 (5.2)
			Front Right	22 (6.9)	21 (6.9)
			Left	14 (4.4)	14 (4.6)
			Right	7 (2.19)	7 (2.3)
Total	**959(100)**	**834 (86.97)**	**Total**	**320 (100)**	**306 (95.6)**

Table 4. Cheer-Related Head Impact Factors

Position	Total n(%)	Females n (%)	Real Impact n (%)
Back	126 (13.1)	85 (10.2)	1 (1.0)
Main Base	190 (19.8)	120 (14.39)	5 (5.0)
Secondary Base	162 (16.9)	156 (18.7)	2 (2.0)
Flyer	187 (19.5)	186 (22.3)	17 (17.0)
Spotter	38 (3.96)	38 (4.6)	1 (1.0)
Tumbling	167 (17.4)	167 (20.0)	56 (56.0)
N/A	89 (9.28)	82 (9.83)	18 (18.0)
Activity			
Tumbling	167 (17.4)	167 (20.0)	53 (53.0)
Stunting	696 (72.6)	578 (69.3)	22 (22.0)
Dance	10 (1.0)	10 (1.2)	0 (0)
Not Related	85 (8.9)	77 (9.2)	24 (24.0)
Jumping	1 (0.1)	1 (0.1)	1 (1.0)
Correct			
Yes	811 (84.6)	696 (83.5)	63 (63.0)
No	31 (3.2)	28 (3.4)	4 (4.0)
N/A	117 (12.2)	110 (13.2)	33 (33.0)
Landing			
Soft	472 (49.2)	404 (48.4)	5 (5.0)
Hard	309 (32.2)	263 (31.5)	51 (51.0)
N/A	143 (14.9)	136 (16.3)	39 (39.0)
Fall	35 (3.65)	31 (3.7)	5 (5.0)
Total	**959(100)**	**834(86.97)**	**100 (100)**

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V. MANUSCRIPT

RELIABILITY OF THE TRIAX SMART IMPACT MONITOR – G SYSTEM ON HEAD IMPACTS IN COLLEGIATE CHEERLEADERS

Ashley Allenstein, MS; Darcy Downey, DEd; Melissa Fraser, PhD

*Texas State University, San Marcos, TX

Abstract

Context: Throughout the years cheerleading has evolved from basic maneuvers to more complex activities, resulting in a higher risk for injury. Currently no cheer-related head impact biomechanics studies exist.

Objective: This study is aimed at verifying the reliability and validity of the Triax Smart Impact Sensor-G (SIM-G), in competitive collegiate cheerleading.

Design: Prospective Cohort Repeated Measures Design

Setting: Clinical setting.

Patients or Other Participants: Collegiate cheerleaders ages 18-24.

Interventions: 26 competitive collegiate cheerleaders wore Triax SIM-G accelerometers for 8 practices. All practices were filmed.

Main Outcome Measurements: Triax data included impact frequency, location, linear (g) and rotational acceleration (rad/s2). Additional data gathered from the video analysis included: sex, activity, position, location (video verified), correct technique, and landing technique.

Statistical Analysis: Non-parametric chi square.

Results: No concussions occurred during data collection. Using video comparison the sensitivity of the SIM-G was 98.0% and the specificity was 99.2%, suggesting that this system is valid and reliable. The most common position that had a possible impact event was the main base followed by the flyer. Stunting was the number one activity that had the most possible impacts. Body was the most common location as determined by video analysis followed by the back of the head. The most frequent impact location reported by Triax was the crown.

Conclusion: The SIM-G sensor was determined to be a reliable sensor in the clinical setting for competition cheerleading. This is the first study to research the cheerleading impacts with the use of sensors

Word Count: 245

Key Words: video analysis, stunting, SIM-G

<u>Introduction</u>

The early roots of cheerleading (i.e., cheer) involved a group of participants encouraging spectators to cheer in support of their sports team. However, over the years cheer has evolved from basic maneuvers such as jumps and clapping to more competitive activities with acrobatic, gymnastic-like tumbling and stunts such as pyramids and basket tosses.[1]

Cheerleading has evolved from to an entertainment sport now focused on increasing difficulty of stunts and tumbling maneuvers, ultimately increasing the risk of injury.[1-7] Cheerleading is often overlooked as a competitive sport in the athletics world, as cheerleading is considered a feminine activity. Cheer has many inherent risks as demonstrated by the number of cheer injuries increasing two fold from 10,900 injuries in

1990 to 22,900 injuries in 2002 with an average of 16,100 (95% CI: 12,848-19,352) injuries per year. [2,7,8] Stunts have been the main cause for all cheer-related injuries.[1] When looking at concussions in particular, both collegiate cheerleaders and collegiate competition cheerleaders are 3.1 times more likely to sustain a concussion compared to other cheer squads at various levels (including, middle school, high school, and All-Star teams).[3]

In the last few decades, concussions have become an important issue in the athletics with an estimated 1.6 million occurring each year, [9] and are one of the most common injuries among collegiate cheerleaders.[3] In 2012, the national center for catastrophic sport injury conducted research on all sports and compared to all female sport injuries, collegiate cheerleading had the highest rate of direct catastrophic injuries (71.2%) compared to all collegiate female sports injuries over a 30-year time span.[8]

In the last 10 to 15 years research has increased using various head impact biomechanics accelerometer systems to detect the linear (g) and rotational (rad/sec^2) accelerations the head and body receive during an activity.[11-16] Accelerometers that have recently been studied include the gForce Tracker ™ (Gforcetracker Inc., Ontario),[17] Head Impact Telemetry System (HITS) (Riddell, Chicago, IL), [11,12,18-20] X2 mouthguard (X2 Biosystems, Seattle, WA),[14] Xpatch (X2 Biosystems, Seattle, WA),[21] and Smart Impact Monitoring-G (SIM-G) system (Triax Technologies Inc., Norwalk, CT).[16,22-24] These accelerometer-based sensors are constantly evolving in shape, placement, capabilities, and user friendliness; however, they all are programmed to detect impacts to the head and body and report the general impact location and associated forces. A study by Siegumd et al. reported that the HITS sensors detected 861 out of the 896 impacts

(96.1%) and the X2 XPatch detected 845 out of the 896 (95.4%). Linear and rotational acceleration are common measurements recorded by head impact biomechanics sensors. Cheerleaders are constantly changing the direction of their body and they do not wear helmets; therefore using a helmetless sensor would be the most effective device at providing accurate data for these athletes.

Cheerleading is a high-risk sport for concussions, but there is a dearth of research investigating the biomechanics of their injuries. Competitive cheerleaders do not wear helmets and often are required to move in complex patterns (flipping, twisting) throughout their routines. Therefore, light, helmetless sensors, like the Triax SIM-G, are necessary to accurately capture their head motion in order to determine risk and improve safety. To our knowledge, there currently are no field-based reliability studies assessing the Triax SIM-G sensors in cheerleading. It is important to verify the ability of these sensors to consistently measure head impacts/rapid head movements during competitive cheer practices to improve our understanding of concussion risk in cheer. Therefore, the purpose of this study is to verify the reliability and validity of the SIM-G helmetless head impact biomechanics accelerometer system during competitive cheer practices.

Methods

Design

This pilot study was a prospective cohort repeated measures design. Head and body impacts were recorded over 8 collegiate competitive cheer practices by SIM-G sensors (Triax Technologies Inc., Norwalk, CT USA) during the competitive season. The SIM-G sensors measured linear (g) and rotational (rad/sec^2) accelerations and were utilized during a 3-week time period. The researchers attended all practices. The independent variables in the study were activity, positions, location, correct technique, and landing. The outcome variables in the study were the clinical validity and reliability of the SIM-G sensors during cheer-related activities.

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The SIM-G sensor is designed to measure rapid head movement that is often characteristic of head impacts that are associated with sport-related concussion.

Researchers use these sensors to monitor potentially injurious head impacts that athletes experience during practices and games. The Triax SIM-G uses a 3-axis accelerometer and Gyro to obtain linear and rotational impact measurements. The SIM-G minimum linear acceleration threshold for this study was 16g.[22] Linear acceleration is measured by G-force (g) where as rotational acceleration is measured in radians per seconds squared (rad/s^2). Linear acceleration is the rate of change of velocity without a change in direction. Rotational acceleration is the change in angular velocity that a spinning object undergoes per unit time.

The information from the wireless sensor is transmitted to a SKY-I sideline aggregator (Figure 1). Impact data is transmitted within 20 milliseconds to the SKY-I. If the SKY-I is connected to the internet, the data is then transmitted to a cloud-based system allowing for instant notifications of high impact events.[22] The SKY-I receives all impact data (magnitude, location, and duration) from the sensors. All recorded impacts are time and date stamped. The data from the sensors are stored securely on the Triax cloud-based system where it can be accessed, downloaded, and then analyzed by a research team.

The SIM-G is a comparatively new sensor that has yet to be verified by independent researchers for reliability in clinical settings. Without verification of measures by independent researchers, the true utility of this important wearable technology may lead to mis-interpretations of the data.

Figure 1. SKY-I

Instrumentation of the Smart Impact Monitor – G (SIM-G) System

All participants were assigned a SIM-G sensor as well as an appropriately sized headband. The SIM-G was secured in a manufacturer provided Neoprene® headband just around the nuchal line (Figure 2-5). Athletes wore the device during 8 practice sessions. None of the cheerleaders reported that the device negatively affected their performance at practice. Each SIM-G sensor was handed out to each participant at the beginning of each practice and collected by the researchers after practice. Following practices the information from the SKY-I that was downloaded from the Triax cloud-based system to an excel sheet.

The Triax system data is determined by the location of the impact to the head. The azimuth and elevation is determined from the acceleration vector. If the elevation is greater than 45 degrees, the location is marked as 'crown', and if elevation is less than -45 degrees, it is labeled 'base'. For all other directions, the azimuth is placed into one of 8 equal 22.5-degree locations. These locations are starting at the front and moving clockwise as seen from the top of the head looking down: 'front', 'front right', 'right', 'back right', 'back', 'back left', 'left', 'front left'.

Figure. 2 Front view Triax SIM-G sensor placement in custom head

Figure 3. Back view Triax SIM-G sensor placement in custom headband

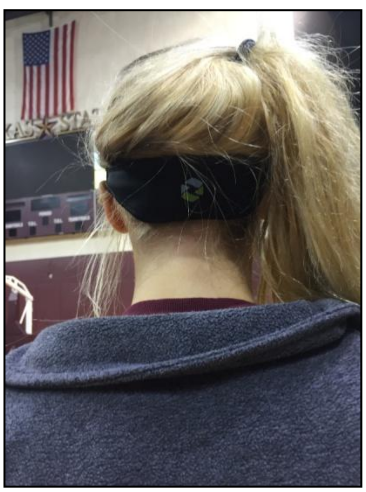

Figure. 4 Correct Triax SIM-G headband placement back view

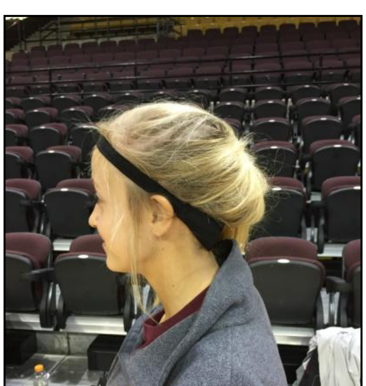

Figure 5. Correct Triax SIM-G headband placement side view

Video Anaylsis

Our study compared video recordings of the practices with the SIM-G data gathered during the same cheerleading practices. In order to confirm if a sensor correctly identified a head impact and the impact location we employed the use of a sideline video camera to provide recorded evidence to determine if head movement and/or head/body impacts occurred as reported by the SIM-G. The video recorder was time synced with the SIM-G. When video analyses were performed the researchers watched video and matched it with impact times to determine if a possible impact event may have occurred.

A Sony Handycam video camera (Tokyo, Japan) was used to video all cheer practices. The video camera recorded 60 frames per second. The camera was placed 20 feet in front of the practice area in the university gym (Figure 6) and 20 feet diagonal to the practice mat in the cheer gym (Figure 7). The camera was used during every practice that the cheerleaders wore the SIM-G sensors. The tripod of the video camera sat at 4 feet 1 inch tall. The tripod sat this tall and the camera is placed 20 feet away to ensure a complete view of the practice area. The video was time and date synced with the SIM-G sensors. This was important because it helped improved the researchers' ability to match the sensor data to the video data. The video did have a time stamp on the camera but when it was transferred over to a university computer it was no longer available. To correct for this, the researchers recorded what time it was when they started filming each practice and when each practice ended. They also recorded the time each sensors was registered with a hit according to the SKY-I.

The video was used to confirm impact location by viewing the videos multiple times to slow down the frames to determine if an impact actually occurred at the time the Triax registered an impact. When participants went out of the video frame researchers graded those impacts as ‘unsure’ since we were not able to identify what happened. A body impact was any impact to the body. Potential impact events that were not associated with an impact to the body or head were classified as “none” (e.g., athlete removed their headband, headband came off). This was done to help compare actual impacts with the Triax. It was done by syncing the video and the Triax at the same time for every practice. We wanted to compare Triax and video locations to see if there were any discrepancies between the two. Using some of the same impact locations helped decrease the discrepancies.

Statistical Analysis

Non-parametric chi-square analyses were utilized to determine the reliability and validity of the SIM-G data compared to the video verified potential impact events. The impacts collected were compared to two or more categorical data that have been arranged into nine categories. SAS 9.4 (SAS Institute Inc. Cary, NC) was used for all statistical tests.

<u>Results</u>

Twenty-six collegiate competition cheerleaders initially participated in the study (females=20). Due to attrition only 20 participated in all 8sessions. A total of 1048 possible impact events were identified over these 8 practice sessions. After exclusion of the SIM-G impacts that could not be verified through video analyses (n=89) we included 959 possible impact events in our final analyses. The two most common positions involved in possible impact events were the main bases (19.8%) and flyers (19.5%) while stunting (72.6%) was the most common activity. No concussions were reported during this study. Almost 85% (n=811) of the stunts and tumbling passes were performed using correct technique, and nearly 50% of the landings were graded as being soft (n=472). Two different methods were utilized to identify impact location: the Triax impact sensor data and video confirmation. The video locations most commonly reported were none (77.9%), followed by body (12.3%). The most common Triax impact site was the crown (36.9%) (Table 3).

Chi-Square was run on all the factors that could have had an influence on the impact data. These factors included sex, position, activity, correct technique, landing, and location (Triax and video verified). Table 8 presents the frequency and percentages for these variables.

Table 2. Cheer-Related Head Impact Factors

Position	Total n(%)	Females n (%)	Real Impact n (%)
Back	126 (13.1)	85 (10.2)	1 (1.0)
Main Base	190 (19.8)	120 (14.39)	5 (5.0)
Secondary Base	162 (16.9)	156 (18.7)	2 (2.0)
Flyer	187 (19.5)	186 (22.3)	17 (17.0)
Spotter	38 (3.96)	38 (4.6)	1 (1.0)
Tumbling	167 (17.4)	167 (20.0)	56 (56.0)
N/A	89 (9.28)	82 (9.83)	18 (18.0)
Activity			
Tumbling	167 (17.4)	167 (20.0)	53 (53.0)
Stunting	696 (72.6)	578 (69.3)	22 (22.0)
Dance	10 (1.0)	10 (1.2)	0 (0)

Not Related	85 (8.9)	77 (9.2)	24 (24.0)
Jumping	1 (0.1)	1 (0.1)	1 (1.0)
Correct			
Yes	811 (84.6)	696 (83.5)	63 (63.0)
No	31 (3.2)	28 (3.4)	4 (4.0)
N/A	117 (12.2)	110 (13.2)	33 (33.0)
Landing			
Soft	472 (49.2)	404 (48.4)	5 (5.0)
Hard	309 (32.2)	263 (31.5)	51 (51.0)
N/A	143 (14.9)	136 (16.3)	39 (39.0)
Fall	35 (3.65)	31 (3.7)	5 (5.0)
Total	**959(100)**	**834(86.97)**	**100 (100)**

Table 3. Video and Triax Impact Locations

Video Location	Total n (%)	Female's n (%)	Triax Location	Total n(%)	Female's n(%)
Front	7 (0.7)	6 (0.7)	Back	30 (9.4)	28 (9.2)
Back	51 (5.3)	43 (5.2)	Back Left	4 (1.3)	4 (1.3)
Top (crown)	24 (2.5)	21 (2.5)	Back Right	8 (2.5)	7 (2.3)
Left	9 (0.9)	5 (0.6)	Base	47 (14.7)	43 (14.1)
Right	3 (0.3)	3 (0.4)	Crown	118 (36.9)	114 (37.3)
Body	118(12.3)	118 (14.2)	Front	54 (16.9)	52 (17.0)
None	747 (77.9)	638 (76.6)	Front Left	16 (5.0)	16 (5.2)
			Front Right	22 (6.9)	21 (6.9)
			Left	14 (4.4)	14 (4.6)
			Right	7 (2.19)	7 (2.3)
Total	**959(100)**	**834 (86.97)**	**Total**	**320 (100)**	**306 (95.6)**

Table 4. Video versus Triax Impact Incidence

		Triax SIM-G				
Video	Video Confirmed Potential Impact Event	Real Impact	NIT	No Impact Recorded	Total	
	No	2 0.21 0.30 2.00	27 2.82 4.07 12.27	635 66.21 95.63 99.37	664 69.24	Frequency Percent Row Percent Column percent

	Yes	98 10.22 33.22 98.00	193 20.13 65.42 87.73	4 0.42 1.36 0.63	295 30.76	
	Total	100 10.43	220 22.94	639 66.63	959 100.00	

Row percent is the % of total impacts that occurred in that row for each cell
Column percent is the % of total impacts that occurred in that column for each cell

Table 5. Means, and Standard Deviations for the SIM-G Real Impacts versus NIT Impacts

Impact Type	# Obs	Variable	N	Mean	Std Dev	Min	Max
Real Impact	100	Linear Acceleration (g) Rotational Acceleration (krad/s^2)	100 100	42.4 5.6	15.9 2.6	17.7 0.9	99.4 13.3
NIT Impact	220	Linear Acceleration (g) Rotational Acceleration (krad/s^2)	220 220	45.6 4.9	19.8 3.4	17.4 0.6	117.2 17.1

Table 6. Triax Impacts Locations

	Video Location	Triax Location	Triax Location Merged
Top/Crown	8	38	38
Front	2	8	16
Front Left		4	
Front Right		11	
Back	12	10	14
Back Left		2	
Back Right		5	
Left	3	6	9
Right	1	2	9
Base/Body	40	14	14
None	34		

Locations were merged together to get a better comparison of the Triax and the video location.

Discussion

This is the first study to investigate the reliability and validity of the Triax SIM-G sensors in a cheer-related clinical setting. Our data show that the sensitivity of the SIM-G was 98.0% and the specificity was 99.2%, suggesting that this system is valid and reliable in this enviroment. The researchers identified 4 (0.4%) possible impact events that the SIM-G did not record as an impact. Thus we feel that the SIM-G is an acceptable sensor in determining head impacts in this population. The use of video confirmation allowed the reserachers to determine the relationship between several cheer-related factors (position, activity, correct, landing, video location, and Triax location) and the SIM-G data (Table 2).

Previous studies using the HITS and X2 mouthguard were able to detect 96% of impacts.[17] The SIM-G was able to detect 98.0% of possible impact events in this study. Our data show the Triax SIM-G is comparable to the HITS and X2 mouthguard in impact detection. Future research should consider using the SIM-G sensor in other sports to examine the validity of the SIM-G in those activities. Due to our small competive collegiate sample size and brief data collection period our data is not generalizable to all cheerleading groups and may only be reflective of the weeks leading up to national competitions. The authors recommend future studies include a wider age range and various levels of cheer. In addition, our data are not generalizable to other sporting event, thus future studies should also include other sports to determine if these sensors are reliable and valid in those clinical settings. In this study the sensors were easy to use and rarely experienced problems with them. The only problem the researchers had was that the headband would occasionally come off when a cheerleader was performing a tumbling pass. This should not be a problem for helmeted sports since the headband should stay in place under the helmet.

This pilot study was limited to Texas State University male and female competition cheerleaders. Our data collection took place over 8 practice sessions and did not represent an entire season. Research has shown that stunts are the most common risk of injury. Our video confirmation data show that stunts represented 696 of 959 potential impact events, which suggests that stunts may either 1) be the most dangerous due to high magnitudes, or 2) injuries occur more frequently during stunting because it is the most common activity. Future research should investigate these relationships.

Three hundred and twenty possible impact events were recorded and documented by the SIM-G and/or the video recordings. Out of those 320, only 100 (31.25%) were recorded as real impacts by the SIM-G sensor and confirmed by the video. NIT impacts comprised 68.75% of the SIM-G sensor data. 220 NIT possible impact events were recorded by the SIM-G and the video confirmed 193 of those possible impacts. The authors believe these impacts may have been classified as NITs due to the nature of the sport. The NIT impacts were classified as impacts that were a direct hit to the sensor. The researchers verified through video analysis that 39 of these NIT impacts occurred when the participant hit the back of their head (Triax sensor) on the shoulder, chest, or arm of another cheerleader. This finding indicates the Triax system may misclassify impacts as NIT leading to an underestimation of impact frequency, especially for flyers. This should be taken into consideration by researchers, clinicians, and cheer coaches if they are trying to determine impact frequency or impact location without video confirmation.

The mean g-force for this study was 42g and the range was 17.7-99.1g. These numbers are comparable to linear accelerations mean reported in football studies (59.1),[19] thus giving support the cheerleading being classified as a high-risk sport and also why they are at risk for incurring serious injuries.

The linear acceleration for the 100 real and 220 NIT video confirmed impacts averaged 42.4g. and 45.6g, respectively. The rotational acceleration for the 100 real and 220 NIT impacts was 5.6 krad/s^2 and 4.9 krad/s^2, respectively. These differences cannot be explained by our data, but future research should investigate if the nature of these impacts differs in location, activity, or position.

Athlete positioning within a routine is an important factor in a cheerleading performance. The main bases and flyers are some of the most important positions. The main base must support the majority of the flyer’s weight during tosses and catches, while the flyer is the individual performing the potentially dangerous and difficult stunts in the air. In this study, these two positions were also the most likely to receive an impact. Interestingly there was not much of a difference between positions in impact frequency. Main bases accounted for 190 (19.8%) of the possible impact events and flyers recorded 187 (19.5%) possible impact events, followed by the secondary base 162 (16.9%) and tumblers 167 (17.4%) positions. The impact frequency for the bases and flyers most likely did not differ much since they are the primary stunt positions resulting in frequent contact between them. Not surprisingly, the spotters had the lowest possible impact event frequency (38/959) with only one impact being recorded by the SIM-G sensors. We believe this is because this position does not play a critical role in stunting. Of the real impacts classified by the SIM-G, tumblers were associated with the highest amount of impacts (n=56) for the positions, followed by the flyers (n=17), and main bases (n=5). In previous studies stunting has been determined to be the primary cause of most injuries with the flyers incurring the most injuries. However, our data show that that the tumblers sustained the greatest number impacts registered by the SIM-G sensors. This could be due to the high number of NIT impacts in the flyer group from direct impacts to the SIM-G, or it could be related to differences in the linear and rotational accelerations generated during their position-related activities. Future research should investigate this further.

Our data found activity-related differences in competitive cheer practices. As previous studies suggested, stunting was the most common activity. This finding is not surprising since four to five people are included in a stunt, whereas only one person may be tumbling or dancing at any given moment. Stunts comprised the majority (72.6%) of the possible impact events. This supports previous research indicating that stunts are the main cause for head injuries in cheerleading.[1,5] Tumbling accounted for 158 (16.5%) of the possible impact events. When tumbling, these cheerleaders were landing on a hard floor. Depending on if their pass technique (correct vs. incorrect) and the severity of their landing (soft vs. hard) they would have been more or less likely to register an impact.

Football studies have found that incorrect technique is associated with higher magnitude impacts. Impacts associated with proper body position resulted in an average linear acceleration that was 1.34g lower than impacts associated with poor body position.[26] The worst body position impacts had 3 times greater risk of having a higher impact magnitude.[26] Similarly, the correct execution of tumbling and stunting maneuvers is an important head impact biomechanics factor because if performed incorrectly there could be an increased risk of falls or collisions which could result in injury. The execution of correct technique accounted for 84.6% of the possible impact events. Only 31/959 (3.2%) possible impact events were not performed with correct technique and 12.2% were classified as not applicable. Proper technique was associated with a lower number of impacts compared to poor technique.

If a stunt is performed correctly the body position should be controlled and result in a soft landing with lower impact magnitudes.[3] Correct technique accounted for 811 of the activities confirmed by video. Of these correct activities 63 of them registered as impacts by the SIM-G sensors. Incorrect technique accounted for 4 SIM-G impacts. Throughout our study a few cheerleaders would land hard on their heels with little ability to correctly absorb the impact with their joints and muscles due to their momentum following a tumbling pass. This is an example of a hard tumbling landing. About 50% (472) of the total landings were soft with only 6 registering as SIM-G impacts. Hard impacts were associated with 309 potential impact events, with 51 registering as SIM-G impacts. Not surprisingly, hard impacts accounted for the greatest number of SIM-G video verified impacts. Of those 51 hard impacts, 38 of them were from tumbling and 13 were from stunting. We did not investigate in the magnitudes of the impacts but tumbling had almost 2 times more impacts than stunting.

Two different methods were used to determine impact location: the Triax impact location, and the video confirmation. The most common impact location reported by Triax was the crown 118/320. The most common impact location using video confirmation was none 747/959 follows by body 118/959. The frequency of back-of head impacts for the SIM-G (n=30, 9.4%) and video confirmation (n=51, 5.3%) were similar for the 100 video confirmed potential impact events. The Triax recorded 320 possible impact events and the researchers were able to confirm 295 possible impact events through video analysis. This indicates that the reliability between the two different methods for back-of-head impact location was the most reliable of the impact locations.

This could have been due to the fact that the Triax system categorizes impacts locations into10 different categories and the video analysis only use 7 location categories. In an effort to mathematically correct for this discrepancy we merged the Triax locations into the same 6 head locations (Table 6). This did not improve our findings. The most common possible impact event using video confirmation location was none (n=747, 77.9%). This was expected as someone is included in an activity, but they are not always going to sustain a hit. For an example, in football there are 22 people on the field at any one time, but most will not sustain a recordable impact during a single play. Our data supports this with the majority (77.9%) of the possible impact events resulting in no impact. This could be a result of the cheerleaders' good technique and the ≥16g linear threshold required to trigger a SIM-G impact.

An important finding to consider in this study is that the video saw more impacts to the back of the head than the Triax did. As mentioned previously, this potentially could have been due to the nature of how some stunts were performed. When a flyer landed in a cradle, the video was able to see the back of the flyers' head hitting the bases' chest or shoulders. This could have been classified as a NIT from the Triax, when really it should have been included as an impact as seen on video. Again, we feel that this should be an important consideration for future studies and may prove to be a contraindication for SIM-G use in cheer due to the mechanics of some cheer activities.

The study was limited to Texas State University male and female competition cheerleaders only. This was appropriate since both males and females commonly participate in competitive cheerleading. It was limited to a small sample size of 26 cheerleaders. This was acceptable because the normal number of people on a collegiate large competition team is 20 on the mat. The study took place over 8 practice sessions and did not represent and entire season. We do not feel that our limited data collection period negatively affected our results for two reasons. First, this was a feasibility pilot study and second we still were able to collect a significant number of possible impact events (959). We did experience some difficulty in identifying impact incidence and impact location due to only using one camera. However, even with only one view, we were still able to accurately identify impact incidence and location in over 91% of the possible impact events. We do recommend that future studies incorporate two cameras to reduce the number of unidentified impacts and to improve ease of grading these impacts. Overall we feel that the benefits of our pilot study outweigh our limitations.

Conclusion

This study was an initial exploration in determining the clinical reliability and validity of the Triax SIM-G sensor. To our knowledge, this is the first study to utilize the Triax SIM-G sensor in cheerleading. Our study supported the feasibility and the clinical validity of the SIM-G sensor in this setting. Future studies should investigate the relationships between impact frequency, magnitude and closing distance during specific activities (i.e., varying stunt and pyramid heights). Additionally, future studies should investigate the relationships between impact data and landing techniques, cheer-related experience and stunting technique. In this study, the authors did not determine if mistakes, falls, magnitude impact, or a harder landing may have been related to fatigue, supervision, or focus. These associations should be investigated in future studies.

In summary, this is the first study to investigate head impact biomechanics in cheerleading with the use of the Triax SIM-G sensor. It is also the first study to validate the SIM-G in a clinical setting. Our data is a first step at understanding cheer-related head impact biomechanics. We believe that further research can help inform coaches on how to improve the safety of their sport through better understanding of the nature of impacts in cheerleading.

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