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Wearable Sensors for Head Impact Dosimetry

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***Abstract*— This paper discusses the design and performance of a wearable head impact dosimeter that can be utilized to detect the onset, spatial variation, and temporal evolution of physiological changes in the brain caused by sub-concussive head impacts, enabling important new head injury prevention initiatives.**

Keywords*—wearable sensor, dosimeter, sub-concussive head impacts, diffuse axonal injury, brain imaging, damage threshold*

I. Introduction

Wearable sensors are routinely used in many recreational, medical, industrial, and military applications as injury prevention dosimeters. These devices monitor and limit exposures below tissue/organ damage thresholds from environmental hazards such as ultraviolet light, loud noises, high temperatures, toxic chemicals, biological agents, ionizing radiation, and X-rays. A variety of personal monitoring devices are also used to monitor and protect athletes [1] from the damaging consequences of conditions such as dehydration, physical exhaustion, high blood pressure, low blood oxygen, and elevated/irregular heart rate, including in-situ [2] and real-time wireless [3] monitoring during sporting events.

Designing wearable sensors that can help monitor and reduce head impact injury risks in athletic, military, and industrial environments has emerged as an important new challenge in preventative medicine. The direct medical costs for sports and recreational concussions in the US currently exceed $100 billion each year, yet concussions are now known to represent just the tip of the iceberg. A significant body of research published since 2010 has revealed that physiological changes in the brain resulting from the accumulation of many small direct or indirect head impacts, none of which on their own trigger any concussion symptoms, can also lead to neurological injuries and long-term degenerative neural disorders [4-8]. Because of this evidence, concussions are beginning to be viewed not as a single distinct class of injury, but as one segment of a wide and continuous spectrum of cumulative head impact injuries that all trigger some level of axonal damage, often referred to as diffuse axonal injury (DAI) [9]. Although all 50 states have now introduced youth head injury safety laws, and stricter head injury safety guidelines have been introduced by the NCAA, the current standard of care is still to wait until an athlete demonstrates observable concussion symptoms before they are removed from play, even though such symptoms may take several days to fully present, and even though the far greater number of sub-concussive head impacts may be causing even greater risks to athletes' physical and academic performance.

A wide range of wearable devices and computerized neurocognitive testing tools has been developed to try and diagnose concussions once they have already occurred [10-12]. While these tools can be helpful, none of them are able to see below the "tip of the iceberg" to monitor physiological changes in the brain resulting from cumulative sub-concussive head impacts.

In this paper, we demonstrate a promising new class of wearable head impact dosimeter that leverages advanced sensor and imaging informatics to deliver the injury screening capabilities of an MRI machine in a sensor that is worn behind the ear as a small adhesive patch, and can monitor the onset and accumulation of both transient and persistent physiological changes in the brain resulting from repetitive sub-concussive head impacts. We discuss key sensor design considerations to enable high-volume manufacturing of a universally deployable wearable head impact dosimeter.

II. Methods

Members of the UCSB NCAA D1 women's soccer team (along with a group of age-matched controls) were monitored for the effects of cumulative head impacts throughout a 3-month soccer season and a 3-month post-season washout period. Data from prototype skin-affixed wearable sensors (X2 Biosystems X-Patch) were used to quantify the number and severity of head impacts. The cumulative impact power transferred from the external environment to the brain was calculated and utilized as a neuro-mechanical biomarker to monitor the onset and accumulation of both transient and persistent physiological changes in the brain resulting from sub-concussive head impacts [8]. In parallel, high angular resolution diffusion spectrum MRI (DSI) of white matter (WM) and voxel-wise multi-dimensional diffusion anisotropy (MDA) data were acquired and used to quantify corresponding physiological changes in the brain [8].

III. Results

A. Impact Data

An average of 215 head impacts per player were registered over the season (low = 95, high = 327), or ~20 impacts per player per week. Fig. 1 shows histograms for the calculated (a) total power (linear + rotational) transferred to the brain from all individual head impacts, and (b) the daily total cumulative impact powers for all athletes over the entire 3-month season. Routine headers, tackles, collisions, and falls are observed to deliver 0.25kW and 5kW per impact to the brain, which is significantly lower than the single impact values of 15-20kW that have been reported to have a high probability of causing a concussion [13], and none of the athletes were diagnosed with or reported any concussion symptoms. The cumulative daily impact power distribution reveals routine daily impact loads extending out to 60 kW, with 6 players receiving daily impact loads between 68kW and 110kW.

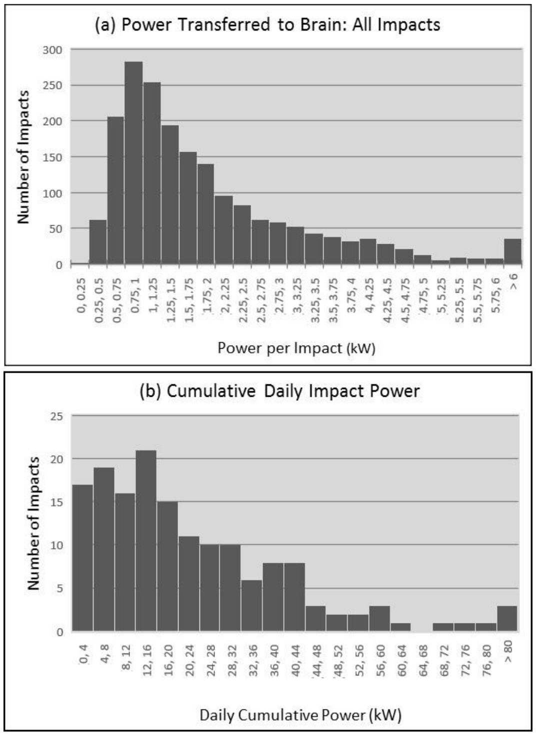

Figure 1. Histograms of (a) total impact powers (linear + rotational) transferred to the brain for all individual head impacts, and (b) the daily total cumulative impact powers for all athletes throughout the 3-month soccer season.

B. Imaging Data

The imaging results revealed the accumulation of widely distributed clusters of "outlier voxels" for the athletes, showing significant changes in WM diffusion anisotropy throughout the season, when normalized with respect to baseline values [8]. For the controls, none of the in-season scans were statistically different from the corresponding baseline scans. These clusters of outlier voxels were observed for the players in both deep WM and at the white matter-cortical border, including at the cortical sulci. This observation is consistent with finite element modeling of head impacts, which predict that relative displacements and deformations are widely distributed throughout the brain due to coupling of linear and rotational degrees of freedom [14,15]. More advanced finite element brain models that include tissue-specific mechanical properties and detailed structural morphologies have predicted several additional important impact responses, including spatial localization of stress fields and tissue damage at morphologic features such as the cortical sulci [16], which we have also observed.

One implication of these findings is that even modest impacts, at levels traditionally thought to be safe, may generate localized regions of high stress and potentially irreversible changes in the brain. This localization and change of cellular function has been proposed as one possible explanation for recent observations that beta amyloid deposition is concentrated at the cortical sulci in the brains of professional football players who were diagnosed post mortem to have suffered from CTE [17,18]. The prevalence of CTE in subjects with no history of concussion suggests that sub-concussive hits are sufficient to lead to the development of CTE [18], and it has recently been argued that it is the chronic and repetitive nature of head trauma, irrespective of concussive symptoms, that is the most important driver of disease [18]. The results reported here demonstrate the potential ability to monitor, and even prevent, the onset of such localized damage using a wearable head impact dosimeter.

C. Correlating Sensor and Imaging Data

When the number of outlier voxels in the above WM clusters was plotted as a function of the maximum cumulative daily impact dose, along with the total cumulative impact power measured over the 2, 3, and 4 week periods immediately preceding each player's mid-season scan (Fig. 2), the data exhibited a non-linear relationship, with a pronounced threshold behavior for the onset of outlier voxels.

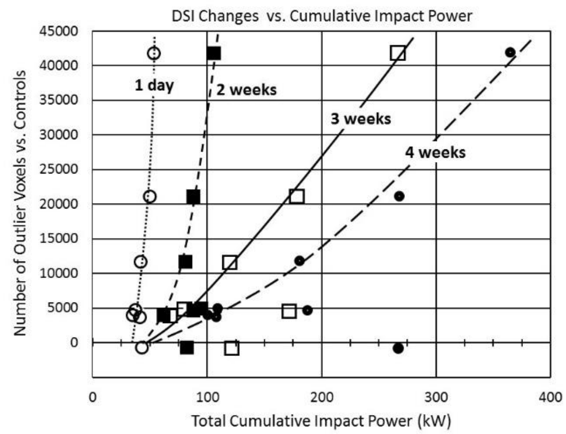

Figure 2. Calculated number of outlier voxels vs. maximum cumulative daily impact dose, and total cumulative impact power measured over 2, 3, and 4 week periods immediately preceding each player's mid-season DSI scan.

The cumulative power threshold above which outlier voxels are observed is on the order of 35-50 kW, which falls within the range of typical cumulative daily impact loads for all athletes in this study. The differences between the results as a function of time indicate that a significant fraction of the observed outlier voxel groupings emerge and persist during the two-week period following impact exposure, and that some fraction then begins to dissipate. Accumulated daily exposure doses of 35-50 kW triggered transient changes (present for in-season scan, but not in post-season washout scans), whereas accumulated daily exposure doses above 100 kW triggered persistent WM changes (observed for in-season scans and post-season washout scans).

IV. Discussion

A. Understanding the Observed Threshold Behavior

The threshold behavior observed in Fig. 2 has several potential explanations. Recent studies using cultured neurons and atomic force microscopy to directly measure the threshold forces required to morphologically deform axons, mechanically break microtubules in axons, impair axonal transport, trigger focal axonal swelling (FAS), and eventually compromise axonal survival, have also observed an initial threshold for transient local deformation of the axons, and a more abrupt higher threshold above which irrecoverable axonal damage occurs [19,20]. These threshold forces fall well within the range predicted by finite element models to be generated by routine sub-concussive head impacts in many athletic activities [15].

B. Optimizing Dosimeter Design

The prototype sensors used in the above study suffered from many design limitations. The excessive size of the devices requires that great care be taken to avoid having them worn partially on the neck, as illustrated in Fig. 3(a), instead of fully on the mastoid, which results in corruption of the motion data due to excessive soft tissue motion [21]. The size and capacity limitations of wearable batteries, coupled with the power consumption of available processor, MEMS sensor, and wireless connectivity ICs, also severely limited operational lifetimes of these skin-affixed sensors between re-charging, and restricted device clock speeds and sampling rates to levels that may not fully capture the impact frequency response relevant to injury [22]. Additional flaws included zero level offset errors due to mechanical distortions within the sensors, and the presence of large numbers of non-impact-related accelerometer and gyroscope traces generated by loosely attached sensors, device handling, and other spurious motion. The dosimetry application demonstrated in this present study required extensive manual inspection and manipulation of impact data to remove spurious traces and correct for offsets, followed by complex data analytics, machine learning, and finite element analyses to achieve acceptable sensitivity and specificity. The dosimeter design illustrated in Fig. 3(b) overcomes the above limitations, leveraging recent innovations in electronic processor, sensor, battery, wireless charging, and wireless communication components, along with system-in-package (SIP) integration. In addition to enabling embedded neuro-mechanical biomarker firmware algorithms that eliminate the need for extensive data processing and analytics, this design also significantly improves device-to-device performance uniformity, and enables high-volume manufacturing, automated testing, and much lower unit costs. These advances will enable delivery of larger numbers of the devices for more comprehensive field testing, and investigations of dosimeter threshold variations across larger study populations.

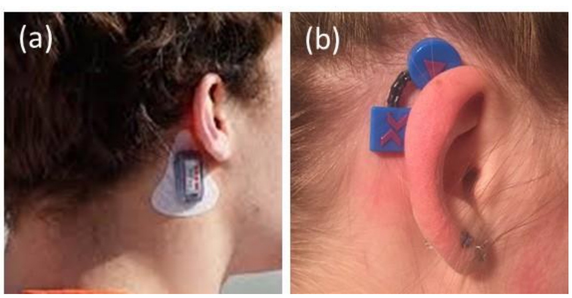

Fig. 3. The size of current skin-affixed head impact sensors forces them to be worn (a) partially on the neck, which, combined with the excessive weight of the devices, results in corruption of the motion data due to excessive soft tissue motion. The sensor design shown in (b) eliminates these limitations.

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