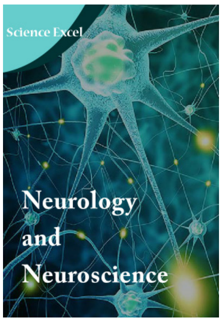

Concussions in Boxers: Head Rotations and Neck Stiffness

Chiming Huang[1*], Kimber Husak[1], Vaidyhanathan Vaishnavi[2], Rosa Huang[2]

[1]*School of Biological and Chemical Sciences, University of Missouri-Kansas City, Kansas City, Missouri, USA*

[2]*School of Medicine, University of Missouri-Kansas City, Kansas City, Missouri, USA*

*Correspondence

Chiming Huang

School of Biological and Chemical Sciences, University of Missouri-Kansas City, Kansas City, Missouri 64110, USA

E-mail: huangc@umkc.edu

- Received Date: 08 Apr 2021
- Accepted Date: 27 Apr 2021
- Publication Date: 05 May 2021

Keywords: concussions, neck stiffness, pitch, roll, yaw .

Abstract

Background: The human head-and-neck has three degrees of rotational freedom – pitch, roll, and yaw. While the evolution of the head-and-neck mobility may have increased the overall fitness of *homo sapiens*, our head-and-neck mobility may have also introduced some differential vulnerability to injuries in impact-induced head rotations about the pitch, roll, and yaw axes.

Methods and Findings: We examined impact-induced head rotations in boxing matches by analyzing videos. Our objective was to seek a quantitative relationship between impact-induced head kinematics and the knockout outcome. For each of the three rotational degrees of freedom, head angular velocities of impact-induced head rotations were significantly higher in knockout hits than in control hits without a knockout ($p < 0.02$). Knockout thresholds in pitch-roll-yaw measured as impact-induced head angular velocities were anisotropic with the lowest threshold in roll and became progressively higher in yaw and pitch, in that order. Regardless of the pitch-roll-yaw bearing, the velocities of the striking fists in knockout hits were not significantly higher than those in control hits.

Conclusions: Accurate prediction of knockout via head kinematics was possible with pitch-roll-yaw information. Impact-induced head kinematics was strongly influenced by neck stiffness, making a case for the utility of reflexively increasing neck stiffness as an effective way to reduce impact-induced head rotations and concussion risk.

Introduction

Concussions or mild traumatic brain injuries (mTBI) have serious long-term consequences, including chronic traumatic encephalopathy (CTE), which has no known cure and is linked to excessive aggression, depression, dementia, and suicide [1,2]. In the course of normal aging, similar behavioral and functional deficits in cognition, memory, and neuropathological signs such as brain plaques and neurofibrillary tangles, typically take seven to eight decades to develop. It is as though some of these processes are greatly accelerated by mTBI since the same symptoms have been observed in athletes as young as 18-25 years old [3,4].

From experiments with squirrel monkeys starting in the 1970's, Ommaya and Gennarelli reported that it was difficult to cause loss of consciousness if the head was restrained and could not rotate upon impact [5]. Other investigators have also observed that the best predictors for the risk of concussion in humans are rotational accelerations or forces [6-8]. These results suggested that both monkeys and humans are vulnerable to rotational forces in mTBI.

The human head-and-neck has three degrees of rotational freedom – pitch, roll, and yaw [9]. Nodding to gesture yes requires head rotations about the pitch axis or in the sagittal plane. Shaking one's head to gesture no involves head rotations about the yaw axis or in the horizontal plane. Bending the head toward one's shoulder is a head rotation about the roll axis or in the coronal plane. These three degrees of rotational freedom have co-evolved with the underlying musculo-skeletal elements of the head-and-neck and have become central to head-and-neck function. Over the evolutionary time scale, head-and-neck mobility have also been integrated with the central nervous system, which constantly collects and analyzes all types of information about the outside world from the eyes, ears, the vestibular system, and the proprioceptive system [9]. In monkeys and big apes, head movements about the pitch and yaw axes have increasingly become more functionally significant. For example, pitch head rotations are needed for tilting the head to look up to avoid predators or falling objects from above or to bend down such as in foraging for food. Yaw head rotations are required for looking to the left or the right such as in surveying the environment. These head movements and head-and-neck mobility may also have been particularly relevant to our bipedal ancestors as these immediate ancestors of modern humans were not particularly powerful predators or swift prey [10]. By contrast, roll head rotations have remained less employed and almost enigmatic. While the evolution of the human head-and-neck

Citation: Huang C, Husak K, Vaishnavi V, Huang R. Concussions in Boxers: Head rotations and neck stiffness. Neurol Neurosci. 2021; 2(1):1-6.

mobility in its rotational anisotropy may have in some way increased the overall fitness of the species, such head-and-neck mobility may have also introduced some differential vulnerability to injuries in impact-induced head rotations in pitch-roll-yaw.

The literature on the role of head rotations in mTBI, including studies on laboratory animals, has been reviewed recently [11]. These investigators tabulated at least 11 studies on human subjects. Nine of the most recent studies were published between 2003 and 2015. In their Figure 1, "concussive thresholds" in HAV (head angular velocity) appeared not to be different for head rotations in the coronal, sagittal, and horizontal planes. However, the significance of the head-and-neck anisotropy in concussive events has been suggested in several studies on Australia football players. These investigators have reported that in 100 cases of medically verified concussions, the majority (86%) of the impacts were to the tempero-parietal region [12,13]. This was consistent with results reported by Gennarelli et al [14] in a study on 45 primates (*Macaca Mulatta*) as well as results on human subjects from other investigators [15,16].

Knockouts in boxing are related to mTBI in other contact sports. During a typical boxing match, boxers may endure hundreds of head hits. These considerations suggest that boxing matches can be a promising area to explore the relationship between rotational forces and mTBI. In the present study, an objective was to use boxing matches as a backdrop and seek a quantitative relationship between impact-induced head kinematics and the knockout outcome as a function of the directionality of head rotations. In particular, we asked if impact-induced rotations of the human head-and-neck about the more mobile rotational axis such as the pitch and yaw axes pose more or less of a risk for mTBI than impact-induced head rotations about the roll axis. A related objective is to see whether we could reliably predict KOs from an analysis of the head angular velocities about the three degrees of rotational freedom. We also propose that the intrinsic head-and-neck anisotropy may be an important biomechanical property underlying impact-induced mTBI in addition to the magnitude and directionality of the external impact force.

Methods

The raw data in the present study came from YouTube videos of professional boxing matches. The videos are readily and freely available in the public domain. We grouped heavyweight with middle heavyweight class together in the present study. Walilko et al [17] showed that differences in the biomechanics of punches thrown by boxers across four different weight classes (from flyweight to super heavyweight) failed to reach statistical significance at the p=0.02 level.

Initially, we identified ~50 such videos by using search keywords including boxing, knockout, heavyweight, middle heavyweight. Because an objective of the present study was to examine whether the human head-and-neck is differentially vulnerable to hits associated with head rotations in pitch, roll, and yaw, we selected only matches that ended in KO or TKO in which the final and decisive head hit resulted in excessive head rotation in pitch, roll, or yaw. Although a potentially productive area of study would include oblique head hits with the resultant head rotations containing head angular accelerations in some combinations of pitch, roll, and yaw, oblique hits were not included in the present study. This is because oblique hits inevitably would entail movements perpendicular to the image plane, making it difficult, if not impossible, to extract kinematic information with the video approach.

Once we tentatively selected a YouTube match video, we immediately fast-forwarded to the end of the match and identified the decisive KO (or TKO) head hit, which typically lasted four to six video frames. We then carried out a frame-by-frame inspection of the KO head hit based on a number of criteria. First, the head of the boxer being hit must be clearly in view and identified as executing a rotational movement in pitch, roll, or yaw as a result of the head hit. This then ensured we could analyze, frame by frame, the position and the angle of the head for the derivation of the head angular velocity. Second, the gloved fist of the hitting boxer must also be clearly visible in the same four to six video frames of the head hit, as we also wanted to analyze the glove velocity as an important control factor. Third, the starting position of the head immediately before the hit must be at 0º in the pitch, roll, or yaw angles (i.e., the head must be in a normal, upright position such as that defined by the position of the boxer's head in Figure 1 before the hit). This was to ensure nearly identical initial biomechanical conditions for all the head hits, as such initial boundary condition helps to control variations in the resting lengths (and thus the tensions) of the numerous neck muscles and the configuration of the cervical vertebrate column. Fourth, once we identified the KO or TKO hit at the end of the match, we also made efforts to identify control or NKO hits from the same boxer during the same match (defined as head hits that did not result into a KO or TKO decision). NKO head hits selected for analysis must also meet the same set of selection criteria as the KO hits. While searching for suitable NKO controls, we backed up the video from the time of KO or TKO hit and selected control NKO hits as close in time as possible to the KO head hit, thereby minimizing differences in the condition of fighters such as fatigue of the boxer being hit as well as his opponent. Finally, we also aimed to end up with approximately the same number of KO cases with head rotations in pitch, roll, or yaw. In this way, nineteen of the ~50 videos were selected for detailed study. Of the nineteen, six ended in pitch KOs, six ended in roll KOs, and seven in yaw KOs. This sample distribution, however, does not imply that boxing KOs were more or less evenly distributed in hits about the pitch, roll, or yaw axes.

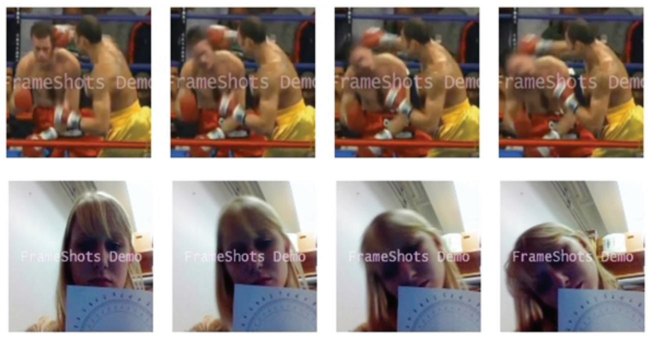

Figure 1. Top*: Sample video images of the head of boxers.* The video is taken from a boxer during a knockout hit associated with excessive head rotations about the roll axis. The human head-and-neck is not sufficiently stiff so that a well-placed hit can readily cause such head rotations. Bottom*: A scoring system for data reduction.* As the video may be shot from different distances and angles, precise assessment of the head size and head angle is a challenging task. To obtain data on head angle from images of the head as shown in the top panel, we devised a scoring system, assigning each image a head angle from a dictionary of images taken from one of us (KH) imitating the head angle of the fighter.

The top panels in Figure 1 show four frames of a typical YouTube video segment from a KO hit associated with head rotations about the roll axis. We had no control over the distance between the camera and the fighter or the angle of the camera. The sizes and the viewing angles of the fighters' heads were therefore different in different videos. To overcome the difficulty caused by such variations in the raw video data, it was necessary to devise a scoring system in order to normalize the measured data on head angular velocities of boxers from different matches. The key to the scoring system consisted of still photos of one of us (KH) showing systematically the many different head angles in pitch, roll, and yaw (bottom panels in Figure 2). We then compared the orientation of the fighter's head in single frames of our video segments with the photos in the scoring system. The head angle associated with that photo was determined and entered into a database. Multiple scorers (KH, VV, and CH) were involved in this scoring process. The values of correlation coefficient between head angle values derived from different scorers were routinely ≥ 0.95.

The lack of control over the distance between the camera and the fighter as well as the angle of the camera also made difficult the analysis of the spatial position and the velocity of the hitting fist. Because the hitting fist was always near the head being hit during the four to six video frames of the head hit, we used the head size of the boxer being hit as a yardstick to derive a normalized distance of travel for the gloved fist in different boxing matches (e.g. later in Figure 4). For the head size, we assumed the boxers have average head sizes, which we looked up from a published database. Instantaneous linear velocities of the fist were obtained by calculating the differences in normalized distance units from successive frames and dividing by the elapsed time between successive frames.

In this way, we reduced single frames of the video segment of interest into head angles as a function of time (at 30 frames per second, the elapsed time between adjacent frames being 33.3 milliseconds). Head angular velocities were obtained by calculating the differences in head angle from successive frames and dividing by the elapsed time between successive frames. Since one of our primary interests was to compare impact-induced rotations about the roll axis with those about the pitch and yaw axes, a pair-wise Student's t-test was used.

For YouTube videos, the sampling rate was 30 frames per second. As such, the values of our head angular velocities were in good agreement with those reported based on similar video analysis [12,13]. If the observed changes in adjacent frames actually occurred in a period less than 33.3 milliseconds, actual peak values of instantaneous head angular velocities would be higher. Indeed, a period of 14-20 milliseconds has been reported as the time span over which the initial impact energy is transmitted to the receiving party in football head impacts [18] and in boxing [19]. This consideration also helped us to settle a related methodological issue. Although velocities give rise to accelerations with one additional time derivative, the benefit of the conceptual rigor in tracking accelerations over velocities cannot be realized at the relatively slow sampling rate or the film rate at 30 fps. In the present study, we therefore chose velocities over accelerations.

The video analysis methodology used in the present study was similar to those used in studies on the biomechanics of head movements in athletes [12,13]. We therefore refer the readers to this reference for additional information on the calibration, measurement of error, and other details.

Results

Rotation of the head

Figure 2 shows typical profiles of head angle as a function of time in head hits from a number of boxers associated with head rotations about the pitch axis. Initial contact of the fist with the head immediately caused a rapid change in head angle. Viewed at a qualitative level, head hits that did not lead to KOs were associated with lower angular velocities while the ones that caused KOs involved higher angular velocities.

From plots like Figure 2, we derived the maximal impact-induced head angular velocity during the four to six video frames of the head hit (Figure 3). Values of maximal head angular velocities in KO head rotations were lower in hits associated with head rotations about the roll axis (Mean ± SEM as 502 ± 59 °/s) than in hits associated with head rotations about the pitch and yaw axes (1200 ± 202 °/s and 744 ± 64 °/s, respectively). The difference were significant. Pair-wise comparisons

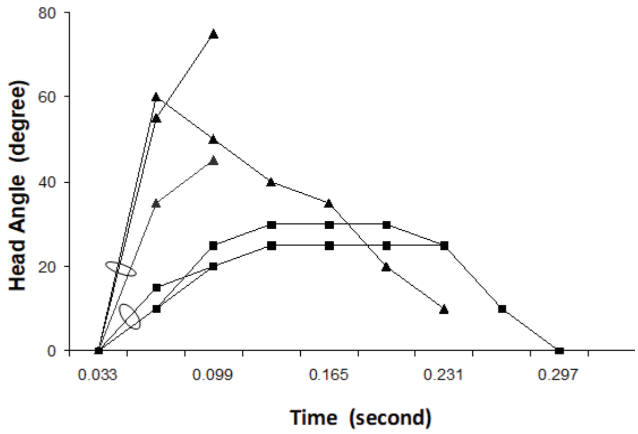

Figure 2. *A sample plot of head angle as a function of time in pitch head rotation in KO vs. NKO head hits.* The head angle changes with time in both KO and in NKO head hits. The slope of this change is greater in KO hits. Triangles: KO hits; squares: NKO hits. The head angle value of zero, which is derived from the first video frame, represents the initial head angle.

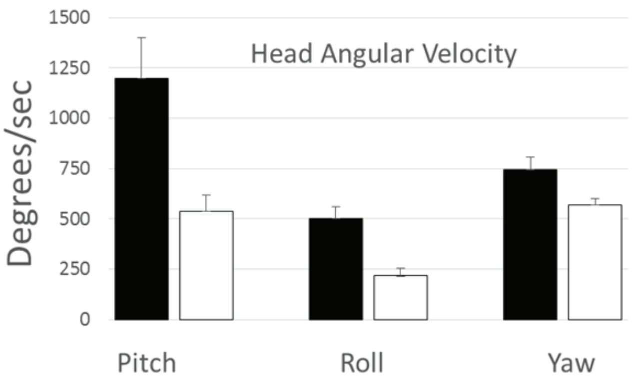

Figure 3. *Bar graph of maximal impact induced head angular velocities in KO (black bars) and NKO (no knockout, white bars) head hits.* KO head hits always involve head angular velocities that are significantly greater than those in NKO head hits regardless of the head rotations being about the pitch, roll, or the yaw axis. The KO-NKO data (lower panel) is 1200 ± 202 vs. 538 ± 81 °/s, 502 ± 59 vs. 217 ± 36 °/s, and 744 ± 64 vs. 569 ± 32 °/s, for pitch, roll, and yaw, respectively. The differences were significant with p-values of $7x10^{-3}$, $1.5x10^{-3}$, and $1.4x10^{-2}$ for pitch, roll and yaw KO-NKO comparisons, respectively. Mean head angular velocities in KOs with head rotations about the roll axis was 502 ± 59 °/s, slightly lower but not statistically significant than mean head angular velocities in NKO hits about the pitch and yaw axis (538 ± 81 °/s and 569 ± 32 °/s, respectively).

with Student's t-test generated p-values of 0.008 and 0.007 for pitch-roll and yaw-roll comparisons in KO head hits, respectively. The p-value for pitch-yaw comparisons in KO head hits was not significant (p=0.074). The implication of this finding is that the data suggest an anisotropy with respect to pitch, roll, and yaw in the concussive thresholds.

Next, we compared head angular velocities in KO head hits and those in NKO head hits. Head angular velocities in KO head hits were consistently higher than those in NKO head hits regardless of the observed head rotations about the pitch, roll, or yaw axes of rotation. The KO-NKO contrast was 1200 ± 202 vs. 538 ± 81 °/s, 502 ± 59 vs. 217 ± 36 °/s, and 744 ± 64 vs. 569 ± 32 °/s, for pitch, roll, and yaw, respectively. The differences in NKO-KO comparisons were significant with p-values being 7×10^{-3}, 1.5×10^{-3}, and 1.4×10^{-2} for pitch, roll, and yaw, respectively. The implication of this finding is that an accurate prediction of knockout is possible (e.g. better than p = 0.014) when head hits are analyzed separately in pitch-roll-yaw.

Head angular velocities in control NKO head rotations were also lower in hits associated with head rotations about the roll axis (217 ± 36 °/s) than in hits associated with head rotations about the pitch and yaw axis (538 ± 81 °/s and 569 ± 32 °/s, respectively). The difference was significant. Pair-wise comparisons with Student's t-test generated p-values of 6×10^{-4} and 1.4×10^{-5} for pitch-roll and yaw-roll comparisons in NKO head hits, respectively. (The p-value for pitch-yaw comparisons in NKO head hits was 0.065.) It suggests a higher stiffness or the ability of the human head-and-neck to resist impact force about the roll axis with respect to the pitch and yaw axes assuming the forces delivered by the fist were relatively uniform regardless of the three axes of rotational freedom (see later in Figure 4). The implication of this finding is not immediately apparent.

Taken together, KOs with head rotations about the roll axis occurred at lower head angular velocities than KOs with head rotations about the pitch or yaw axis. Indeed, the average head angular velocities in KOs with head rotations about the roll axis was 502 ± 59 °/s, only slightly lower than the average head angular velocities in NKO hits with head rotations about the pitch and yaw axes (93% and 88%, respectively, but the differences were not statistically significant). This observation suggests that magnitudes of head angular velocity alone without specifying the pitch, roll, or yaw axes would not be predictive of a KO. However, within hits that cause head rotations about a single axis (pitch, roll, or yaw), reliable prediction of KOs based on head angular velocity measurements can reach ≥ 98% confidence level.

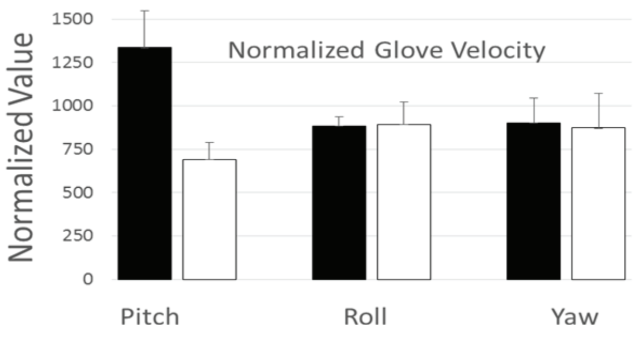

Figure 4. *Bar graph of normalized maximal fist velocities in KO head hits (black bars) and NKO hits (no knockout, white bars).* Fist velocities in KO hits were not significantly higher than that in NKO hits regardless of the pitch, roll, or yaw hits. The KO-NKO data is 1335 ± 214 vs. 690 ± 97, 883 ± 56 vs. 893 ± 131, and 902 ± 143 vs. 872 ± 201 for pitch, roll, and yaw hits, respectively (in relative units). The differences between KO hits and NKO hits were not significant (p-values being 0.045, 0.96, and 0.91 for pitch, roll, and yaw NKO-KO comparisons, respectively). Within head hits causing head rotations about a single axis of rotation (pitch, roll, or yaw), reliable prediction of KO cannot be made based on fist velocities alone.

Movement of the fist

We next derived the maximal fist velocities (in normalized units, see Methods) within the period characterized by rapid changes in head angles (Figure 4). Fist velocities in control NKO head rotations were not significantly different in hits associated with head rotations about the roll axis (893 ± 131, in normalized velocity unit) than those associated with head rotations about pitch and yaw axes (690 ± 97 and 872 ± 201, respectively). Pair-wise comparisons with Student's t-test generated p-values of 0.33 and 0.93 for pitch-roll and yaw-roll comparisons in NKO head hits, respectively.

Fist velocities in KO head hits, like those in NKO hits, were also not significantly different in hits associated with head rotations about the roll axis (883 ± 56) than those associated with head rotations about pitch and yaw axes (1335 ± 214 and 902 ± 143, respectively). Pair-wise comparisons with Student's t-test generated p-values of 0.094 and 0.87 for pitch-roll and yaw-roll comparisons in KO head hits, respectively.

Moreover, the velocities of the striking fists in KO head hits were not significantly higher than those in control NKO hits regardless of the impact-induced head rotations being in pitch, roll, or yaw – the KO-NKO contrast being 1335 ± 214 vs. 690 ± 97, 883 ± 56 vs. 893 ± 131, and 902 ± 143 vs. 872 ± 201 for pitch, roll, and yaw, respectively. Examinations of fist velocities between KO hits and NKO hits generated p-values 0.045, 0.96, and 0.91 for pitch, roll, and yaw NKO-KO comparisons, respectively. Lumping KO and NKO hits together, the mean fist velocities are all within 3% of each other, being 862, 888, and 887 for pitch, roll, and yaw hits.

Taken together, KOs with head rotations about the roll axis did not occur at lower fist velocities than KOs with head rotations about the pitch or yaw axis. Moreover, within head hits associated with head rotations about a single axis of rotation (pitch, roll, or yaw), reliable prediction of KOs cannot be made based on fist velocity alone as if the external impact force, by itself, is not a reliable or sufficient determinant of the KO outcome. However, the significance of these findings on the lack of correlation between fist velocities and the KO outcome in the present study is limited since we did not have the opportunity to systematically vary the fist velocities. One can still draw the conclusion that both the nature of the impact force (magnitude, directionality, etc.) and the biomechanical properties of the head-and-neck are important to the KO outcome. Relevant biomechanical properties include the structural and functional anisotropy in pitch-roll-yaw as well as the neck stiffness which measures how the head-and-neck can resist impact-induced head rotations.

A cursory examination of Figure 4 readily reveals that values of fist velocities in hits associated with head rotations about the roll and yaw axes are generally close, irrespective of the head hits being of the KO or the NKO type. The statement could also cover fist velocity in NKO hits with head rotations about the pitch axis. A singular item that seems out of place is the higher maximal value and the larger range of fist velocity in KOs associated with excessive head rotations about the pitch axis (although not statistically significant, p = 0.045).

There may be a practical explanation. There are three major types of punches to the head in boxing – the uppercut, the jab, and the hook. The hook, depending on the exact location of the head where the fist lands, e.g. near the temple or the jaw, can produce head rotations about the roll or the yaw axis. If all head hits in the yaw and roll axis in the present study can be attributed to the hook, this can explain the similarities in mean fist velocities in hits associated with head rotations about the roll and yaw axes. A jab almost never resulted into a KO outright, but repeated jabs can certainly do their damage. Comparing the hook and the uppercut, the uppercut is more of a full-body effort. The power of the uppercut is generated from the ground up – a strike that requires a sequential synchronization from the feet, legs, through the hip with a winding or twisting motion involving the trunk, the shoulder, and the upper limbs. The motor control involved in the uppercut is far more complex and involves more muscles than in the hook, hence the timehonored instructions in boxing to focus on the technique rather than power, shifting body weight, and footwork, etc. Therefore, it should not be surprising that the fist velocity in the uppercut alone may involve a larger range of variation (Figure 4). Taken together, we conclude that fist velocities, loosely related to the impact force of the fist, are not statistically different in KO vs. NKO hits and in hits associated with head rotations round the pitch, roll, or the yaw axis. The implication of this finding is that the fist data reinforces the notion that the outcome of a head-impact event is dependent upon the nature of the impact force as well as the biomechanical properties of the head-and-neck.

Discussion

MEMS Sensor Utility: Pitch, Roll, and Yaw Information

Rowson et al [18] used helmets with MEMS sensors (MicroElectroMechanical System) and recorded a total of 1712 impacts ≥ 10 g, with 172 impacts ≥ 40 g in linear acceleration and 143 impacts ≥ 3000 rad/s^2 in angular acceleration (one g refers to force exerted to an object by normal earth gravity). They concluded that linear and rotational forces to the head are both significant in tackles. In a more detailed study, Broglio et al [7] attempted to correlate head impact data with concussions; 54,247 impacts (≥15g) and 13 concussions were recorded over four seasons of play in two high school teams (78 players, or a concussion rate of ~4% per player per season). The magnitudes of impact force were similar to those in Rowson et al [18]. Broglio et al [7] identified that rotational accelerations ≥ 5582.3 rad/s^2, linear accelerations ≥ 96.1 g, and impact location (front, top, back) yielded the highest predictive value of concussions by fitting a classification tree with queries at five levels, including the magnitudes of the linear and rotational acceleration as well as the location of the hit. To predict a priori 13 concussions in 54,247 hits, the ratio is 0.024%. With the queries, concussion prediction improved steadily from 1.9% (one question) to 55.6% (all five questions). The rate of false positive, however, is 98% – mTBI did not occur in impacts involving angular accelerations > 5582 rad/s^2 in 671 of the 684 hits. Broglio et al [7] concluded that prediction of concussions from biomechanical data alone has a success rate of 55.6% at best (near chance level). This conclusion was consistent with an earlier investigation by Guskiewicz and his colleagues [6]. Subsequent attempts to improve the analytical methodology have made incremental but not fundamental improvements [20-22].

In previous studies, investigators apparently lumped pitch, roll, and yaw rotations together [9-12]. Such lumping may be why investigators consistently failed to find the underlying associative relationship between mTBI and rotational forces. A finding in the present study is that rotations in pitch, roll, and yaw are not equally potent in causing KOs. The average impact-induced head angular velocities in KOs with roll head rotations is only slightly lower than the average head angular velocities in NKO hits associated with pitch or yaw rotations and the difference is not statistically significant (Figure 3). Although our results are derived from boxing, the results reflect the importance of the intrinsic anisotropic properties of the human head-and-neck in vulnerabilities to concussions and may be relevant to football and other contact sports. Simply setting a single value of head angular acceleration, e.g. 5582.3 rad/s^2 as concussion threshold without taking into consideration differential vulnerability of the human head-and-neck to rotational forces in pitch, roll, and yaw may not be enough [7,21,22].

Figure 3 also suggests a path forward toward the goal of MEMS technology in the detection, identification, and diagnosis of mTBI. Concussive threshold is likely to be anisotropic with respect to pitch, roll, and yaw. Each of the thresholds in pitch, roll, or yaw will be somewhere between the tops of the clear bars and the filled bars. The derivation of the concussive thresholds requires two pieces of information. First, we need more data on non-injurious head kinematics, such as those in Figure 3. Second, we need to establish the relationship between such data and the concussion thresholds. In sum, more work is needed.

Concussion Prevention: Neck Strength and Neck Stiffness

When a hit occurs to the head, the physics of the event is described by Newton's Second Law, $f = m_h a_h$, where $[m_h]$ is the mass of the head being hit and $[a_h]$ is the head acceleration immediately after the hit. Since the severity of the head injury is expected to be directly proportional to the magnitude of $[a_h]$, we can reduce injury by choosing a larger $[m_h]$. This can be accomplished by increasing the neck stiffness, defined as the ability of the head-and-neck to resist impact-induced head movements [23,24].

A key factor affecting the effective head mass $[m_h]$ is therefore the head-and-neck musculature. Conventional neck strength is defined as how much force can be exerted by the muscles of the head-and-neck. While neck strength is a significant predictor of concussions [25], football players with great neck strength are still regularly concussed if an impact force catches the head and neck in a state of low stiffness. In boxers with substantial neck girths, their head-and-necks are not sufficiently rigid to withstand well-placed head hits from highly trained opponents [Figure 1]. Therefore, addressing neck strength alone may not be sufficient to reduce concussion risk [26]. Neck stiffness, however, may be the most promising route for attenuating the risk of mTBI during head impact events [27-29].

Consistent with the notion above that the evolution of human head-and-neck may have favored mobility over strength, both the mass and strength of the head-and-neck musculature are relatively meager in comparison with limb muscles for grasping and locomotion. Consequently, when the head of a boxer is hit, exaggerated head rotations are readily evident.

For a demonstration of the feasibility of increasing neck stiffness to reduce mTBI risk, one can check out the YouTube video on a head butt between a goat and a cow at https://www.youtube.com/watch?v=YGa3_EvIShA in which the goat walked away while the cow lay concussed. A plausible explanation for such an improbable outcome is that the goat had a high neck stiffness at the moment of impact. With the impact force and the reactive force being the same for both the cow and the goat, increasing the effective mass of the head $[m_h]$ will lead to a decrease in impact-induced head acceleration $[a_h]$. A very stiff neck can elevate the effective mass for the goat's head sufficiently to allow the goat to walk away without a concussion. For this reason, early investigators have postulated that a stiffer neck can reduce head acceleration during impact [24]. While athletes may not have much control on an external impact force to his or her head, one certainly retains some control over his own neck stiffness. If a goat could avoid a concussion when confronted by seemingly large odds, there may yet be hope for humans under similar circumstances. One can make a case for the role of neck stiffness in modulating impact-induced head rotations and thereby reducing mTBI risk.

Acknowledgements

The authors express their gratitude for the Acute Effects of Neurotrauma Consortium in assisting and coordinating the conduct of this project. This study was supported by the Leonard Wood Institute in cooperation with the U.S. Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-14-2-0034. This study was also supported by the Helen S. Boylan Foundation and a grant from the UMKC Institute for Data Education, Analytics and Science.

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