Computational helmet ranking outcome is affected by the choice of injury metrics

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I. INTRODUCTION

Traumatic brain injury (TBI) in cyclists is a growing public health problem and the bicycle helmet is the most commonly used gear for injury prevention. The finite element (FE) head model has been increasingly used to engineer safer helmets by mitigating brain strain peaks. Existing research primarily used maximum principal strain (MPS) as the injury parameter, while white matter (WM) tract-related strains, increasingly recognised as effective injury predictors, have rarely been used for helmet evaluation. The current study aimed to evaluate how close the tract-related strains discriminate the helmet performance compared to the prevalently used MPS.

II. METHODS

Experimental Testing

All experiments were performed by the Folksam Insurance Group and are described in greater detail in [1]. In brief, 17 commercially available bicycle helmets (helmets A–Q, Fig. 1(A)) were purchased and tested in the laboratory to obtain impact kinematics. Each helmet was coupled with a 50th percentile male Hybrid III headform and dropped onto a 45° anvil (impact speed: 6 m/s) at three different impact conditions (Fig. 1(B), referred to as XRot, YRot and ZRot), each of which was expected to cause rotational motion primarily within one anatomical plane. In total, 51 helmeted impact experiments were performed, with linear and angular accelerations at the centre of gravity of the headform recorded.

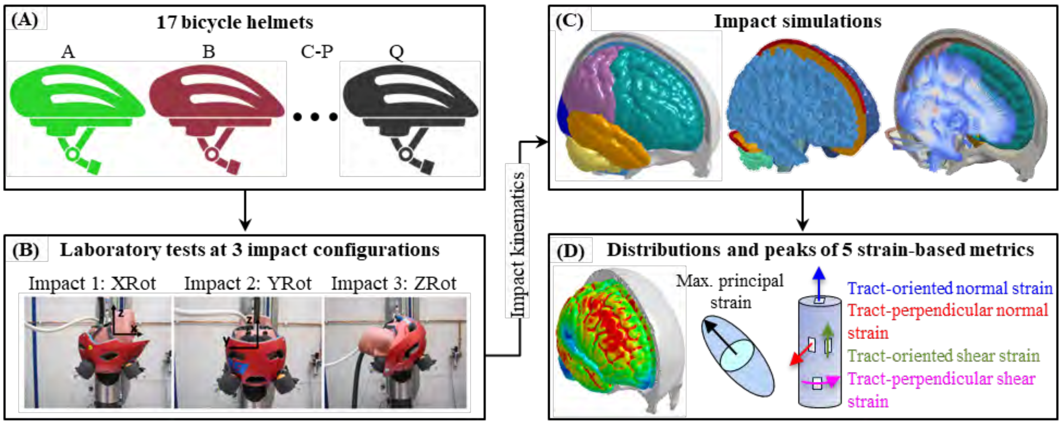

Fig. 1. Illustration of study design and methodology.

Computational Modeling

To estimate the localised brain strain responses, the experimental kinematics from the helmeted laboratory tests were imposed to an anatomically detailed computational head model with embedded fiber tracts (i.e. the ADAPT model in Fig. 1(C)) [2]. To evaluate the brain responses in helmeted impact simulations, 5 strain-based metrics were employed (Fig. 1(D)), including one brain tissue-level strain (MPS) and four WM tract-related strains (i.e. maximum tract-oriented normal strain (MTON), maximum tract-perpendicular normal strain (MTPN), maximum tract-oriented shear strain (MTOS), and maximum tract-perpendicular shear strain (MTPS)). The MPS was extracted for all brain elements and directly output from the simulation. The tract-related strains were only computed for WM elements with the exact mathematical equations presented earlier [3]. The peak values accumulated over time were extracted for all strain-based metrics. We ranked the 17 helmets (Helmets A–Q) based on the strain peaks averaged across three impact conditions, the same approach as used previously [4].

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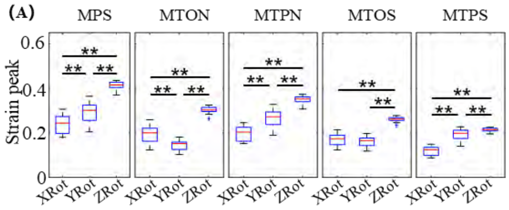
III. INITIAL FINDINGS

The helmeted impact condition affected brain strain peaks, but the effect was inconsistent among the five metrics (Fig. 2(A)). In the 17 helmets, strain peaks based on MPS, MTPN and MTPS were significantly different ($p < 0.001$) in all three impact conditions, in which the ZRot induced the highest values, followed by YRot and XRot. For MTON, the ZRot remained as the condition with the highest value, while the YRot produced significantly smaller strain peaks than the XRot. When switching to MTOS, no significant difference ($p = 0.19$) was noted between XRot and YRot, while the ZRot instigated higher values than the other two impact conditions.

For the helmet ranking, the same results were noted among the five strains for the high-ranked helmet, while significant disparities were noted in median-ranked and low-ranked helmets (Fig. 2(B)). For example, Helmet Q was ranked the top (i.e. lowest strain), followed by Helmet D as the second and by Helmet M as the third, independent of the strain type. For the low-ranked helmet, Helmet P was ranked lowest based on MPS, MTPN, MTOS and MTPS, while Helmet N was ranked lowest based on MTON. We further quantified this ranking-related disparity using Kendall's tau test (Fig. 2(C)), with the coefficient value varying from 0.58 to 0.93. When grouping the three impact conditions together, only three Kendall's tau tests attained coefficient values over 0.8 (i.e. MPS vs. MTPN, MTON vs. MTOS, and MTPN vs. MTPS).

(A)



(B) Low-ranked (Large strain) ↔ High-ranked (Small strain)

MPS	P	G	K	B	N	C	A	F	I	E	J	L	O	H	M	D	Q
MTON	N	B	P	G	C	K	A	I	F	E	J	L	O	H	M	D	Q
MTPN	P	G	B	K	N	C	A	F	I	E	J	L	O	H	M	D	Q
MTOS	P	N	G	B	K	C	A	F	I	E	J	L	O	H	M	D	Q
MTPS	P	K	B	G	N	A	F	C	E	I	J	L	H	O	M	D	Q

(C)	MPS	MTON	MTPN	MTOS
MPS				
MTON	0.64			
MTPN	**0.93**	0.58		
MTOS	0.78	**0.83**	0.74	
MTPS	0.77	0.42	**0.83**	0.57

Fig. 2. (A) Summary of 5 strain-based metrics for three loading conditions (**$p < 0.001$, Wilcoxon matched-pairs signed-rank test). (B) Ranking of 17 helmets based on 95th percentile strain peaks averaged from three impact conditions. (C) Kendall's tau coefficient values to evaluate the influence of strain metrics on helmet ranking.

IV. DISCUSSION

The current study investigated the peaks of 5 strain-based metrics in 51 helmeted impact simulations (17 helmets, 3 impact conditions). Our results showed that both the helmet type and the impact condition affected the strain peaks. The helmet ranking was affected by choice of injury metrics, providing new insights on the virtual evaluation of helmet efficacy. The study might also serve as a reference for helmet improvement, especially to those intended to mitigate fiber deformation.

In our earlier study [3], eight FE head models were used to evaluate helmet performance. The current work significantly extended our earlier effort by utilising the ADAPT model that uniquely featured with conforming meshes for the interface between the brain and cerebrospinal fluid, providing complementary and independent information to its eight counterparts used in [4]. Moreover, current literature employed MPS to evaluate helmets, with only three previous studies, to the best of the authors' knowledge, using MTON [5-7]. Thanks to the embedded fiber tracts in the ADAPT model, we were able to assess helmets by collectively examining the normal and shear strains along and perpendicular to the fiber tract as well as MPS (Fig. 1(D)).

As both the current work and the early one [3] used the same helmet tests [1], results from these two studies could be compared and integrated. When ranking the 17 helmets, our study found the outcome was dependent on the choice of strain type (Fig. 2(B)–(C)). Comparable disparities were also presented by Fahlstedt *et al*. [4], with a primary focus on how the choice of FE head model affected the helmet ranking outcome. As no consensus has been reached on the best brain injury predictor and discordant responses were noted among different FE head models, these two successive studies collectively highlight that caution should be exercised when using computational models to rank helmet performance.

V. REFERENCES

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