Direct-Interpolation-Based Prediction of White Matter Brain Peak Maximum Principal Strain in Varsity Canadian Football Players Considering Brain Volume

Véronique Bouvette, Yvan Petit, Louis De Beaumont, Samuel Guay and Eric Wagnac

I. INTRODUCTION

Recent studies have underscored the crucial role of repetitive subconcussive head impacts (rSHI) in the development of long-term neurodegenerative conditions [1], prompting biomechanical investigations into their effects on brain tissue. American football serves as an exceptional model for studying rSHI, with on-field head kinematics easily measurable using head-impact measurement devices. The recorded time-history of head kinematics can be translated into mechanical responses of the brain, such as maximum principal strain (MPS), which is a predictive measure of injury [2], using validated head finite element models (hFEM). Personalising hFEM to accommodate player-specific geometrical variations has been shown to enhance injury prediction [3], with brain scaling to players' brain volume used as a simple yet effective personalisation method.

However, hFEM simulations are time-consuming, posing a challenge to the study of rSHI as football players undergo numerous impacts per season. To address this challenge, machine-learning models have been developed to predict brain MPS based on head kinematics time-histories [4]. These models often face issues with generalisations because they are heavily influenced by the specific type of impact on which they were trained [5], neglecting player-specific geometrical variations.

This study aims to develop a predictive model of brain white matter (WM) peak MPS responses using on-field head kinematics time-histories captured from a cohort of varsity Canadian football players, accounting for brain volume through direct interpolation techniques.

II. METHODS

Data Collection

Throughout an entire regular season, a varsity Canadian football player consistently wore the Vector (Athlete Intelligence) instrumented mouthguard during both games and practices. This equipment recorded a total of 628 head impacts, capturing triaxial time-histories of linear and rotational accelerations and rotational velocity. In parallel, cerebral imaging was conducted on a group of 22 players to measure their brain volume, acquiring magnetic resonance (MR) images on a 3-T Siemens Prisma MR imager using a high-resolution 32-channel head coil.

Optimal Experimental Design: Regular Season

Each of the 628 head impacts was then simulated by applying triaxial linear and rotational accelerations time-histories to the centre of gravity of the Total Human Model for Safety (THUMS) hFEM AM50 by Toyota [6]. Prior to simulations, adjustments were implemented to the hFEM by uniformly scaling it across all three dimensions to match the brain volume of the individual player in question.

Following the simulations, the peak MPS of the brain's WM was measured for each impact. These MPS responses, along with uncorrelated kinematic characteristics of impacts – specifically, triaxial head impact directions – were utilised to establish an optimal design of experiments (ODE) for the entire season.

To achieve ODE, an A-optimal scheme was deployed through Lunar CAE Odyssee (Hexagon) software. This optimisation process involved streamlining the number of head impacts deemed representative of an entire football season down to 20. These 20 impacts served as the foundation for building the interpolation model.

Interpolation Modeling

Modeling Dataset. To incorporate the effect of brain volume while minimising sample size, a periodic sampling approach was employed, selecting six brain volumes from the total of 22 measured. THUMS models were then adjusted to match the specific brain volume of each of the six players. Subsequently, the 20 impacts considered representative of a season, forming the ODE, were simulated for each of these adjusted models, resulting in 120 scenarios. The peak MPS of WM was calculated across these scenarios.

Performance dataset. A separate dataset, distinct from the modeling dataset, was created for evaluation purposes. This dataset consisted of 20 randomly selected distinct impacts from the 628 initial complete dataset and two different brain volumes, again distinct from modeling dataset, totalling 40 scenarios. The scenarios were

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simulated using scaled THUMS hFEM, and WM peak MPS responses were measured and designated as expected values for comparison with the interpolation model.

Impact Feature Extraction. Sensitivity analysis on the modeling dataset explored the influence of kinematics on WM peak MPS responses. This analysis led to the selection of 75 coefficients derived from the Haar wavelet transformation of triaxial rotational velocity time-history for each head impact. Additionally, brain volume was considered, resulting in a total of 76 features per scenario. These features served as inputs for the interpolation model.

Predictive Modeling. With 76 features to predict WM peak MPS, the best direct interpolation method was determined through cross-validation using Lunar CAE Odyssee (Hexagon) software. Radial basis function (RBF) and inverse distance weighted (INVD) interpolation methods were tested with complete cross-validation of 120 folds. The best method was selected based on a criterion of the coefficient of determination r^2.

Predictive Capabilities. The interpolation method minimising the r^2 criteria was chosen and tested on the performance dataset. Predictive capacities were assessed by calculating r^2 between the predicted and true values of the performance dataset. The normalised mean absolute error (NMAE, normalised with range of expected peak MPS) was also calculated. To evaluate the model's prediction capabilities for changes in brain volume only, a new performance evaluation was conducted using the 20 impacts utilised in modeling and an unseen brain volume.

III. INITIAL FINDINGS

Adaptive RBF interpolation yielded the best results, with an average r^2 of 0.999 for cross-validation. However, its predictive accuracy diminished when applied to the 40 unseen scenarios of the performance dataset, resulting in an r^2 value of 0.252. The NMAE stood at 0.234. The evaluation for unseen brain volume only with modeling head impacts revealed an r^2 of 0.982 and a NMAE of 0.109. Figure 1 shows performance evaluations.

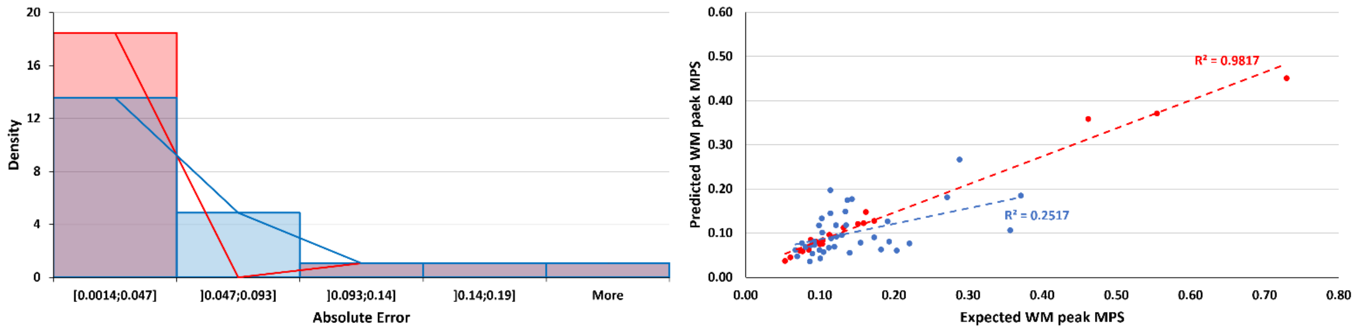

Fig. 1. Density curve of absolute errors distribution (left) and correlation (right) between expected and predicted WM peak MPS for new head impacts and brain volumes (blue) and for new brain volume only (red).

IV. DISCUSSION

Prediction capabilities for changes in brain volume show promise, but further refinement is necessary to ensure accurate predictions that encompass head impacts over an entire season. Initial findings indicate that using 20 head impacts do not adequately represent the impacts experienced throughout a full season. Therefore, alternative methods need to be explored, such as various reduction techniques and adjustment of impact counts. The selection of representative impacts based on extracted features should be considered. Additionally, careful attention should be given to the criteria used to select the interpolation method. Since r^2 does not provide information on the direction and position of the prediction line formed by the predicted and expected values, it may not be sufficient for selecting the most appropriate interpolation method to accurately capture the effects on brain volume. However, the initial findings suggest that volume can be integrated into the interpolation model of MPS, and brain volume personalised MPS prediction model could be achieved, facilitating the study of rSHI.

V. REFERENCES

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ERRATUM

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After publication, it was acknowledged that three contributors were mistakenly omitted from the list of authors: **Nicolas Bailly, Lionel Thollon, and Dorian Salin**.

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