The effect of head-forward posture on risk of lower neck dislocation during head-first impacts: a computational investigation

Mario Mongiardini, Duane Cronin, Ryan D. Quarrington

Abstract Despite the established link between head-first impacts (HFI) and subaxial cervical facet dislocation (CFD), developing an accurate injury model has proven challenging. Previous experimental studies indicate that pre-HFI head-forward posture (HFP) may increase CFD risk, but this has not been confirmed. The aim of this study is to investigate the effect of anterior head eccentricity on head-neck kinematics, kinetics, and CFD risk, during HFI. A sensitivity analysis was conducted using computer simulations with a modified and adapted GHBMC head-neck model. Pre-impact head eccentricity (head-T1 horizontal distance; horizontal Frankfort Plane) was varied between 0 mm and 50 mm, at 5 mm increments. Peak C7/T1 shear load, a predictor of lower neck dislocation, was highest in the HFI simulations for anterior head eccentricity greater than 20 mm. This result is consistent with a recent pilot HFI experiment, highlighting the need for further computational and experimental investigation of pre-HFI head-neck posture on neck injury risk. Future studies should focus on potential variations of this critical threshold when considering the combined effect of pre-impact head flexion and extension rotation.

Keywords Cervical facet dislocation, GHBMC, head-first impacts, head-forward posture, sensitivity analysis.

I. INTRODUCTION

During inverted head-first impact (HFI), the sudden stop of head motion causes the torso to transfer a downward inertial load through the cervical spine [1]. Such events may occur during vehicle rollovers, exerting significant force on the neck and causing subaxial cervical facet dislocation (CFD) [2]. Despite this established causal link between HFI and CFD, replicating the injury in experimental HFIs has proven challenging. CFD has occurred sporadically during inverted drop HFI experiments, but the factors influencing its occurrence for those specimens are unclear [3-4]. More controlled, low-rate experimental studies have repeatedly produced CFD in head-neck specimens by allowing anterior head translation and maintaining a horizontal Frankfort Plane (FP) while applying quasi-static axial compression [5-6]. This loading produces an 'S-shaped' or 'ducking' neck posture, causing lower-neck intervertebral flexion and anterior shear that leads to CFD. The influence of head inertia was not considered in these quasi-static experiments, but the eccentric head-forward posture (HFP) that was created likely increases the risk of CFD during an actual HFI.

Preliminary results from a recent combined computational and experimental study of head-neck inverted drops with a pre-impact HFP (horizontal FP) recorded the ducking neck posture immediately after impact, followed by high intervertebral compression and shear forces in the lower neck (an indicator of CFD risk) as the torso compressed the neck [7]. Despite limitations of the neck tissue injury criteria that precluded the computer model from replicating a CFD, the simulations predicted a high CFD risk for impact velocities of 2 m/s, which is lower than the minimum velocity previously reported for neck injuries [4]. Follow-up HFI physical testing (HFP: 30 mm eccentricity, horizontal FP) produced C7/T1 CFD, supporting the simulation predictions but also highlighting some limitations of the model response to HFI. High simulated peak impact forces and excessive head bouncing, relative to the experiments, were consistent with observations from similar HFI simulations [8]. These simulation limitations precluded a detailed analysis of the head-neck mechanics immediately following impact and may confound future simulation-based investigations of HFI and CFD.

The main aim of this research activity was to conduct a comprehensive sensitivity analysis, using detailed computer simulations, to explore the potential role of pre-impact head forward eccentricity on the risk of CFD during HFI. As part of this simulation activity the previous head-neck model was also improved to overcome current limitations.

II. METHODS

A sensitivity analysis on the effect of pre-impact anterior head eccentricity on head-neck mechanics during HFI was conducted. A modified version of the Global Human Body Models Consortium 50th percentile male detailed head-neck model (GHBMC M50-HN, Version 6.0) was set up to simulate a typical inverted HFI test configuration, as shown in Fig. 1.

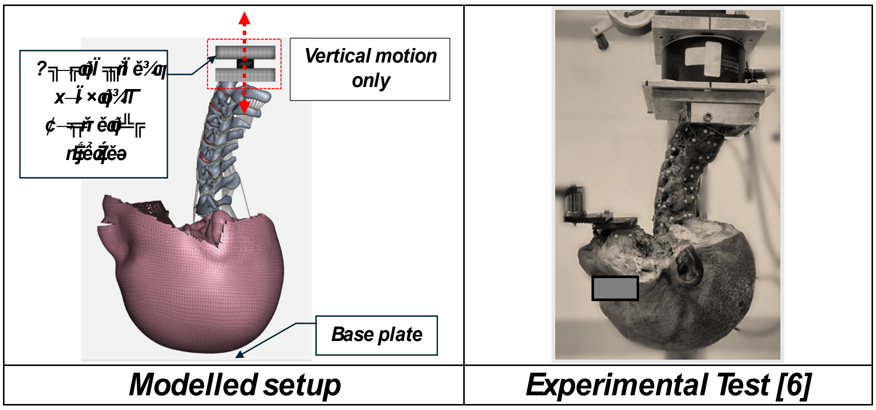


Fig. 1. Modeled test setup (left) and corresponding experimental setup (right).

GHBMC model modifications and setup

A previously validated modified version of GHBMC M50-HN head-neck model was used as the baseline model to simulate the selected HFI scenarios [6]. To replicate the conditions of prior HFI experiments [4], the neck flesh, all musculature, tendons, hyoid bone and mandible, and all attachments were removed from the original GHBMC head-neck model, and the model was rotated so that T1 was 25° relative to the horizontal plane. The modifications described below were made to the scalp and the skull to better match the model's response to existing experimental HFI data. The material properties of the GHBMC scalp flesh were replaced with those used in the Total Human Model for Safety (THUMS) [9]. Furthermore, the inner and outer shell elements of the skull cortical bone were deleted and the elastic modulus of the cortical bone modelled using solid elements was reduced in an attempt to dampen the higher initial peak load compared to what was observed in experimental tests. Considering our main focus on the neck kinematics and kinetics, these changes to the scalp and skull were not deemed to detrimentally affect the previously validated components of the upper spine of the GHBMC model.

Pre-impact head-neck posture

Prior to each HFI simulation, model pre-positioning was performed to obtain each of the desired initial levels of head eccentricity (0 mm to 50 mm, at 5 mm increments), defined as the horizontal distance between the centre of the skull's foramen magnum and the posterior-inferior corner of T1, whilst maintaining a horizontal Frankfort Plane. Pre-positioning stresses and deformations of the head-neck assembly were retained at the beginning of the drop simulation. Each of the prepositioned head initial eccentricities is shown in the Appendix.

Modeled inverted HFI drops

The inferior portion of T1 was rigidly connected to a simplified geometrical representation of an instrumented overhead drop carriage (17 kg effective torso mass [4]) typically used in inverted drop test of head-neck assemblies. To simulate a typical drop rail, this simplified carriage assembly was constrained to vertical translation only. A rigid surface modelled the impact plate of the drop-tower, with an assigned coefficient of friction as measured from experimental friction tests between human skin and an aluminium plate ($\mu = 0.52$). HFI was simulated by assigning an initial velocity of 2 m/s to the head-neck model, with the head positioned closely above the impact plate. Loads acting on the impact surface, drop carriage as well as intervertebral loads and kinematics were extracted using a variety of outputs from the simulation results.

III. RESULTS

Validation of the modified head model

The modification of the scalp material reduced the head bouncing upon initial impact, compared to the original GHBMC model (Fig. 2). Despite some residual bouncing still existing, the modified head model comes back into contact with the bottom plate sooner than the original model. This allows a reduction in the amount of unloading of the partially loaded neck assembly as well as a reduction in the phase offset between the peak loads during that initial impact and the following major impact.

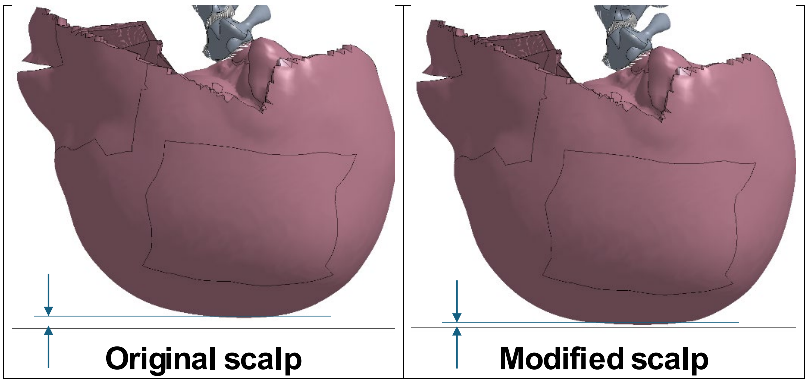
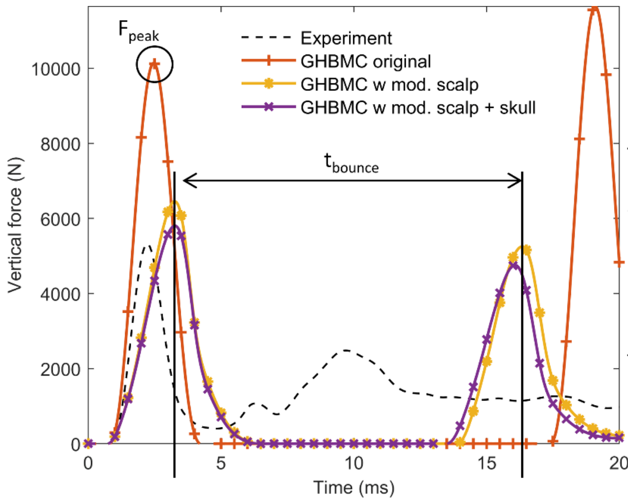


Fig. 2. Simulated peak head bouncing upon impact with the bottom plate - Original GHBMC scalp properties (left) and modified scalp properties (right).

Additionally, the deletion of the inner and outer shell elements of the skull cortical bone in combination with the reduction in the elastic modulus of the solid elements of the cortical bone allowed for a better match of the simulated first peak load at the bottom of the neck (i.e. vertical force measured between T1 and the carriageway load cell). The time offset (t_{bounce}) between the first simulated peak and the following peak after the bouncing was also reduced with the use of these combined modifications. The comparison of the vertical load transferred to the bottom neck with and without these skull modifications is provided in Fig. 3.



Dataset	F_{peak} (kN)	T_{bounce} (ms)
Experiment	*5.3*	*7.4*
Original	*10.1*	*16.7*
Mod scalp	*6.5*	*13.1*
Mod skull	*5.8*	*12.8*

Fig. 3. Experimental and simulated vertical load on bottom neck during the early phase of the drop test with a 30 mm initial head eccentricity – the modified skull replicates the experimental initial peak load more closely than the original model and also reduces the gap to the second peak load created by the initial bouncing.

Sensitivity to initial head forward eccentricity

The simulated neck deformations for a selected sample of the considered eccentricity scenarios 20 ms post initial impact are compared in Fig. 4. A comparison for the full matrix is shown in the Appendix. As expected, the neck 'duck shape' became increasingly more prominent with the increase of the initial eccentricity.

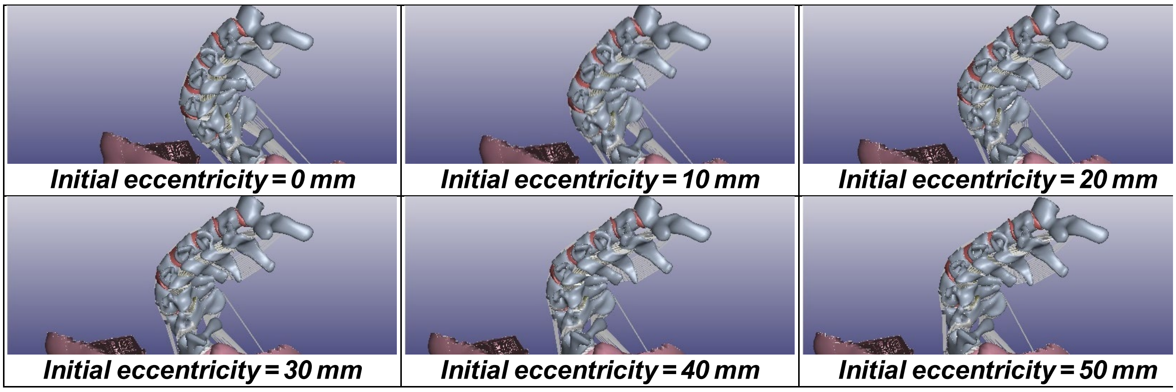


Fig. 4. Simulated neck deformation for selected eccentricities (20 ms after initial impact).

The simulated shear force between T1 and C7 for each of the considered eccentricity scenarios is shown in the time history plots of Fig. 5. While the initial peak load tended to increase with larger initial head eccentricities, the second peak that developed at about 20 ms (i.e. when CFD may occur after the small initial head bouncing) tended to reach its maximum for initial head eccentricities equal to or above a critical threshold of 30 mm. The scatter plot in Fig. 6 concisely summarises the effect of the initial head eccentricity on the second relevant peak value of the C7-T1 shear force.

The peak shear load in the experimental test occurred in conjunction with failure of the interspinous ligaments (ISLs) [7]. However, delayed incomplete ISL failure in the simulations caused the peak shear load to be delayed by about 10–15 ms compared to the test.

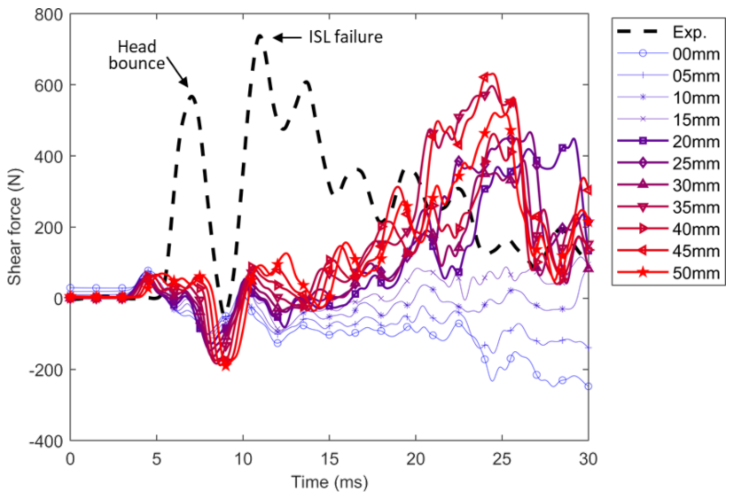


Fig. 5. Simulated time history of the C7-T1 shear force for each investigated level of initial head eccentricity.

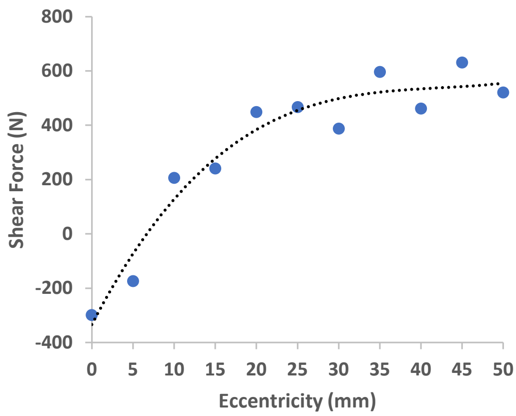


Fig. 6. Simulated C7-T1 peak shear force for each considered initial eccentricity (positive in anterior direction) – peak force tends to plateau for eccentricities equal to or greater than 20 mm.

IV. DISCUSSION

Based on the simulated peak resultant force between C7 and T1, the risk of CFD during HFI scenarios at a low-impact speed tends to become considerable for initial forward eccentricities equal to or above 20 mm. Indeed, at this eccentricity threshold the C7-T1 peak shear force reaches 400 N, which is consistent with, albeit lower than, what was observed just before CFD started to occur in recent HFI experimental testing [7]. The fact that similar peak loads start to be obtained for all the initial eccentricities larger than 20 mm appears to indicate this to be a critical threshold level for lower neck injuries. Therefore, CFD injuries are expected to also occur in a similar fashion for initial head eccentricities above this critical threshold. However, for very large initial eccentricities (>70 mm), a gradual reduction in the risk of severe neck injury may start to occur due to a corresponding reduction in neck tendency to deform in a 'S-shape' manner, as suggested by Maiman *et al.* [10].

Currently, the simulation outcomes of this research activity have been validated only for the scenario of a 30-mm initial eccentricity. Therefore, future validation against experimental HFI testing conducted with an initial head eccentricity in excess of 30 mm would be required to confirm these hypotheses.

This research has been limited to varying the head forward position with an initial neutral sagittal-plane rotation (i.e. initially positioned at a horizontal Frankfurt Plane). Pre-HFI head flexion or extension may reduce neck deflection at low speeds, which appears to be the mechanism leading to the development of CFD during a HFI scenario [7][10]. It is expected that the critical threshold eccentricity may vary based on the combined effect, with different levels of initial flexion/extension. Therefore, a future expansion of this ongoing research will focus on the combined effect of eccentricity and head flexion/extension.

This research has been based on outcomes of computer simulations using a previously validated head-neck model that proved to be capable of reproducing the overall kinematics and dynamics of HFI scenarios at the desired low-impact speed. Modifications to the skull of this model allowed us to further improve the simulated dynamics during the initial phase of the HFI event. Some residual bouncing of the head, unmatched with the experimental results, was still present in the simulations. Despite a marginal timing shift, this residual head bounce does not appear to have affected the overall kinematics and dynamics of the neck during the critical phase of the HFI event when subaxial CFD started to develop. Further additional improvements to the head flesh and the skull may be needed to prevent this unexpected initial head bounce. Additionally, the current neck model does not allow for the simulation of physical shearing of the intervertebral disc as expected during CFD injuries [7]. Therefore, implementing failure of these components will be necessary to further improve the reliability of this model for simulating HFI events leading to CFD, possibly also in combination with improvements to the observed, currently limited failure of the neck tendons under this type of event.

V. CONCLUSION

A head forward posture due to eccentricity exceeding 20 mm induces lower neck kinematics and kinetics likely to produce CFD at low speed. This result is consistent with previous HFI experimental tests and further confirms that it is correct to focus on this reference value in future injury prevention research activities. The potential combined effect of initial eccentricity and head flexion/extension should be investigated in the future. Despite the current suitability of the model for simulating HFI events, further improvement is needed to prevent the initial, small, residual head bounce upon impact as well as implement shear failure of the intervertebral discs.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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VIII. APPENDIX

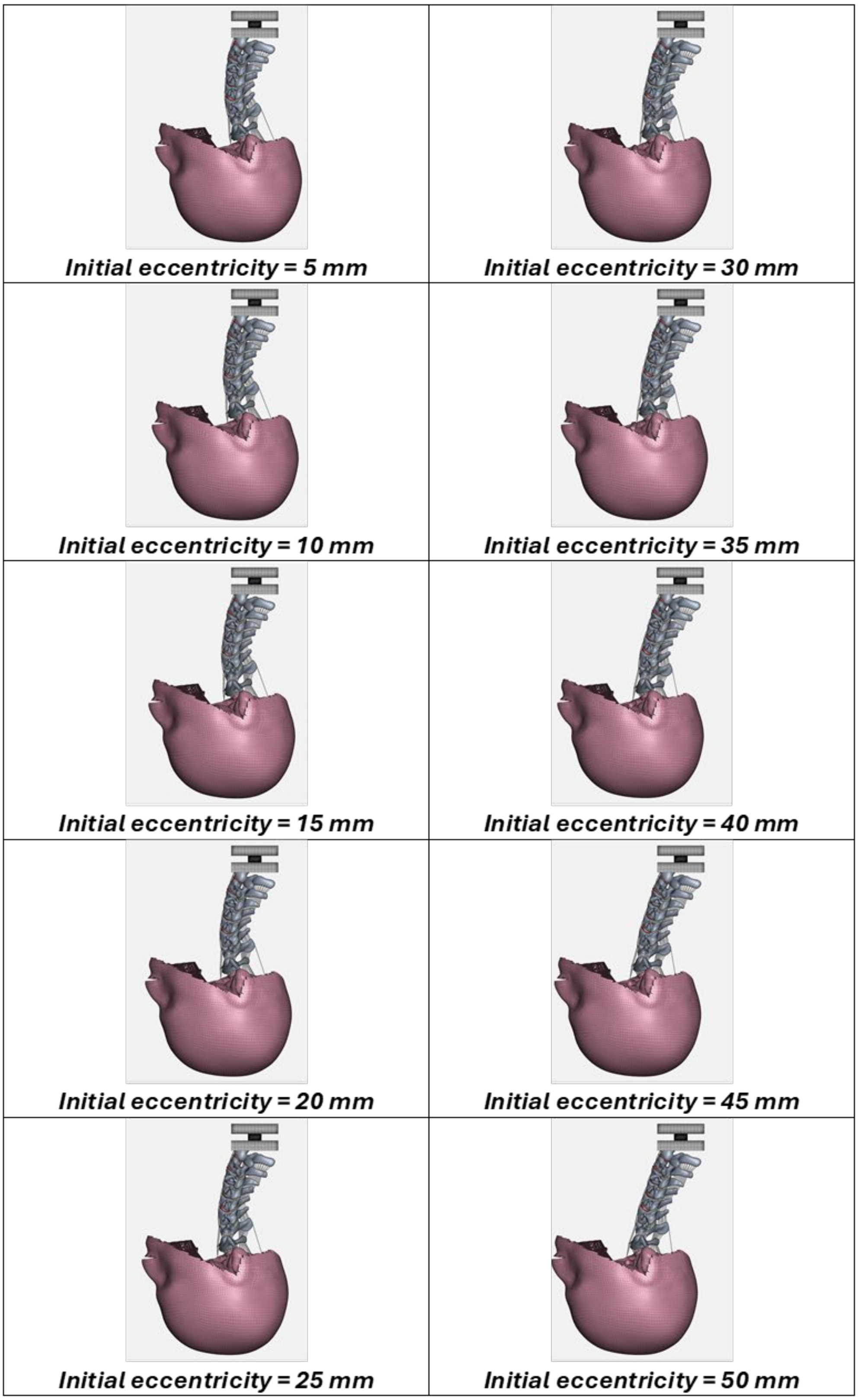

Fig. A1. Pre-positioned head at the beginning of the drop simulation for each investigated eccentricity.

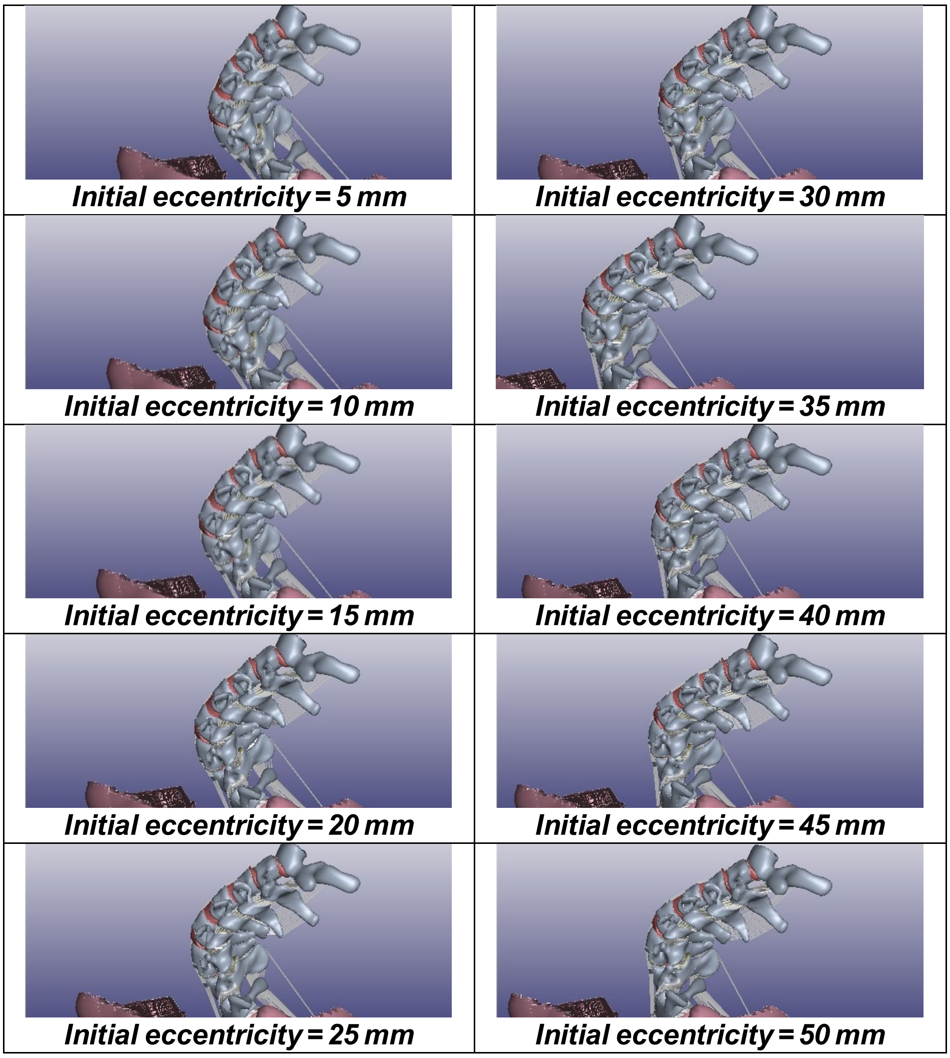

Fig. A2. Comparison of the simulated neck deformation for each investigated eccentricity (20 ms from initial head impact).