Finite Element Simulations of a Concussion Case in High School Soccer

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I. INTRODUCTION

Finite element (FE) analysis is an important computational method for relating the kinematics of head impacts to the mechanical responses of discrete brain regions and specific injury outcomes. Earlier studies reconstructed sporting head impacts from video to obtain kinematics of the head, which were used to drive FE models of the human head. The Royal Institute of Technology (KTH) FE Human Head Model was used to simulate 58 head impact cases in professional American football (25 concussion, 33 no injury) [1] that were previously reconstructed using video analysis and anthropomorphic test devices (ATDs) [2]. Maximal principal strains of 0.21 in the corpus callosum and 0.26 in the grey matter were associated with a 50% risk of concussion. The KTH model was also used to simulate 40 cases of head impact in professional Australian football and rugby (27 concussion, 13 no injury) [3] that were previously reconstructed using video analysis [4] and rigid body modelling [5]. For a 50% risk of concussion, maximal principal strains of 0.13, 0.15, and 0.26 were reported for the thalamus, corpus callosum and white matter, respectively.

More recently, advances in technology have enabled the development of wearable sensors, which have been used to monitor head impacts of athletes *in vivo*. A previous study [6] used the Stanford instrumented mouthguard sensor (MiG) to monitor the head impacts of collegiate American football players. One player was diagnosed with concussion having sustained 15 impacts in the four days leading up the diagnosis. When simulated with the KTH model, 14 of the impacts resulted in 95th percentile maximal principal strain values of lower than 0.15 for the whole brain, but the remaining impact had an approximate value of 0.45. There is limited FE modeling of video-verified head impact sensor data of concussion cases, which are necessary to establish injury tolerance limits. Therefore, the aim of the current study was to contribute to this knowledge by simulating the impacts associated with a concussion case in male high school soccer using an FE human head model.

II. METHODS

As part of a larger study, high school soccer players wore headband-mounted Triax Smart Impact Monitor (SIM-G) sensors during competitive games [7]. The SIM-G has been shown to correlate with reference measures, underestimating magnitudes by 15% when tightly coupled [8], but errors increased when coupling became sub-optimal [9]. Games were filmed to video-verify head impacts recorded by the SIM-G sensor. One male player sustained a concussion, which was associated with two consecutive impacts that were recorded by the sensor and captured on video. The first impact was to the front of the head from the shoulder of an opposing player with peak kinematics of 27.6 g, 19.2 rad/s and 2318 rad/s^2. The player subsequently fell to the ground and the second impact was to the rear of the head with peak kinematics of 39.7 g, 34.9 rad/s and 4858 rad/s^2.

The KTH model is a detailed and parameterised FE model, which has been previously described [1]. The model included the scalp, skull, brain, meninges, cerebrospinal fluid, parasagittal bridging veins, and a simplified neck based on the anatomy of a 50th percentile male human head. Brain tissue was modelled using a nonlinearly elastic 2nd order Ogden model coupled with broad spectrum viscoelasticity. The model has been extensively compared with post-mortem human subject experimental data [10]. The dura mater was tied to the skull to run simulations using high-performance computing [11]. The skull was approximated to be rigid, and the time histories of linear and angular acceleration from each impact event were prescribed to the head centre of gravity of the model. The 95th percentile values of maximum principal strain were calculated for the main brain regions.

III. INITIAL FINDINGS

The first impact to the shoulder of the opposing player was found to have 95th percentile maximum principal strain values that were approximately half that of the values calculated for the second impact to the ground (Table I). In addition, values of 95th percentile maximum principal strain from the first impact were below previously published values associated with a 50% likelihood of concussion.

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TABLE I:
SIMULATIONS OF SPORTS-RELATED HEAD IMPACTS USING THE KTH FE HUMAN HEAD MODEL

Study	Kinematics Data	Sport	Metric	Region	Value
[1]	ATD reconstructions	Male professional American football	MPS associated with a 50% risk of concussion	Corpus callosum	0.26
				Grey matter	0.21
[3]	Rigid body reconstructions	Male professional Australian football and rugby	MPS associated with a 50% risk of concussion	Thalamus	0.13
				Corpus callosum	0.15
				White matter	0.26
[6]	Stanford MiG sensor	Male collegiate American football	MPS of 15 impacts in four days before concussion	Whole brain	Up to 0.45
Current study	Triax SIM-G sensor	Male high school soccer	95th percentile MPS of first impact to the shoulder of opposing player	Thalamus	0.08
				Corpus callosum	0.10
				White matter	0.09
				Grey matter	0.10
				Whole brain	0.09
			95th percentile MPS of second impact to the ground	Thalamus	0.16
				Corpus callosum	0.22
				White matter	0.19
				Grey matter	0.21
				Whole brain	0.19

ATD: anthropomorphic test device. MPS: maximum principal strain.

IV. DISCUSSION

Using video-verified data from wearable sensors for a concussion sustained by an adolescent soccer player, the current study found whole brain 95th percentile maximum principal strain values from the second head impact to the ground that were above previously reported tissue-level axonal injury strain values [12]. Furthermore, 95th percentile maximal principal strain values were greater than the thresholds of 50% risk of concussion in multiple brain regions developed in previous studies of professional American football, Australian football and rugby using the same head model [1,3]. Strains in these specific brain regions (e.g., thalamus, corpus callosum), some higher than whole brain estimates, were previously identified as good predictors of diagnosed injury [1,3]. Most studies of concussion using FE analysis have focused on adult professional and collegiate athletes, and it remains unknown how age may affect injury susceptibility and functional deficits for similar head kinematics and tissue-level deformations. Furthermore, it has been suggested that repeated head loading in short time periods may increase injury risk [13]; however, current FE head models are only able to simulate discrete impacts and cannot incorporate residual damage from previous impacts. Future efforts should simulate head impacts in a variety of youth sports using FE head models to establish injury tolerance limits, which are required to inform injury prevention efforts in sports, such as rule changes and protective equipment.

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