Multi-Sport Evaluation of Concussive Brain Strain via Instrumented Mouthguard Kinematics

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I. INTRODUCTION

Mild traumatic brain injury (mTBI), or concussion, is a pressing global health issue, with an estimated 1.6–3.8 million cases annually in the United States alone [1]. Head impact biomechanics, characterised by multidirectional linear and rotational kinematics, are strongly associated with brain injury risk [2]. Specifically, rotational forces have been found to lead to greater brain tissue deformation and an elevated risk of concussion [3]. Advancements in sensor technology, particularly instrumented mouthguards (iMGs), have set a new standard in capturing on-field kinematic dynamics of head impacts, including those resulting in concussion. IMGs offer high accuracy in kinematic measurements due to the tight coupling to the upper dentition, which minimises the potential for relative motion between the sensor system and the skull [4]. Additionally, iMGs can directly measure the six-degree-of-freedom linear and rotational accelerations of head impacts, in contrast to methodologies that estimate rotational measurements [5]. Though previous studies have reported on-field kinematics and brain strains associated with concussion, this study marks the first dataset with direct measurements rotational acceleration during concussive impacts across a wide range of sports, levels of play, and both genders. The aim of this short communication is to identify the 95th percentile maximum principal strains (MPS) for impacts associated with clinically diagnosed concussions or visual signs of concussion in this broader athletic context.

II. METHODS

Impact Selection

Leveraging open-source and previously published datasets [2][4][6-7], we analysed 26 impacts associated with either visual signs of concussion or diagnosed concussions, collected using the Stanford MiG2.0, in-mouth (ADXL377/L3G4200D), and Prevent Biometrics iMG. These impacts represent a range of sports, including professional mixed martial arts, high school lacrosse, collegiate rugby, and both high school and collegiate American football. Within this dataset, two impacts involved female athletes from lacrosse and rugby. Thirteen impacts displayed immediate visual signs of concussion (VSC) without clinical diagnosis, while six were recognised as concussive by reports from athletes or trainers. The remaining seven impacts were identified as concussive based on having the highest angular velocities on the date of concussion diagnosis. This approach was adopted to address the challenge of confirming concussions in the absence of clear video evidence, and the difficulty in isolating the injury-causing impact in sports where athletes frequently sustain numerous high-magnitude impacts in rapid succession. Additionally, we compared a control dataset of 1,795 non-concussive impacts from collegiate and high school football players [4].

To ensure comparability between the Stanford and Prevent iMGs, non-concussive impact data from both devices were compared. The cumulative distribution function for key kinematic measures (e.g. peak linear acceleration, peak angular acceleration, and peak angular velocity) was analysed, and a good correlation in peak angular velocity was found across the two measurement devices. Kinematics processing and filtering methods for the utilised mouthguards are described in detail in prior work [2][4][6-7].

Maximum Principal Strain Calculations

A deep learning head model [8] was used to calculate the peak maximum principal strain (MPS) in each brain element for every impact. For regional comparisons, MPS values from the considered dataset were aggregated for each brain region, and the 95th percentile of these values was calculated (MPS95), providing a single metric of brain deformation for each region (Table I). A similar method was applied for global comparisons, where MPS values from all brain elements were compiled from the same dataset to calculate the global MPS95 (Fig. 1).

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III. INITIAL FINDINGS

Regional and global MPS95 thresholds were established for each dataset (Table I). The Injury group combines VSC and concussive impacts. MPS95 for the Injury group was significantly greater than the No Injury group for all considered brain regions ($p<.001$) (Table I). This same finding was observed for global comparisons of MPS95 between groups ($p<.001$) (Fig. 1). Notably, the brainstem and cerebellum exhibited the lowest strains compared to other brain regions of interest, while the corpus callosum and midbrain exhibited the largest strains across both groups. For all comparisons, a Wilcoxon Rank Sum Test at a significance level of 0.01 was used to compare two conditions, with a Bonferroni correction of n=7 during regional comparisons.

TABLE I
REGIONAL DIFFERENCES IN MPS95 BETWEEN DATASETS

	MPS95			
Region	***Injury (n=26)***	***No injury (n=1795)***	***Concussive (n=13)***	***VSC (n=13)***
Brainstem	0.10	0.04	0.11	0.09
Corpus Callosum	0.24	0.07	0.31	0.17
Cerebellum	0.06	0.02	0.07	0.05
Gray Matter	0.20	0.07	0.24	0.16
Midbrain	0.19	0.08	0.22	0.16
Thalamus	0.15	0.05	0.18	0.11
White Matter	0.19	0.07	0.23	0.14

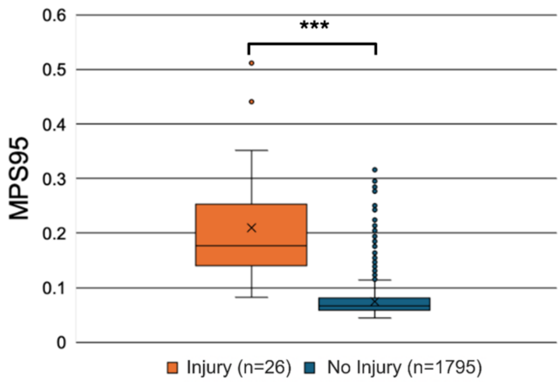

Fig. 1. MPS95 values for Injury and non-Injury impacts. MPS95 was significantly greater in the Injury group (** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$).

IV. DISCUSSION

This study presents the largest dataset of iMG-measured concussive impacts and their associated strains across diverse contact sports. Regional and global brain strains from the Injury group are consistent with concussive impacts documented in NFL studies [9-11], while control group strains are notably lower [9]. These discrepancies might reflect differences in play styles between collegiate/high school and professional football, and recent updates to the NFL kinematics data which inform these established thresholds [11]. In our analysis, the brainstem and cerebellum experienced lower strains, contrary to other reports of high strain in these areas [5][12].

The findings of this study can increase the precision and generalizability of strain-based metrics in predicting clinical injury. Moreover, by identifying regions of the brain susceptible to strain-related damage, this study informs the development of protective headgear designed to minimize region-specific injuries. Future research will focus on validating deep learning head model predictions of brain strain against a validated FE model.

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