AN ANALYSIS OF HEAD KINEMATICS IN WOMEN'S ARTISTIC GYMNASTICS

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Abstract

Concussions in gymnastics have scarcely been researched; however, current evidence suggests that concussion rates may be higher than previously reported due to underreporting among coaches, athletes, and parents. The purpose of this study was to outline a method for collecting head impact data in gymnastics, and to provide the first measurements of head impact exposure within gymnastics. Three optional level women's artistic gymnasts (ages 11-16) were instrumented with a mouthpiece sensor that measured linear acceleration, rotational velocity, and rotational acceleration of the head during contact and aerial phases of skills performed during practice. Peak linear acceleration, peak rotational velocity, peak rotational acceleration, duration, and time to peak linear acceleration were calculated from sensor data. Kinematic data was time-synchronized to video and then sensor data was segmented into contact scenarios and skills characterized by the event rotation, apparatus, landing mat type, skill type, skill phase, landing stability, and body region contacted. The instrumented gymnasts were exposed to 1,394 contact scenarios (41 per gymnast per session), of which 114 (3.9 per gymnast per session) contained head contact. Peak kinematics varied across skill type, apparatuses, and landing mats. The median duration of impacts with head contact (177 ms) was longer than measured impacts in youth and collegiate level soccer. Results from this study help provide a foundation for future research that may seek to examine head impact exposure within gymnastics to better inform concussion prevention and post-concussion return to play protocols within the sport.

Keywords: *head impact exposure, gymnastics, concussion, head injury.*

INTRODUCTION

Between 1.1 and 1.9 million sports- and recreational- related concussions occur each year among youth athletes in the United States (Bryan, Rowhani-Rahbar, Comstock, Rivara, & Bryan, 2016). While concussions are commonly associated with player-to-player collisions in contact sports such as American football (Buzas, Jacobson, & Morawa, 2014; Lincoln et al., 2011), concussions can also occur from falls or collisions with objects in sports such as gymnastics. Repeated epidemiological studies have shown a low incidence of concussions in both youth and collegiate level gymnastics activities (Caine et al., 2003; Marshall, Covassin, Dick, Nassar, & Agel, 2007); however, current research suggests that the incidence of concussion in gymnastics may be higher due to underreporting among athletes (Meehan, Mannix, O'Brien, & Collins, 2013), and a lack of knowledge of concussion signs and symptoms among coaches (Mannings, Kalynych, Joseph, Smotherman, & Kraemer, 2014). A recent survey by O'Kane reported that over 30% of retired gymnasts had sustained a blow to the head followed by at least one concussion symptom during their gymnastics careers (Kane, Levy, Pietila, Caine, & Schiff, 2011). Since gymnastics is not normally associated with concussions, it is possible that athletes, coaches, and parents may not be adequately educated on the symptoms, guidelines, and risks associated with the injury. A recent case report published by Knight et al. highlights this issue as the parents of a young gymnast diagnosed with a mild traumatic brain injury ignored the medical professional's recommendations and allowed their daughter to compete in a regional competition where she later sustained a second mild traumatic brain injury (Knight, Dewitt, & Moser, 2016).

Gymnastics is a broad term used to describe six unique disciplines: women's and men's artistic gymnastics, rhythmic gymnastics, acrobatic gymnastics, trampoline and tumbling, and aerobic gymnastics, where athletes utilize various apparatuses to perform complex somersaulting and twisting maneuvers. Within each discipline, athletes perform a variety of distinct skills on various apparatuses (e.g. balance beam) and landing surfaces (e.g. crash mats). These combinations of skills, apparatuses, and landing surfaces result in unique movement profiles and head injury mechanisms. For instance, previous research has shown that landing forces can vary across surfaces (McNitt-Gray, Yokoi, & Millward, 2016), apparatuses (Burt, Naughton, & Landeo, 2007), and heights (Mcnitt-Gray et al., 1993). Therefore, as the environment and movement characteristics of the gymnastics skill change, the risk for head injury may also change.

Understanding the specifics of head motion during play is essential to better define concussion mechanisms, risk, and return to sport safety. While the kinematics of the head in sports such as American football and soccer have been extensively studied (Cobb et al., 2013; Miller, Pinkerton, et al., 2019), only one study to date has attempted to measure the kinematics of the head during gymnastics related activities (Beck, Rabinovitch, & Brown, 1979). This study, by Beck et al., set out to understand the acceleration of the head during full body swings around the high bar (Beck et al., 1979). To do this, Beck et al. utilized a plastic helmet equipped with accelerometers that provided approximate motion of the head during the gymnastics skill. Current advancements in sensor development now allow researchers to measure head accelerations without the use of helmets, and may provide a more accurate estimate of head motion. Of these devices, a mouthpiece-based sensor has been suggested to be ideal as it provides tight coupling with the upper dentition and skull (Wu et al., 2016) and is easy to wear in a variety of sports. These devices have been utilized in previous studies with soccer athletes (Miller, Pinkerton, et al., 2019; Rich et al., 2019) and may be useful for studying head kinematics within gymnastics.

Despite the growing concern over concussions in sport, there is a paucity of data examining head injury mechanisms and head impact frequency within gymnastics, a sport in which concussions can occur and head impacts may be common. Therefore, the purpose of the current study was to outline a method for measuring and analyzing head kinematics in gymnastics. A secondary goal of the current study was to provide the first measurements of head kinematics and head impact exposure within gymnastics.

METHODS

Three optional level club women's artistic gymnasts (11-16 yrs) capable of performing a wide range of gymnastics skills were recruited to participate in this study. Gymnasts were excluded from this study if they were below the optional level and/or did not participate on a competitive USA gymnastics sanctioned team. The sample size was limited to three gymnasts due to the pilot nature of this study and primary objective of developing a method to measure and analyze head kinematics in gymnastics. The study protocol was approved by the Wake Forest University School of Medicine Institutional Review Board (IRB), and parental consent and participant assent were properly acquired for participation in the study. The gymnasts were instrumented for a combined total of 34 practices over a six month period with a validated custom fit mouthpiece (Rich et al., 2019) outfit with a triaxial accelerometer and gyroscope. To prevent changes in the conformation of the mouth from resulting in sensor coupling errors, gymnasts were excluded if they had been continually wearing orthodontic braces for less than six months. The mouthpiece was custom fitted to a 3D printed dental model created from a high resolution scan (3shape, Copenhagen, DK) of the upper dentition obtained by a trained staff member and reviewed by a dental technician to ensure proper fit and tight coupling to the upper dentition. Two time-synchronized cameras, arranged such that all apparatuses were in full view of at least one camera, filmed the gymnasts during each practice. Data acquisition of the sensor is controlled by a user-defined linear acceleration trigger threshold. When this value is exceeded for a prescribed period of time, the device records linear acceleration and rotational velocity at sample rates up to 4,681 Hz and 800 Hz, respectively.

Other research using the same mouthpiece-based sensor has used a sampling frequency of 4,684 Hz and an acceleration threshold of 5 g's sustained for greater than or equal to 14 samples to collect 60 ms of data per recording (Rich et al., 2019). Although there have been many previous studies that examine head impact exposure using similar instrumentation, the gymnastics environment is different from most team sports. Therefore, a frequency analysis was performed by calculating the fast Fourier transform (FFT) of all events collected during a single session at 350 Hz to identify the ideal sampling frequency for this environment. A sampling frequency of 350 Hz was chosen as it was the maximum sampling frequency that the researchers could successfully time synchronize the data with video and capture the full duration of contact events due to sensor limitations. The dominant frequencies of the head during gymnastics skill motion were at or less than 35 Hz. Therefore, a sampling frequency of 100 Hz, was deemed sufficient to capture head kinematic data. The number of pre-impact samples and post-impact samples were extended so that both contact (i.e. when a gymnast comes in contact with a surface) and aerial (i.e. when an athlete performs a skill) data could be recorded by the mouthpiece sensor. The extended time of recording not only improved video pairing, but ensured that all contact scenarios within a skill series could be recorded. The final configuration utilized a sampling frequency of 100 Hz and a trigger threshold of 4 g sustained over 3 samples.

Data collected by the sensor was processed according to the methods of Miller et al. (Miller et al., 2018) and Rich et al. (Rich et al., 2019); excluding the filter since the sampling frequencies in the current study were much lower. Briefly, linear acceleration and rotational velocity data were rotated to align with an anatomic coordinate system (X points from posterior to anterior, Y points from right to left, Z points from inferior to superior), rotational acceleration was computed by numerically differentiating the gyroscope data using a five-point difference formula, and finally linear acceleration was transformed to the head center of gravity (CG) using rigid body dynamics.

Recorded mouthpiece events were paired with observed events on film using the mouthpiece timestamp and the video time to the nearest second. A frame-by-frame analysis was conducted for each event by identifying when the initiation of the peak linear acceleration occurs. Then the mouthpiece data was synchronized to the frame of the video where the athlete initially contacted the surface. In cases where an event was triggered without surface contact (e.g., from the linear acceleration produced by the athlete's rotation during a skill) the initiation of the peak signal was synchronized to the initiation of movement by the athlete. All kinematically-significant movements by the athlete (e.g., initial contact of foot, initiation of hip circle, etc.) were then identified in the video and matched to the event recording. Contact scenarios were segmented from the time of initial surface contact to the time the athlete's body part left contact with the surface or when the athlete's motion stopped (Figure 1). Skills, defined as gymnastics-related actions performed by the gymnast (e.g., back handspring), were segmented from the time of initial contact or initiation of movement, to the time the athlete's body part left contact with the apparatus or when the athlete's motion stopped (Figure 1). Segmented contact scenarios and skills were then zeroed to the mean of the previous five samples of the recording. If the start of the scenario occurred at the beginning of the recording, the first five samples of the contact scenario or skill were used to zero the segmented data.

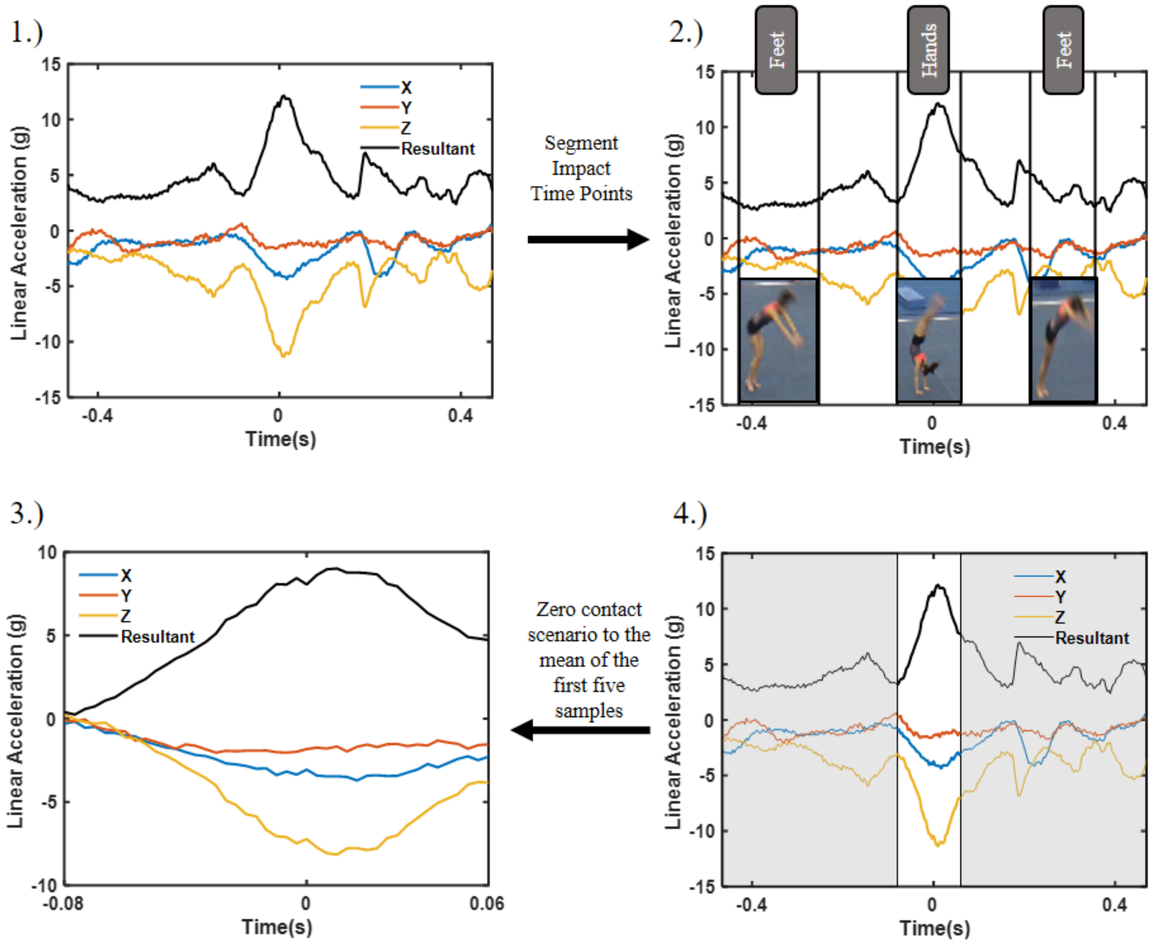

Figure 1. From plot 1-4, transformed data (1) is segmented (2) and then individual contact scenarios (3) are zeroed to the mean of the previous five samples of the recording (4).

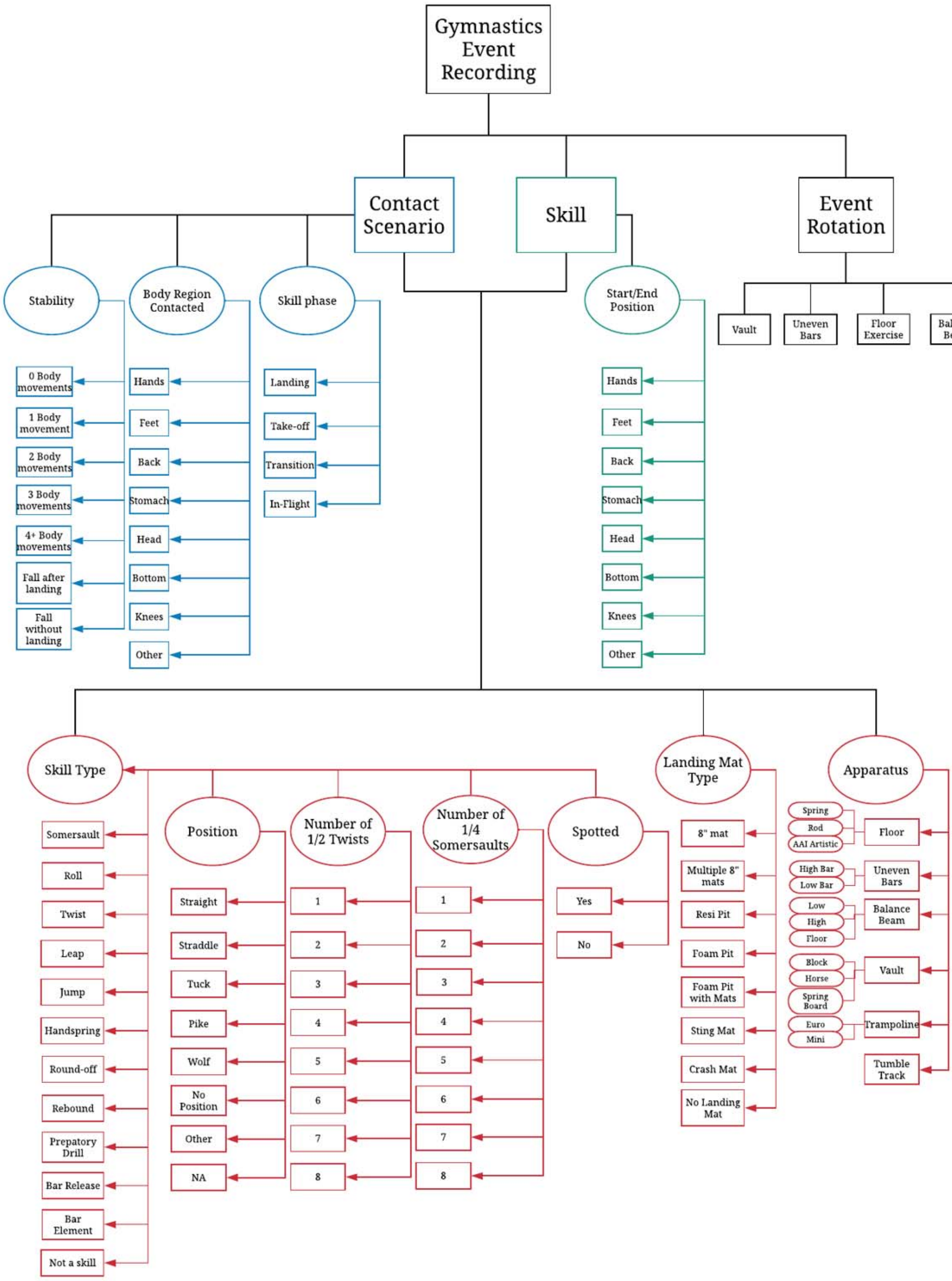

Figure 2. Flow chart outlining all possible categorizations of event recordings, contact scenarios, and skills.

Each recording was categorized by the series of skill types the gymnast performed before and after the event trigger (Figure 2). Then, each *contact scenario* during the recording was categorized by characteristics of the skills preceding and following contact (type, number of somersaults, number of twists, body position, presence of a spotter), initial body region contacted, apparatus, landing mat type, skill phase, and landing stability (for feet landings only). Landing stability was quantified by the number of body movements (i.e. arm circle, step) performed after landing. Each *skill* during the recording was categorized by characteristics of the skill (type, number of somersaults, number of twists, body position, presence of a spotter), preceding skill type, following skill, apparatus, and type of landing mat used. Contact scenarios and skills were only defined if the recording included both the initiation and completion of the contact scenario or skill.

Peak resultant linear acceleration (PRLA), peak resultant rotational velocity (PRRV), and peak resultant rotational acceleration (PRRA) were calculated for each contact scenario and skill. Additionally, the duration was calculated as the time between the first minimums before and after the PRLA magnitude was below 10% of the maximum magnitude. The time to PRLA, was calculated as the time between the PRLA and the first minimum before the PRLA magnitude was below 10% of the maximum magnitude. In cases where segmented contact scenarios or skills did not contain a minimum below 10% of the maximum magnitude either before or after the PRLA (e.g. flat trace), the first or last sample of the segmented recording was used to calculate time to PRLA and duration.

Summary statistics of peak kinematic data were evaluated by skill type, skill phase, apparatus, landing mat type, body region contacted, landing stability, and presence of a spotter. 5th, 50th, and 95th percentile values for PRLA, PRRV, PRRA, duration, and time to PRLA were reported for all categories.

RESULTS

Of 34 data collection sessions, 29 contained event recordings that were paired with video for analysis. Athlete A participated for 10 sessions before sustaining a concussion and retiring from gymnastics. Athlete B participated for 9 sessions before sustaining a foot injury and was not able to participate further. Athlete C participated for 24 sessions, 9 of which were concurrent with Athlete B. Throughout the 29 analyzed practices a total of 1,394 contact scenarios (41 per day per athlete) and 516 skills (19 per day per athlete) were segmented from 1,270 event recordings. Events were triggered by 55 different skill series with the most common skill series being round-off back handspring somersault. The kinematics of skills were not analyzed in this paper. The majority of contact scenarios occurred during the floor rotation (55.6%) followed by the vault (18.3%), balance beam (15.1%), and bars (11.0%). Whereas, contact scenarios most frequently occurred on the floor apparatuses (52.6%), the trampoline apparatuses (16.6%), and the balance beam apparatuses (12.6%). The most frequently contacted body regions were the feet (64.4%), hands (23.1%), and back (7.1%). While, only 12 contact scenarios contained direct contact to the head, 114 contact scenarios contained direct head contact or secondary head contact (e.g. the gymnast landed on their back first and then their head hit a surface) (3.8 per gymnast per session). Additionally, the majority of contact scenarios did not utilize any landing mat (82.1%), but 17.9% of contact scenarios utilized one of seven landing mat setups: an 8” mat (5.2%), crash mat (0.5%), foam pit (1.9%), mats stacked in the foam pit (1.2%), multiple 8” mats (0.5%), Resi pit (7.0%), and a sting mat (1.6%). Only 1.4% of contact scenarios recorded during the practices occurred after or while a coach spotted a gymnast. Lastly, of the contact scenarios with which landing stability could be determined (15.4%), 12.1% had zero body movements (e.g. perfect stability), 25.6% had one body movement, 24.2% had 2 body movements, 8.8% had 3 body movements, 8.4% had 4 or more body movements, 20.5% were from a fall after landing, and 0.5% were from a fall without a foot landing.

Overall, the 5th, 50th, and 95th percentile PRLA magnitudes were 3.5 g, 6.7 g, and 12.4 g, respectively. The 5th, 50th, and 95th percentile PRRV magnitudes were 2.5 rad/s, 8.0 rad/s, and 19.3 rad/s, respectively. The 5th, 50th, and 95th percentile PRRA magnitudes were 71.6 rad/s^2, 190.0 rad/s^2, and 425.9 rad/s^2. Peak kinematic magnitudes did not always occur at the same time. For instance, PRRA and PRRV always occurred after PRLA. The median time differences for PRRA and PRRV were 0.040s and 0.060s after the PRLA.

Skill Types. Rolls had the highest median PRLA (11.3 g, n=2), followed by leaps (9.4 g, n=171), and falls (8.6 g, n=27) (See Appendix Table 1). Similarly, rolls had the highest median PRRV (17.5 rad/s, n=2) followed by handsprings (7.9 rad/s, n=497), then contact scenarios with no skill type (7.6 rad/s, n=67). Once more, rolls had the highest median PRRA (856.4 rad/s^2, n=2), followed by falls (290.5 rad/s^2, n=27), then somersaults (247.6 rad/s^2, n=171). The duration of contact was much shorter for rolls (0.099s) then all other skill types (0.154s-0.214s). Similarly, the time to PRLA was much shorter for rolls (0.026s) then all other skill types (0.060s-0.103s).

Apparatus. Contact scenarios occurring from skills performed on the vaulting horse had the highest 95th percentile PRLA (19.8 g, n=56) followed by the high bar (15.4 g, n=44), then the high beam (13.1 g, n=31) with contact scenarios occurring from skills performed on the low beam having the lowest 95th percentile PRLA (7.0 g) (See Appendix Table 2). However, contact scenarios occurring from skills performed on the spring floor had the highest 95th percentile PRRV (19.7 rad/s, n=51) followed by the low beam (19.6 rad/s, n=62), then the floor beam (18.8 rad/s, n=82) with contact scenarios occurring from skills performed on the low bar having the lowest 95th percentile PRRV (11.3 rad/s, n=33). Contact scenarios occurring from skills performed on the vaulting horse had the highest 95th percentile PRRA (862.4 rad/s^2, n=56) followed by contact scenarios where there was no apparatus (524.8 rad/s^2, n=83), and the AAI artistic floor (485.9 rad/s^2, n=544) with contact scenarios occurring from skills performed on the mini trampoline (192.4 rad/s^2, n=19) having the lowest 95th percentile PRRA. Duration of contact scenarios varied from 0.0160 s on the AAI Artistic floor and vault spring board to 0.331 seconds on the Euro trampoline. Time to PRLA varied from 0.049 seconds for contact scenarios occurring from skills performed on the low bar to 0.173 seconds for contact scenarios occurring from skills performed on the Euro trampoline.

Landing Mat Types. Contact scenarios occurring on mats stacked in the foam pit had the highest 95th percentile PRLA (22.6 g, n=16) followed by the crash mat (16.5 g, n=7), then the 8” mat (14.1 g, n=73) with contact scenarios occurring on multiple 8” mats having the lowest 95th percentile PRLA (6.7 g, n =7) (See Appendix Table 3). Similarly, contact scenarios occurring on mats stacked in the foam pit had the highest 95th percentile PRRV (21.2 rad/s, n=16), followed by contact scenarios occurring on the Resi pit (17.5 rad/s, n=97) and contact scenarios occurring on competition standard equipment (16.1 rad/s, n=1145). Once more, contact scenarios occurring on mats stacked in the foam pit had the highest 95th percentile PRRA (1,406.3 rad/s^2, n=16) followed by contact scenarios occurring on sting mats (691.7 rad/s^2, n=22) and Resi pits (577.6 rad/s^2, n=97). The duration of contact scenarios varied from 0.100 s on mats stacked in the foam pit to 0.488 s when athletes landed in the foam pit. Additionally, the time to PRLA varied from 0.044 s when athletes landed on mats stacked in the foam pit to 0.200 s when athletes landed in the foam pit. Within this study, all contact scenarios occurring on mats stacked in the foam pit occurred while the athlete was rotating more than one full somersault to their back

Body Regions. Direct impacts to the head had the highest 95th percentile PRLA (20.8 g, n=12) followed by impacts to the back (18.3 g, n=99) and bottom (14.3 g, n=30) (See Appendix Table 4). Similarly, direct impacts to the head had the highest 95th percentile PRRV (26.2 rad/s, n=12) followed by impacts to the hands (19.0 rad/s, n=322) and back (18.2 rad/s, n=99) with impacts to the bottom having the lowest 95th percentile PRRV (10.0 rad/s, n=30). Additionally, impacts to the head had the highest 95th percentile PRRA (1,472.2 rad/s^2, n=12) followed by impacts to the back (825.9 rad/s^2, n=99) and feet (429.6 rad/s^2, n=897). Duration of contact scenarios ranged from 0.168s when athletes landed on their back to 0.498 s when athletes landed directly on their head. Time to PRLA ranged from 0.070 seconds when athletes landed on their back to 0.222 seconds when athletes landed directly on their head. When impacts were differentiated by head contact (See Appendix Table 5), impacts with head contact (n=114) had greater 95th percentile PRLA (Y-18.3 g, N- 10.8 g), PRRV (Y-19.1 rad/s, N-15.8 rad/s) and PRRA (Y-866.2 rad/s^2, N-420.6 rad/s^2) and shorter durations (Y-0.177s, N- 0.185s) and time to PRLA (Y-0.071s, N-0.090s) than impacts without head contact.

Skill Phase. Landings had the highest 95th percentile PRLA (14.3 g, n=375) followed by transitions (10.5 g, n=895) and then take-offs (10.1 g, n=121) (See Appendix Table 6). However, transitions had the highest 95th percentile PRRV (n=895, 17.1 rad/s), followed by landings (14.2 rad/s, n=375) and take-offs (12.2 rad/s, n=121). Landings had the highest 95th percentile PRRA (600.5 rad/s^2, n=375), followed by take-offs (508.8 rad/s^2, n=121) and transitions (411.9 rad/s^2, n=895). Duration of contact scenarios was shortest during take-offs (0.140s) and longest during landings (0.210s). However, time to PRLA was shortest during take-offs (0.060 s) and longest during transitions (0.097s).

Landing Stability and Spotting. The 95th percentile PRLA and PRRA did not vary much by landing condition (9.4 g-14.0g, 241.5 rad/s^2-481.3 rad/s^2), but there were large differences in PRRV (6.6 rad/s-17.8 rad/s) with 4+ body movements resulting in the highest 95th percentile PRRV (See Appendix Table 7). Additionally, duration of contact scenarios and time to PRLA generally increased with increasing number of body movements. When contact scenarios were differentiated by spotting (See Appendix Table 8), contact scenarios with spotting had lower 95th percentile PRLA (Y-8.2g, N-11.6g), higher 95th percentile PRRV (Y-16.4 rad/s, N-16.0 rad/s), and lower 95th percentile PRRA (Y-267.3 rad/s^2,N-456.0 rad/s^2) with longer durations (Y-0.260s,N-0.183s) and time to PRLA (Y-0.110s,N-0.090s) than impacts without spotting.

Concussion. During the study period, one gymnast sustained a concussion after a fall to their back from the high beam. The PRLA, PRRV, and PRRA for this contact scenario were 21.2 g, 26.8 rad/s, 1512.4 rad/s2, respectively. Figure 3 shows the corresponding linear acceleration, rotational velocity, and rotational acceleration over time and compares the PRLA and PRRA of the concussive impact event to all other recorded events. The concussive event had the second highest PRLA and the second highest PRRA, but the highest combined probability of concussion risk (Rowson & Duma, 2013), compared to all other impact events.

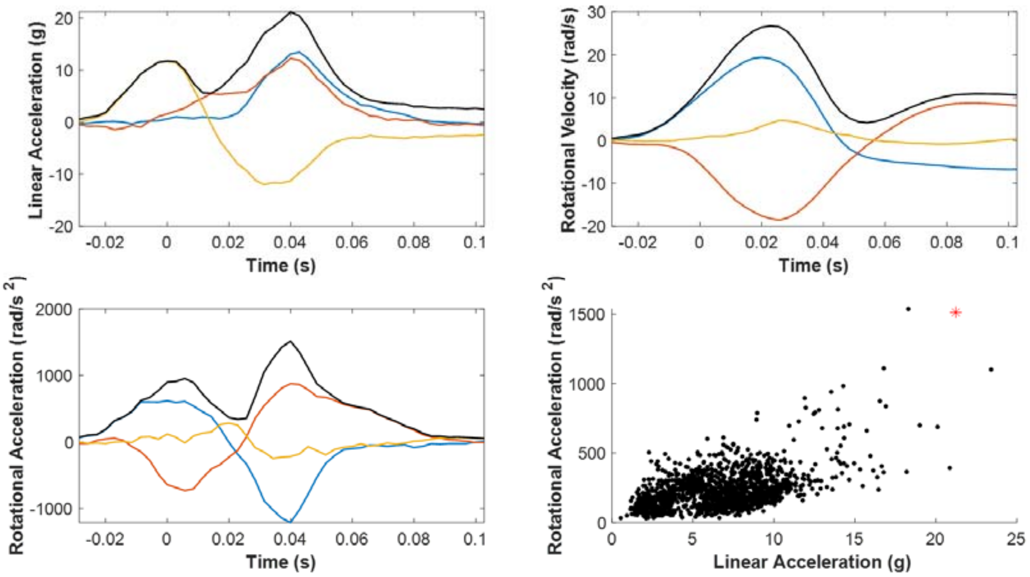

Figure 3. The linear acceleration (top left), rotational velocity (top right), and rotational acceleration (bottom left) during an injurious fall from high beam. Plot (bottom right) compares the peak resultant linear and rotational acceleration magnitudes from this contact scenario (represented by *) to all other recorded contact scenarios.

DISCUSSION AND CONCLUSIONS

This study developed a methodology to measure and evaluate head kinematics in gymnastics. Additionally, head kinematics of one to three optional level gymnast's ages (11-16) were analyzed during 29 practices. To the best of the researcher's knowledge, this is the first study to measure head kinematics across a variety of contact scenarios commonly experienced in women's artistic gymnastics. From these data, it is possible to characterize the frequency and magnitude with which the head accelerates during gymnastics skills. Collectively, the gymnasts sustained over 1,000 contact scenarios (41 per gymnast per practice), 10% of which contained head contact. Head contact was associated with greater peak kinematic magnitudes and shorter impact durations compared to contact scenarios without head contact. These data provide a framework to help inform and guide evidence-based decisions regarding return to gymnastics and concussion safety within gymnastics. The frequency of head contact events per gymnast per session (3.8) was slightly higher than the frequencies reported in collegiate and youth soccer practices (1.86 (Press & Rowson, 2017)-3.52 (McCuen et al., 2015),1.69 (McCuen et al., 2015)). However, median PRLA (6.7 g) and PRRA (190.0 rad/s^2) magnitudes were below those reported in soccer (9.4 g, 689.1 rad/s^2) (Miller, Pinkerton, et al., 2019) and youth football (21.7 g, 973 rad/s^2) (Urban et al., 2013). Interestingly, the duration of impacts was on average much longer (177 ms) than impacts reported in soccer (Miller, Pinkerton, et al., 2019) (17.2 ms), potentially due to the compliant surfaces gymnasts contacted. So, while gymnasts may be exposed to more frequent low magnitude head contact scenarios, they experience these acceleration events for longer durations which may have an effect on concussion risk.

An interesting finding from this study was that in addition to experiencing a high frequency of head contact scenarios, gymnasts experienced an even higher frequency of body-contact acceleration events that were the result of surface contact with a body part other than the head during gymnastics skills such as: leaps, jumps, somersaults, and handsprings. Head contact is typically associated with concussions (Buzas et al., 2014); however, it is not a requirement, and concussions following surface contact to a body region other than the head have been documented within gymnastics (Knight et al., 2016). Within this study, impacts without head contact were below magnitudes thought to increase risk of head injury and generally consistent with values reported in everyday activities (Miller, Urban, et al., 2019). PRLA magnitudes were greatest when the athlete contacted the surface on their bottom, which occurred during unintentional falls after landing or intentional skills performed on the floor or trampoline apparatuses. However, PRRV and PRRA magnitudes were higher when the athlete's feet were the point of contact such as when the athlete was performing a somersault, round-off, handspring, etc. It is likely that during these scenarios the head is accelerating as the athlete rotates, looks for the ground, or falls resulting in higher rotational magnitudes. Additionally, a smaller number of contact scenarios where the athlete contacted their bottom were measured compared to foot landings, and it is possible that apparatus, skill type, and skill performance variations during these contact scenarios could have skewed impacts with bottom contact towards smaller kinematic magnitudes.

It is well documented in the gymnastics literature that ground reaction forces during landing can be reduced by decreasing skill height, and using landing mats (McNitt-Gray et al., 2016; Mcnitt-Gray et al., 1993; Mills, Yeadon, & Pain, 2010). In contrast to these data, this study found that peak acceleration magnitudes were higher in contact scenarios that contained landing mats compared with scenarios performed on competition standard surfaces where no safety mat was used. While this study contained a limited number of contact scenarios across mat types, this contrary result may also be due in part to the preference of using landing mats only when performing higher difficulty skills with greater height and rotational speed. Thus, while comparisons of landing mat performance cannot be derived from these data, these data do provide evidence for understanding scenarios where more appropriate landing mats should be used. For instance, mats were stacked in the foam pit when gymnasts performed yurchenko timers on the vault, a skill in which the gymnast performs a back handspring over the vaulting table and rotates to their back. This skill series reported a maximum peak linear acceleration of 23.4 g, a maximum peak rotational velocity of 22.1 rad/s, and a maximum peak rotational acceleration of 1,537.3 rad/s^2, which were similar to that of the concussive impact observed in this study. It is possible that a more compliant landing mat placed in the foam pit would help to reduce peak impact magnitudes when performing this skill series.

This study also found that acceleration magnitudes were highest on the vaulting horse, followed by the high beam, and the AAI artistic floor. In contrast, ground reaction forces have been reported highest on the floor exercise compared to the beam (Burt et al., 2007). However, the height of the apparatus in addition to the apparatus stiffness has an effect on accelerations experienced on the event (McNitt-Gray et al., 2016; Mcnitt-Gray et al., 1993). While, almost all contact scenarios that arose from skills on the AAI artistic floor finished on the same equipment, beam and vault apparatuses contain a dismount component that requires the gymnast to jump from the elevated apparatus to a landing mat placed on the ground. So, although contact scenarios from skills performed onto the high beam and vault may expose athletes to lower accelerations than floor impacts, dismounts and/or falls off these apparatuses expose athletes to high head acceleration magnitudes that may result in injury.

The results of our study demonstrate that head acceleration magnitudes are affected by apparatus, body region, and landing mat usage. For instance, while the maximum linear acceleration for rolls was 16.8 g, a result of an athlete performing a backward extension roll on the floor apparatus with head contact and no landing mat, the minimum peak linear acceleration for rolls was 5.9 g, the result of an athlete performing a forward dive roll with head contact onto a sting mat on the floor apparatus. In one case, the athlete's head was unprotected by the equipment and poor rolling technique led to forceful head contact with the apparatus; whereas, in the other case, the athletes rolling technique prevented forceful head contact and the presence of a landing mat potentially contributed to a reduction in acceleration magnitudes. Therefore, when examining concussion risk and head impact exposure during gymnastics, all components of gymnastics skills: the apparatus, landing mat, skill type, and skill technique, should be considered.

In addition to frequent body-contact impacts, gymnasts are exposed to a number of non-contact head acceleration events during gymnastic skills with high rotational components such as: twists, somersaults, and bar elements. The peak linear accelerations during these skills may reach magnitudes similar to that of foot impacts; however, the duration of these events is much longer, reaching upwards of 2.7 seconds. During this time, rotational velocities may reach magnitudes of up to 25.9 rad/s. Rotational velocities during these skills may vary by athlete growth (Ackland, Elliott, & Richards, 2003), anthropometrics (Ackland et al., 2003), skill level, and skill technique (King & Yeadon, 2004), and while it is unlikely that an athlete will sustain a concussion from the proper performance of these skills, it is possible that high rotational velocities experienced during recovery from concussion may result in symptomatic episodes. This study provides an initial glimpse of the rotational velocity experienced during common gymnastics movements and provides insight and consideration towards the development of return to sport guidelines following concussion in gymnastics.

This study was limited by inherent constraints of the wearable mouthpiece sensor used in the study. The data storage on the device and download rate limited the sampling rate to 100 Hz. Previous research examining head impacts in sport utilize much higher sampling rates to identify high rate, short duration head impact events. It is possible that these types of contact scenarios may occur when an athlete contacts an unprotected apparatus or floor, resulting in higher frequency events where aliasing may occur at a lower sampling rate. The sensor was also limited in its ability to precisely time synchronize events to the video within 1 second. Because of this, variations due to time-matching error may have resulted in small errors in calculated durations and time to peaks. This was accounted for by calculating the duration of the contact scenario separately from the video; however, future research should aim to improve the device time synchronization precision to obtain more precise duration and time to peak data. Lastly, head impact frequencies reported in this paper may be lower than what is truly experienced by gymnasts due to sensitivity limitations resulting from pre-set sensor configurations that filter out low magnitude contact scenarios and device limitations that result in missed contact scenarios when multiple events (true and false) occur in quick succession of one another. Future efforts of calculating head impact frequency in gymnastics should combine video and sensor data to improve accuracy.

An additional limitation of this study was the low sample size, small number of practice days, and sole use of optional level gymnasts. The pilot nature of this study provides a limited representation of youth gymnastics as a whole, as all study participants were from the same region and practice within the same gym, but still provides important insights into possible head kinematics experienced in the sport. This sample was selected to achieve the primary goal of developing a method to measure and analyze head kinematics in gymnastics; however, the small sample limits the generalizability of the kinematic measurements reported. During the study, all three gymnasts sustained an injury that required at least a week of recovery before full return to sport, resulting in a limited number of data collection events. Moreover, while optional level athletes can perform more skill types than compulsory (lower level) gymnasts, compulsory gymnasts may obtain more frequent head contact scenarios with lower peak kinematic magnitudes as a result of common preparatory drills performed during the lower levels. Future research should aim to increase sample size and include a variety of different levels of gymnastics to examine the wide range of potential combinations of skills, landing mats, apparatuses, and body regions that may occur in day-to-day practice of gymnastics.

Gymnastics is a sport not commonly considered when discussing concussive injuries; however, concussions in gymnastics do occur, and it is important for parents, coaches, athletes, and medical professionals to better understand the mechanisms for which these injuries can happen in the sport. The data in this study demonstrate that head kinematics and consequently head injury risk in gymnastics are affected by skill type, skill performance, landing mat usage, apparatus, and body region contacted. Medical professionals guiding gymnasts back to sport from concussion should consider these variables and their relationship to non-contact and body-contact head acceleration scenarios to reduce the risk of a second concussive impact and symptomatic episodes during recovery. Future research on head injuries in gymnastics is needed to better understand high risk skills and mechanisms for which risk can be mitigated in the sport.

REFERENCES

Ackland, T., Elliott, B., & Richards, J. (2003). Gymnastics: Growth in body size affects rotational performance in women's gymnastics. *Sports Biomechanics*, *2*(2), 163–176. https://doi.org/10.1080/14763140308522815

Beck, G. R., Rabinovitch, P., & Brown, A. C. (1979). Acceleration forces at eye level experienced with rotation on the horizontal bar. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, *46*(6), 1119–1121. https://doi.org/10.1152/jappl.1979.46.6.1119

Bryan, M. A., Rowhani-Rahbar, A., Comstock, R. D., Rivara, F., & Bryan, M. (2016). Sports-and Recreation-Related Concussions in US Youth. *Pediatrics*, *138*(1), 20154635. https://doi.org/10.1542/peds.2015-4635

Burt, L., Naughton, G., & Landeo, R. (2007). Quantifying Impacts During Beam and Floor Training in Pre-Adolescent Girls From Two Streams of Artistic Gymnastics. *XXV ISBS Symposium*, 354–357.

Buzas, D., Jacobson, N. A., & Morawa, L. G. (2014). Concussions From 9 Youth Organized Sports. *Orthopaedic Journal of Sports Medicine*, *2*(4). https://doi.org/10.1177/2325967114528460

Caine, D., Knutzen, K., Howe, W., Keeler, L., Sheppard, L., Henrichs, D., & Fast, J. (2003). A three-year epidemiological study of injuries affecting young female gymnasts. *Physical Therapy in Sport*, *4*(1), 10–23. https://doi.org/10.1016/S1466-853X(02)00070-6

Cobb, B. R., Urban, J. E., Davenport, E. M., Rowson, S., Duma, S. M., Maldjian, J. A., … Stitzel, J. D. (2013). Head impact exposure in youth football: Elementary school ages 9-12 years and the effect of practice structure. *Annals of Biomedical Engineering*, *41*(12), 2463–2473. https://doi.org/10.1007/s10439-013-0867-6

Kane, J. W. O., Levy, M. R., Pietila, K. E., Caine, D. J., & Schiff, M. A. (2011). *Survey of Injuries in Seattle Area Levels 4 to 10 Female Club Gymnasts*. *21*(6), 486–492.

King, M. A., & Yeadon, M. R. (2004). Maximising somersault rotation in tumbling. *Journal of Biomechanics*, *37*(4), 471–477. https://doi.org/10.1016/j.jbiomech.2003.09.008

Knight, D., Dewitt, R., & Moser, S. (2016). Mild traumatic brain injury in a gymnast. *JAAPA : Official Journal of the American Academy of Physician Assistants*, *29*(7), 30–34. https://doi.org/10.1097/01.JAA.0000483093.43523.0d

Lincoln, A. E., Caswell, S. V, Almquist, J. L., Dunn, R. E., Norris, J. B., & Hinton, R. Y. (2011). Trends in Concussion Incidence in High School Sports: A prospective 11-year Study. *The American Journal of Sports Medicine*, *39*(5). https://doi.org/10.1177/0363546510392326

Mannings, C., Kalynych, C., Joseph, M. M., Smotherman, C., & Kraemer, D. F. (2014). Knowledge assessment of sports-related concussion among parents of children aged 5 years to 15 years enrolled in recreational tackle football. *Journal of Trauma and Acute Care Surgery*, *77*, S18–S22. https://doi.org/10.1097/TA.0000000000000371

Marshall, S. W., Covassin, T., Dick, R., Nassar, L. G., & Agel, J. (2007). Descriptive Epidemiology of Collegiate Women's Gymnastics Injuries: National Collegiate Athletic Association Injury Surveillance System. *Journal of Athletic Training*, *42*(2), 234–240. https://doi.org/10.1016/S0276-1092(08)79204-6

McCuen, E., Svaldi, D., Breedlove, K., Kraz, N., Cummiskey, B., Breedlove, E. L., … Nauman, E. A. (2015). Collegiate women's soccer players suffer greater cumulative head impacts than their high school counterparts. *Journal of Biomechanics*, *48*(13), 3720–3723. https://doi.org/10.1016/j.jbiomech.2015.08.003

McNitt-Gray, J. L., Yokoi, T., & Millward, C. (2016). Landing Strategies Used by Gymnasts on Different Surfaces. *Journal of Applied Biomechanics*, *10*(3), 237–252. https://doi.org/10.1123/jab.10.3.237

Mcnitt-Gray, J. L., Yokoi, T., Millward, C., Gray, L. M., Yokoi, T., & Millward, C. (1993). Landing Strategy Adjustments Made by Female Gymnasts in Response to Drop Height and Mat Composition. *Qriiginal Investigatiiqns Journal of Applied Biomechanics*, *9*, 173–190. https://doi.org/10.1123/jab.9.3.173

Meehan, W. P., Mannix, R. C., O'Brien, M. J., & Collins, M. W. (2013). The Prevalence of Undiagnosed Concussions in Athletes. *Clinical Journal of Sport Medicine*, *23*(5), 339–342. https://doi.org/10.1097/JSM.0b013e318291d3b3

Miller, L. E., Kuo, C., Wu, L. C., Urban, J. E., Camarillo, D. B., & Stitzel, J. D. (2018). Validation of a Custom Instrumented Retainer Form Factor for Measuring Linear and Angular Head Impact Kinematics. *Journal of Biomechanical Engineering*, *140*(5), 054501. https://doi.org/10.1115/1.4039165

Miller, L. E., Pinkerton, E. K., Fabian, K. C., Wu, L. C., Espeland, M. A., Lamond, L. C., … Urban, J. E. (2019). Characterizing head impact exposure in youth female soccer with a custom-instrumented mouthpiece. *Research in Sports Medicine*, *0*(0), 1–17. https://doi.org/10.1080/15438627.2019.1590833

Miller, L. E., Urban, J. E., Whelan, V. M., Baxter, W. W., Tatter, S. B., & Stitzel, J. D. (2019). An envelope of linear and rotational head motion during everyday activities. *Biomechanics and Modeling in Mechanobiology*. https://doi.org/10.1007/s10237-019-01267-6

Mills, C., Yeadon, M. R., & Pain, M. T. G. (2010). Modifying landing mat material properties may decrease peak contact forces but increase forefoot forces in gymnastics landings. *Sports Biomechanics*, *9*(3), 153–164. https://doi.org/10.1080/14763141.2010.524244

Press, J. N., & Rowson, S. (2017). Quantifying Head Impact Exposure in Collegiate Women's Soccer. *Clinical Journal of Sport Medicine*, *27*(2), 104–110. https://doi.org/10.1097/JSM.0000000000000313

Rich, A. M., Filben, T. M., Miller, L. E., Tomblin, B. T., Van Gorkom, A. R., Hurst, M. A., … Stitzel, J. D. (2019). Development, Validation and Pilot Field Deployment of a Custom Mouthpiece for Head Impact Measurement. *Annals of Biomedical Engineering*, *47*(10), 2109–2121. https://doi.org/10.1007/s10439-019-02313-1

Rowson, S., & Duma, S. M. (2013). Brain Injury Prediction : Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration. *Annals of Biomedical Engineering*, *41*(5), 873–882. https://doi.org/10.1007/s10439-012-0731-0

Urban, J. E., Davenport, E. D., Golman, A. J., Maldjian, J. A., Whitlow, C. T., Powers, A. K., & Stitzel, J. D. (2013). Head Impact Exposure in Youth Football: High School Ages 14 to 18 Years and Cumulative Impact Analysis. *Annals of Biomedical Engineering*, *41*(12), 2474–2487. https://doi.org/10.1177/0333102415576222.Is

Wu, L. C., Nangia, V., Bui, K., Hammoor, B., Kurt, M., Kuo, C., & Camarillo, D. B. (2016). In Vivo Evaluation of Wearable Head Impact Sensors. *Annals of Biomedical Engineering*, *44*(4), 1234–1245. https://doi.org/10.1007/s10439-015-1423-3.In

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