Comparison of a 6-year-old child finite element model to a scaled adult model using simulated fall events for three levels of surface compliance

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Abstract— **A newly developed finite element model of a 6-year-old child simulated the brain response to physical impacts onto low, moderate, and high compliance surfaces representing unhelmeted falls, helmeted falls, and well-padded conditions. Results for this model were compared against a scaled version of a currently available adult finite element model used in previous concussive research. The purpose of this study was to compare trends of response and assess how material property definitions, model geometry, and anatomical differences between models affect the peak strain response. The new 6-year-old model, showed lower peak maximum principal strains for low impact durations, but higher strains for moderate and long duration impacts. While both models had a tendency to produce similar values, the 6-year-old model still showed higher strains overall. For representative helmeted impacts, strains likely to cause a concussion were observed, even at a 3.0 m/s from the 6-year-old model. The newly developed model of a 6-year-old child showed different strain responses from a scaled adult model, identifying higher risk of concussive injury even in well-padded conditions.**

Keywords— **Impact biomechanics, child head injury, concussion, finite element modelling, falls**

I. Introduction

By the age of 6 years old, many children are enrolled in sports programs to promote physical activity and learn new skills. As with all sporting and recreational activities, there are inherent risks of accidental injury from falls. Regardless of the cause, falls often result in a head impact. The impacting surface is influential in how forces are transmitted to the head and brain [1]. Different surfaces have varying levels of compliance, which change the impact characteristics as well as the resulting strain on the brain tissue [1]. Impacts to rigid, low-compliance surfaces typically result in high-magnitude short duration events, and softer surfaces yield lower magnitude longer duration events. Using finite element (FE) models, a representation of the strain response of the brain can be calculated to see how the magnitude and duration of the impact interact to cause brain tissue strain. Since concussions are reported to be a strain-based injury [2-5], FE modelling offers a method to understand and quantify the trauma experienced by the brain from head impacts causing concussion in children.

Finite element models are used extensively in adult concussion research, using reconstructions of impact events to determine stresses and strains in brain tissue [5-8]. There are limited studies surrounding the biomechanics of concussion involving young children, including FE models. Recently, an FE model designed for concussion research paired with physical reconstruction techniques was developed by Koncan et al. [9]. Validation data are still very limited for brain models, and often do not cover a large range of impact velocities, durations, or locations, likely due to limitations and complexities of conducting cadaver research. Impact duration is important to consider for FE modeling as the viscoelastic parameters of the brain tissue govern the time dependent shear modulus, which influences the resulting strains in the brain [10]. The rate at which the shear moduli change depends on the viscoelastic parameters that are used, drawn from brain tissue studies. For very short duration impacts, the initial shear modulus may be the most influential parameter on peak strain. When moderate to high levels of compliance are added resulting in longer impact durations (~40 ms), the viscoelastic parameters become more influential.

Running FE models using a variety of impact conditions, magnitudes, and durations will help to establish trends in the brain response. Identifying differences in trends is important for new FE models of children, as it can shed light on how documented differences in size [11], material properties [12-15], and the arrangement of grey and white matter in the brain [11, 16] interact to create risk for concussive injury. Scaling adult models has been used to study concussive impacts in children [17-18], but only size is addressed using this method.

The purpose of this study was to test the sensitivity of the newly developed FE model of a 6-year-old child for simulated falls at three levels of surface compliance. The 6-year-old model was compared against a scaled version of the University College Dublin Brain Trauma Model (UCDBTM) [19-20]. Comparisons between models will be used to assess the influence of the differences in material properties, tissue arrangement, and geometry on the brain strain response.

II. Methods

The 6-year-old model being tested in this study was developed and validated by Koncan et al. [9]. The model was created using an MRI of a 6-year-old child and includes the skull, CSF, pia, tentorium and falx, grey matter, white matter, cerebellum, and brainstem.

A subset of physical impact tests conducted on the Hybrid III 6-year-old head form were taken from a previous study and were simulated in this current study [1]. Impacts were conducted at three levels of surface compliance to elicit three groupings of impact durations typical of sports: short (~5 ms), moderate (~15 ms), and long (~25 ms) [1, 21]. Steel was used to represent a low compliance, characteristic of unprotected falls onto rigid surfaces. A 0.025 m thick vinyl nitrile (VN) foam was used to represent a moderate compliance, characteristic of a protected or helmeted fall [22]. A 0.067 m thick Rubatex R338 rubber foam was used to represent a high compliance for falls onto well-padded surfaces such as a gymnastics mat.

Impacts were conducted at three different velocities: 1.5 m/s, 3.0 m/s, and 4.5 m/s, covering a low to high range of fall velocities which are consistent for children from fall simulations [23-24]. Impacts to steel were not conducted at 4.5 m/s to prevent equipment damage. The front of the head was chosen as the impact location to reflect a common impact site in children's falls. Finite element model responses of the 6-year-old model were compared to a scaled version of the UCDBTM, both run using Abaqus finite element software (Dassault Systèmes, 2019).

Equipment: Impacts were conducted using a monorail drop rig. The head and neck form were attached to a drop carriage, which were then lifted to the prescribed height and dropped onto the anvils. Impact velocity was measured with a time gate positioned 0.02 m of the impact anvil.

An instrumented Hybrid III 6-year-old head form was used in this study, attached to a non-directional neck form. A non-directional neck was used since the standard Hybrid III neck form has a directional design to properly reflect flexion and extension movements from car crash environments [25-27]. The neck form is further described by Oeur et al. [1], along with details regarding data collection, and filtering.

Finite element models: The average version of the 6-year old model presented by Koncan et al. [9] was used for this study. Viscoelastic properties of the 6-year-old brain model and the scaled adult model are shown in Table 1 and Table 2 respectively. The 6-year-old model employs the Ogden hyper-viscoelastic model for the brain tissue, and has a continuous mesh for the brain matter connecting to the CSF, where the scaled adult model has a contact surface definition to allow relative brain-skull motion. For further details regarding model development and validation, readers are directed to the papers by Koncan et al. [9], and those by Horgan and Gilchrist [19-20].

Table 1 Viscoelastic material properties of the brain of the 6-year-old child finite element model

	Initial shear modulus (kPa)	Ogden material constant α	g1, τ1 (s), g2, τ2 (s), g∞
Grey matter	6.97	0.59	0.45, 0.021, 0.30, 0.2, 0.25
White matter	8.71		
Brain stem	15.7		
Cerebellum	6.97		

The 6-year-old model was compared against the scaled version of the UCDBTM [19-20]. The scaled version of the UCDBTM was created by modifying the model to 90% of its original size. While the scaled model does not match the size of the new 6-year-old model, it was scaled based on a brain size study [28], and is being used to serve as a benchmark of response since it has been used in previous studies of concussion in young children [17-18]. Material properties for the scaled model were not altered from the original UCDBTM [19-20], which employs a linear viscoelastic model for the brain tissue.

Table 1 Viscoelastic material properties of the scaled adult brain model

	Short term shear modulus (kPa)	Long term shear modulus (kPa)	Decay constant (s^{-1})	Bulk modulus (GPa)
Grey matter	10	2.0	80	2.19
White matter	12.5	2.5		
Brain stem	22.5	4.5		
Cerebellum	10	2.5		

The model responses were compared based on a commonly used metric in concussive research, maximum principal strain (MPS). Comparisons of MPS were made for responses in the grey and white matter for each model, assessing how strain patterns differ between models.

Statistics: Two factorial ANOVAs were run to identify main effects of velocity and compliance on the model strain responses in the grey matter and white matter. Independent t-tests were then run, comparing the two model responses at each level of velocity and compliance. Statistical tests were run using IBM SPSS Statistics V 19.0 (Armonk, New York, USA) using an alpha level of 0.05 for the factorial ANOVAs ($p<0.05$), and an adjusted alpha level for the t-tests to account for multiple comparisons ($p<0.05/8$, $p<0.0063$).

III. Results

Peak resultant linear acceleration, and peak resultant rotational acceleration results are shown in Table 3 for all velocity and compliance conditions. A summary of the strain responses in the grey and white matter are shown in Fig 1 and Fig 2. Main effects of compliance and velocity were observed for maximum principal strain in the grey matter and white matter ($p<0.05$). Peak strain increased with increasing impact velocity for all cases except in the white matter to the VN foam at 3.0 and 4.5 m/s.

Table 3 Peak resultant linear (PLA, measured in g's) and rotational acceleration (PRA, measured in rad/s^2) for frontal impacts

	Steel		VN foam		Rubber foam	
	PLA	PRA	PLA	PRA	PLA	PRA
1.5 m/s	115.7	4451	17.7	977	9.2	560
3.0 m/s	354.5	17075	41.1	3715	22.4	1445
4.5 m/s	-	-	97.5	7411	46.2	2845

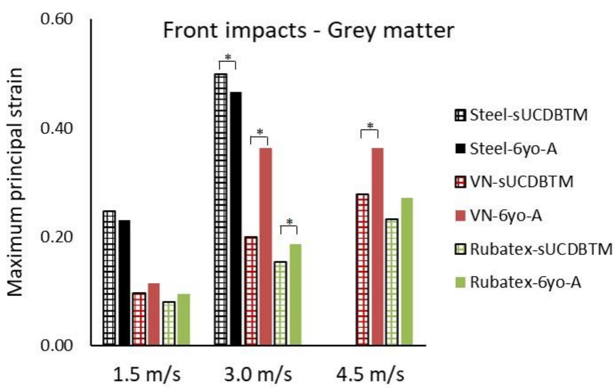

Fig. 1 MPS values in the grey matter for front impacts to low (steel = black), moderate (VN foam = red), and high (Rubatex rubber foam = green) compliance surfaces for two finite element models of the brain. Statistically significant results marked by *

Largest differences in MPS values in the grey matter between the 6-year-old model and scaled UCDBTM were for impacts onto the VN foam at 3.0 m/s (0.36 vs 0.20), where largest differences in MPS values in the white matter were for impacts to steel at 3.0 m/s (0.22 vs 0.43). In the grey matter, the 6-year-old model showed lower strains than the scaled UCDBTM for low duration impacts, but higher strains for the moderate and longer duration impacts. Trends were similar for strains in the white matter, though differences between the two models were minimal for the moderate and longer duration impacts.

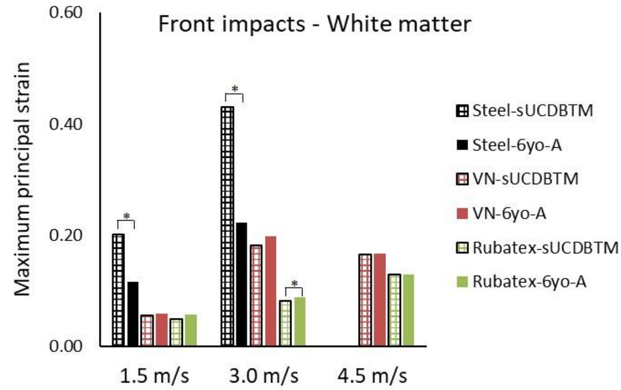

Fig. 2 White matter MPS values impacts to low (steel = black), moderate (VN foam = red), and high (Rubatex rubber foam = green) compliance surfaces for two finite element models of the brain. Statistically significant results marked by *

IV. Discussion

On average, MPS values from the 6-year-old model were 5% lower for low duration impacts, 47% higher for moderate duration impacts, and 25% higher for the long duration impacts in the grey matter. For the white matter, the 6-year-old model had 45% lower strains for low duration impacts, and 6% higher strains for both the moderate and long duration impacts. Despite the 6-year-old model having a more compliant material model than the scaled adult model, strains in the white matter of the 6-year-old model were on average 50% smaller than those experienced in the grey matter, whereas for the scaled adult model, strains in the white matter were 45%, 30%, and 15% smaller for low, moderate, and long duration impacts. The accurate representation of the folds of the white matter of the 6-year-old model added some structural rigidity to the cerebrum since all white matter is connected, whereas in the scaled UCDBTM this is not the case. A sectioned view of the two models is shown in Fig 3, highlighting differences in representation of the white matter.

Geometric differences between models will also have influenced the results, given the two models have different geometry. The scaled adult model is 179 mm long and 143 mm wide, where the 6-year-old model is 179 mm long and 145 mm wide. Geometry is unlikely to affect responses on the same scale as differences from material models. Danelson et al. [29], examined how geometry affects responses of FE models, finding that size differences were more important than shape, however shape could influence the distribution of strain. Since this work examined only frontal impacts, expanding the scope to include other impact locations would be beneficial to better understand how impact location affects how strain moves through the developing brain. Additionally, a better understanding of how strain moves through the brain at different levels of compliance could inform innovations in protective equipment, offering better protection and potentially lower risk of head injuries.

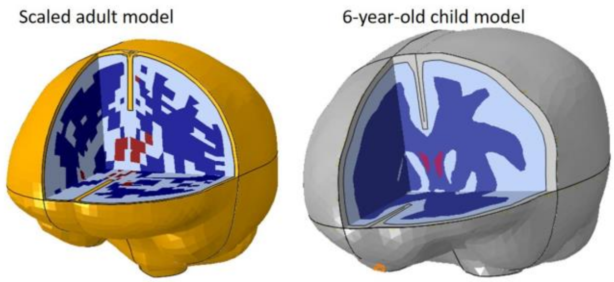

Fig. 3 Sectioned view of the scaled adult model (left) and the 6-year-old child model (right) showing the differences in white matter (dark blue) distribution

The boundary conditions of the two models also differed, with the scaled adult model using a contact surface between the brain and CSF to facilitate relative brain-skull motion, where the 6-year-old model had a continuous mesh, connecting the brain to the CSF. The contact surface modelling approach may lead to strain concentrations in areas with complex geometric contours, where the tied interface would not experience the same phenomena. Despite these differences, the 6-year-old model showed higher strains in compliant conditions, and so it is likely that strain concentrations from contact are not as influential as material model definitions. Further work is required to better understand how head injury differs in children compared to adults, and using youth-specific FE models are a valuable tool for continuing in this line of work.

V. Conclusions

The 6-year-old model showed higher strains in more compliant conditions, with lower strains for short duration events compared to the scaled adult model. The highly accurate representation of the white matter of the 6-year-old model provided added structural rigidity compared to the scaled UCDBTM, and reduced the penetration of strain into the white matter for low duration events, despite a 43% lower shear modulus. Using a scaled adult model to represent children in injury reconstructions is inappropriate as there are significant differences in strain responses that will influence conclusions of studies pertaining to risk of injury. Overall, the 6-year-old model presents a more anatomically precise tool to investigate head injury in young children.

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Conflict of Interest

The authors declare that they have no conflict of interest

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