

Cumulative Directional Strain and Fractional Anisotropy Changes in the Corpus Callosum After a Football Season

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1. Introduction

Repetitive head impacts in contact sports, such as American football, are linked to long-term neurodegenerative impairments (Kwiatkowski et al., 2024). These conditions develop gradually, making early detection challenging. In the short term, repeated subconcussive head impacts can alter brain white matter (WM) microstructure, often measured through changes in fractional anisotropy (Δ FA). Such alterations may emerge after a single season of play, indicating cumulative effects.

Accurately quantifying head impact exposure (HIE) is key to understanding WM changes. While traditional metrics focus on acceleration, strain-based measures—such as the 95th percentile maximum principal strain (95MPS) estimated via finite element modeling—better correlate with Δ FA (Miller et al., 2022). Additionally, the time between hits may influence WM vulnerability, as shorter recovery times could exacerbate structural alterations (Merchant-Borna et al., 2016).

Given the variability in region-specific WM vulnerability, localized strain metrics may better capture the relationship between HIE and FA alterations. Since axonal stretching is a key injury mechanism, investigating strain along different fiber orientations could provide insights into WM disruption. This study examines Δ FA from pre- to post-season in a Canadian varsity

football player and their association with cumulative time-between-hits-95MPS in different fiber directions within the corpus callosum (CC), a region particularly vulnerable to head impacts.

2. Methods

2.1 Changes in fractional anisotropy

FA was measured pre- and post-season in CC subregions: anterior frontal (CC_Fr_1), posterior frontal (CC_Fr_2), occipital (CC_Oc), parietal (CC_Pa), precentral/postcentral gyrus (CC_Pr_Po), and temporal (CC_Te). MRI data were acquired using a Siemens PRISMA 3.0T scanner (Siemens Healthcare, Germany) with a 32-channel head coil. Diffusion MRI data were processed using Tractoflow (Theaud et al., 2020).

Δ FA were calculated as the difference between post- and pre-season values, then normalized to pre-season FA to facilitate regional comparisons.

2.2 Strain metrics

The player wore a Vector instrumented mouthguard (Athlete Intelligence, WA, USA) throughout the season. Triaxial acceleration data were input into a personalized Total Human Model for Safety (THUMS) v4.02, customized based on the player's WM segmentation and brain volume (Bouvette et al., 2025). All head impacts

were simulated, and 95MPS was computed for each CC subregion.

The player’s WM bundle segmentation, derived from diffusion MRI, was registered to THUMS. The diffusion direction of each finite element was estimated by averaging the directions of enclosed voxels, weighted by their distance to the element’s center. The strain tensor was then aligned with these orientations to compute directional strain components: perpendicular (_p) and oriented (_o) (Zhou et al., 2024).

2.3 Cumulative head impact exposure

Within each CC subregion, cumulative strain was computed over the season. Strain from each impact was summed, weighted by the time since the previous impact, following the approach of Merchant-Borna et al. (2016).

2.4 Analysis

Pearson-*r* was used to assess the relationship between cumulative strain metrics (C-95MPS, C-95MPS_p, C-95MPS_o) and normalized ΔFA (n-ΔFA) across CC subregions.

3. Results and discussion

The defensive back sustained 628 head impacts throughout the regular season. The associated cumulative strain across the different subregions of the CC is presented in Table 1 along with the associated n-ΔFA.

Table 1. Cumulative strain metrics and normalized fractional anisotropy changes in corpus callosum.

Regions	C-95mps	C-95mps_p	C-95mps_o	n-ΔFA
CC_Fr_1	1993.1	1200.4	0.0265	0.4458%
CC_Fr_2	1809.0	983.3	0.0220	1.4998%
CC_Oc	1892.1	1142.5	0.0242	-0.7016%
CC_Pa	1860.2	1048.1	0.0242	0.0187%
CC_Pr_Po	1736.2	933.7	0.0218	1.1249%
CC_Te	1905.4	1046.1	0.0233	-0.1863%

The Pearson-*r* coefficients for cumulative strain and n-ΔFA across CC subregions were -0.552 for C-95MPS, -0.606 for C-95MPS_p, and -0.505 for C-95MPS_o. This suggests that ΔFA are better explained by the cumulative HIE derived from the strain perpendicular to the fiber direction. Fig. 1 illustrates the interactions between n-ΔFA and cumulative strain metrics.

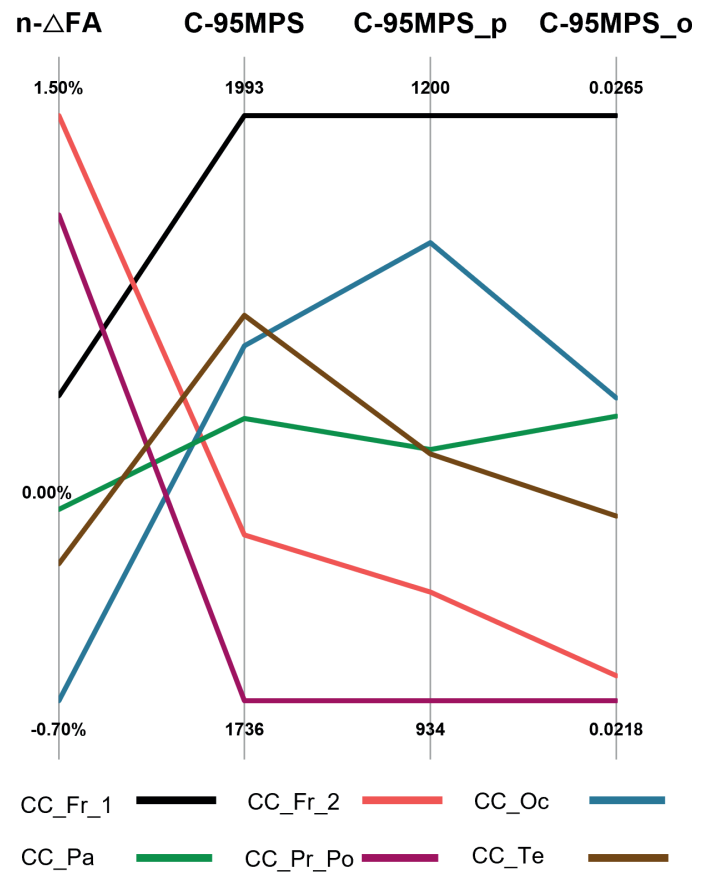


Figure 1. Relative ranking of head impact exposure by metric: n-ΔFA compared to cumulative strain metrics in regions of the CC.

Credit: Véronique Bouvette.

Fig. 1 highlights that the negative Pearson-*r* is primarily driven by CC_Fr_2 and CC_Pr_Po, where the highest n-ΔFA occur despite minimal cumulative strains. CC_Oc, CC_Pa and CC_Te also align with the general correlation trend, but their influence remains more neutral. Interestingly, CC_Fr_1 exhibits high cumulative strain relative to its associated n-ΔFA, contributing in the opposite direction of the overall negative correlation.

The ranking of subregions differs across cumulative strain metrics. While CC_Fr_1, CC_Fr_2, and CC_Pr_Po are consistently ranked, CC_Pa, CC_Oc, and CC_Te show variability. This suggests that different strain metrics capture distinct biomechanical effects, influencing FA differently.

4. Conclusions

Cumulative strain, particularly perpendicular to fiber orientation, correlates with n-ΔFA in CC subregions.

Region-specific strain measures may better capture WM vulnerability than traditional impact-based metrics. However, subregional variations highlight the need for further research to refine player monitoring and injury prevention strategies.

Conflict of Interest Statement

The authors declare no conflict of interest.

Contributor Roles

VB: Conceptualization, Methodology, Formal Analysis, Software, Writing original draft, Visualization; SG: Data curation, Software Investigation, Methodology; YP: Conceptualization, Resources, Supervision; LDB: Resources, Supervision, Funding acquisition; SAV: Investigation; LT: Methodology; NB: Methodology; EW: Conceptualization, resources, Supervision, Writing review & editing, Project administration.

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