Feasibility of a pressure response superposition scheme in blunt head impact

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I. INTRODUCTION

Understanding the causal relationships between brain mechanical responses and kinematic input in blunt head impact is critical to ultimately elucidate the biomechanical mechanisms of traumatic brain injury (TBI). It is well known that linear acceleration ($\mathbf{a}_{lin}$) produces little strain in the brain because of its near incompressibility [1]. A recent dimensional analysis further identified that brain pressure responses are directly determined by a_{lin} (magnitude and directionality), brain size and shape [2]. However, the correlation coefficients (R^2) between coup/contrecoup pressures and peak $\mathbf{a}_{lin}$ magnitudes, based on real-world impacts, differed significantly from the anticipated ±1.0 (neglecting differences in brain anatomy or impact direction). Instead, they ranged between 0.77 and 0.88 [3-4], or even lower (0.35 [5]) when the rotational acceleration ($\mathbf{a}_{rot}$) magnitudes were high. Such a discrepancy suggests the potential significance of $\mathbf{a}_{rot}$-induced pressures, which appears not to have been systematically evaluated before. In this study, we investigate a pressure response superposition scheme based on isolated $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ in blunt head impact. Results from this study may be important to improve the accuracy of real-time estimation of whole-brain pressure responses based on isolated $\mathbf{a}_{lin}$ [6].

II. METHODS

Essentially, acceleration-induced brain pressures are a result of contact forces generated from relative brain-skull normal displacements at the interface. Assuming a linear elastic brain-skull coupling [2], contact forces from isolated $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ are conceptually represented by $k \times x_{lin}$ and $k \times x_{rot}$, respectively, where k is the spring constant. As $\mathbf{a}_{lin}$ induces little strain [1], its influence on $\mathbf{a}_{rot}$-induced deformation is negligible. Consequently, their respective small but non-zero relative normal displacements, x_{lin} and x_{rot}, are likely independent. Therefore, pressure responses induced by isolated $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$, or $P_{a_{lin}}$ and $P_{a_{rot}}$, respectively, are likely additive, leading to the following superposition relationship to establish the pressure responses when both $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ are otherwise applied ($P_{a_{full}}$):

$$P_{a_{full}} = P_{a_{lin}} + P_{a_{rot}} + P'_{err}, \tag{1}$$

where P'_{err} is the error due to the assumptions and simplifications necessary for the conceptualisation.

To test the hypothesis, impact data from two reconstructed vehicular crashes [7] were used for simulation based on the Dartmouth Head Injury Model (DHIM [1-2]). $P_{a_{lin}}$, $P_{a_{rot}}$ and the directly simulated $P_{a_{full}}$ were generated using either isolated $\mathbf{a}_{lin}$, $\mathbf{a}_{rot}$, or their combination as kinematic input, respectively. The acceleration temporal profiles were prescribed to the head center of gravity (skull, face and scalp were assumed rigid). The brain-skull boundary conditions were implemented as nodal sharing with a layer of soft elements in-between to simulate the cerebrospinal fluid [1-2]. The superimposed pressures were compared with their directly simulated counterparts when the resultant $\mathbf{a}_{lin}$ reached its peak magnitude for each case.

III. RESULTS

The magnitude and distribution of the superimposed pressure were nearly identical to the direct simulation response for the first case (top row in Fig. 1). However, large errors were observed for the second case (middle row in Fig. 1) in terms of both pressure distribution and magnitude at the coup and contrecoup sites. The relative percentage errors in the maximum coup (contrecoup) pressures ($P_{a_{lin}} + P_{a_{rot}}$ relative to $P_{a_{full}}$) were 1.7% (0.7%) and 9.5% (11.2%) for the two cases, respectively.

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IV. DISCUSSION AND CONCLUSION

The major $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ peaks happened nearly at the same time for the first case, but significant head rotations occurred before the first major peak in $\mathbf{a}_{lin}$ for the second case (Fig. 1). As $\mathbf{a}_{lin}$-induced pressures are nearly instantaneous, while both $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ were prescribed relative to a fixed coordinate system, an updated head orientation should instead be used to apply $\mathbf{a}_{lin}$. After orientation adjustment via a double-integration of the $\mathbf{a}_{rot}$ profile, the superposition result was much improved (bottom of Fig. 1) in terms of pressure distribution and relative percentage errors (5.5% and 4.9% for the coup and contrecoup pressures, respectively). However, the orientation adjustment appeared unimportant for the first case, likely because the head rotation was small (~4.5°). These results suggest the feasibility of decoupling $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ for whole-brain pressure responses. As the pre-computed brain pressure response atlas was based on $\mathbf{a}_{lin}$ alone [6], findings from this study provide an effective compensation strategy to improve the accuracy of the atlas-estimated, $\mathbf{a}_{lin}$-induced pressures when using full degree-of-freedom, real-world head impacts.

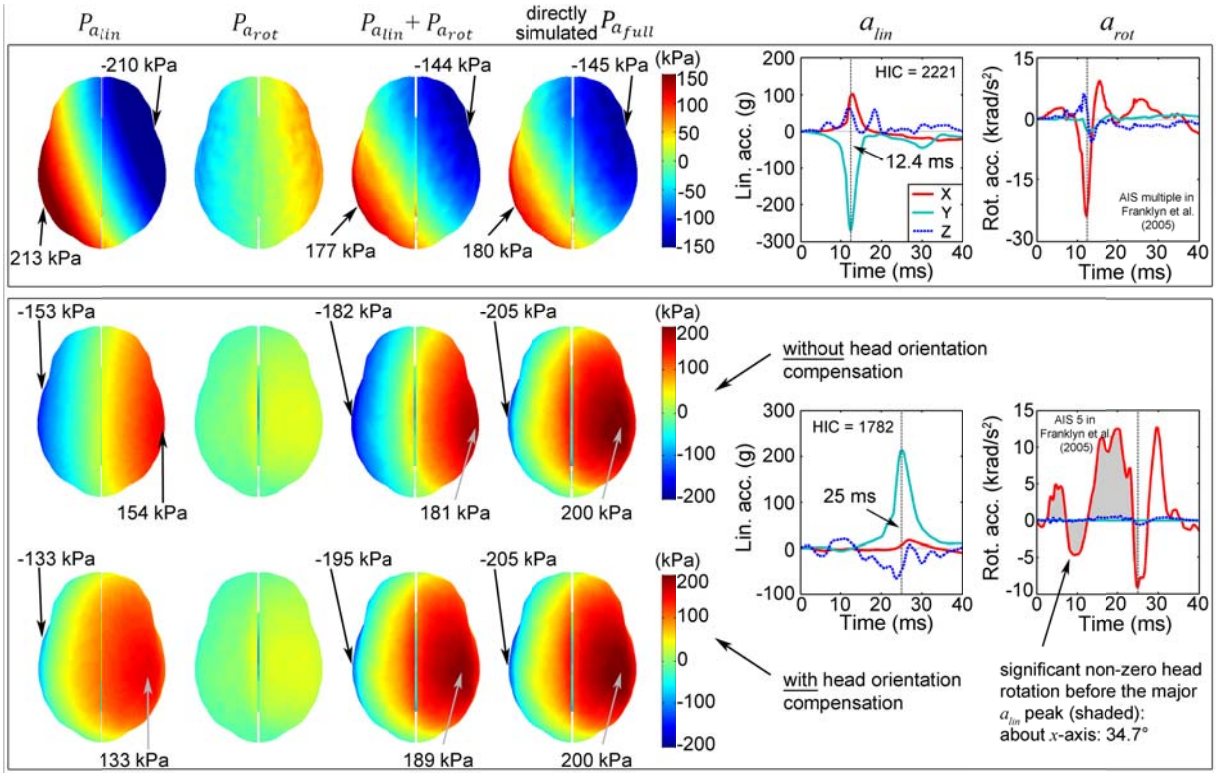

Fig. 1. Illustration of pressure superposition along with their corresponding $\mathbf{a}_{lin}$ and $\mathbf{a}_{rot}$ profiles. Top box: AIS multiple (AIS 2–5; with extradural and subdural haematoma, cerebral swelling and contusion); bottom box: AIS 5 (with extradural haematoma and contusion) without and with head orientaion compensation [7]. Maximum coup/contrecoup pressure magnitudes and locations are identified.

V. REFERENCES

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