Traumatic Brain Injury: Translating Head Kinematics Results between Pig and Human

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I. INTRODUCTION

Traumatic brain injury (TBI) is a major public health issue worldwide and can result from head impacts and rapid head rotations. Studies have shown that head rotational kinematics parameters are related to the brain tissue deformation and stretch of the axons, which are known as the underlying mechanisms of TBI, and thus have the potential to be predictive of likelihood and severity of TBI [1-7]. Many studies have tried to develop a biomechanical foundation for injury prediction, protection and prevention strategies by developing risk curves and determining safe limits or injury thresholds for TBI using head rotational kinematics parameters [1][3][5-6]. Animal models of TBI, in which precise head kinematic loadings can be applied and measured in a controlled laboratory setting and the neuropathology outcomes of TBI can be quantified post mortem, can play an important role in developing such a biomechanical foundation for TBI [4-5][7]. However, the important challenge with animal studies is translating the injury biomechanics findings for human applications. Studies showed that tissue deformation-related TBI thresholds do not vary significantly for different species, which might be attributed to the similarities in cellular structures and pathology alternations of central nervous system tissues across species [1][3]. For example, the finite element (FE)-derived axonal and brain tissue thresholds determined for TBI in piglets [1] are similar to the corresponding ones reported for human TBI in the literature [6]. The objective of this short communication is to determine the appropriate scaling factors for translating head kinematics parameters between pig and human to get similar axonal stretch and brain tissue deformations in these two species.

II. METHODS

The generalised relationship between head kinematic parameters, including peak rotational acceleration and peak angular velocity, and FE-derived axonal and brain tissue deformation parameters, including maximum principal strain (MPS) and maximum axonal strain (MAS) (as described in detail in [1]), were determined for pig through a set of parametric simulations (N=104), as shown in Fig. 1 (first column). For these parametric simulations, idealised full-cycle sinusoidal angular acceleration signals with peak angular velocity and peak angular acceleration ranging from 50 to 400 rad/s and from 25 to 250 krad/s^2, respectively, were used as the loading traces. A newly developed and validated anisotropic multiscale axonal tract embedded brain FE model (FEM) of a four-week-old pig [1] was used for these simulations. The rotational traces were applied to the rigid skull and the pig brain FEM was rotated about the head center of mass. Similar generalised kinematic-based tissue deformation surface contours were previously determined for human by Wu *et al*. [8] using a human brain FEM with a similar material constitutive modelling and embedding technique as used in the pig FEM for this study.

Three scaling approaches, including mass scaling, inertia scaling and optimal scaling [8-9], were used to calculate the scaling factors for angular velocity (λ_ω) and angular acceleration (λ_α) to translate head kinematics parameters between pig and human. These head kinematics scaling approaches were compared to determine how closely they can estimate head kinematics conditions that result in similar overall axonal and brain tissue deformation responses (MAS and MPS) in both pig and human. Sum of the squared error (SSE) and root mean square error (RMSE) between the human (Fig. 1, second column) and scaled pig generalised kinematic-based tissue deformation surfaces (Fig. 1, third to fifth columns) were used for the comparison. The mass scaling and inertia scaling methods are based on dimensional analysis, assuming similarities in mass density and material properties of pig and human brains, and use the ratio of brain mass and brain moment of inertia, respectively, with the formulations given in Table I.

The optimal scaling approach [8], which has been recently introduced in TBI field, takes into account the differences in brain geometry and material properties of the species and determines a set of optimal scaling

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factors for angular velocity and angular accelerations that minimise SSE between the human and scaled animal generalised kinematic-based tissue deformation (MAS and MPS) surfaces using an unconstrained optimisation. The optimal and inertia scaling factors are dependent on rotational directions and were calculated for sagittal rotation in this study.

III. INITIAL FINDINGS

The generalised kinematic-based MAS and MPS surface contours, which represent constant levels of overall axonal/brain tissue deformation responses as a function of head angular velocity and acceleration, showed similar features for both pig and human (Fig. 1), but at different head kinematics. Pig-to-human head kinematics scaling factors for angular velocity and angular acceleration are given in Table I using the three scaling approaches. The scaled pig MAS and MPS surface contours exhibit the most similar responses to the corresponding contours for human (RMSE=0.014-0.023 and SSE=0.019-0.054) when the head kinematics parameters are scaled from pig to human using the optimal scaling factors compared to the mass or inertia scaling methods (RMSE=0.057-0.085 and SSE=0.322-0.709).

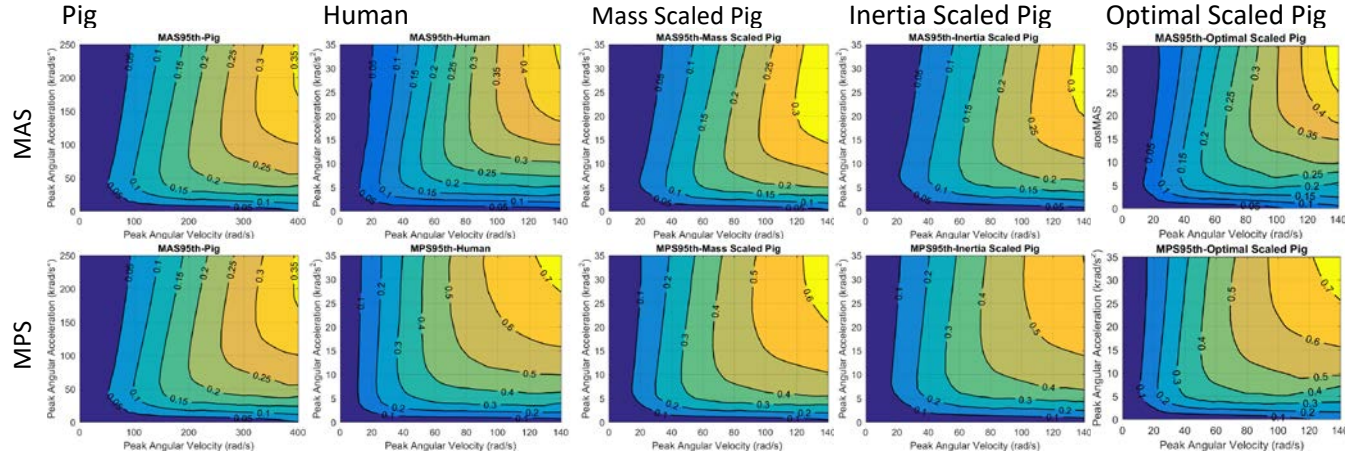

Fig. 1. The generalised kinematic-based MAS (top) and MPS (bottom) surface contours for sagittal rotation for pig, human ([8]) and the scaled pig surface contours using mass, inertia and optimal scaling approaches.

TABLE I

SCALING FACTORS FOR TRANSLATING HEAD KINEMATICS FROM PIG TO HUMAN FOR SAGITTAL ROTATION

Scaling methods	Parameters related to human and pig brain model, scaling factors, human and scaled pig comparison
Mass scaling [9]	$m_{pig-brain} = 63\ gr$, $m_{human-brain} = 1243\ gr$ [8] $\lambda_{\omega-m} = ({}^{m_{pig-brain}}/_{m_{human-brain}})^{\frac{1}{3}} = 0.370$, $\lambda_{\alpha-m} = ({}^{m_{pig-brain}}/_{m_{human-brain}})^{\frac{2}{3}} = 0.137$ MPS: RMSE=0.061 SSE=0.367 MAS: RMSE=0.057 SSE=0.322
Inertia scaling [8]	$I_{pig-y} = 23.3\ kg.mm^2$, $I_{human-y} = 2489.7\ kg.mm^2$ [8] $\lambda_{\omega-Sagittal} = ({}^{I_{pig-y}}/_{I_{human-y}})^{\frac{1}{5}} = 0.409$, $\lambda_{\alpha-Sagittal} = ({}^{I_{pig-y}}/_{I_{human-y}})^{\frac{2}{5}} = 0.167$ MPS: RMSE=0.085 SSE=0.709 MAS: RMSE=0.070 SSE=0.482
Optimal scaling [8]	$\lambda_{\omega-MPS} = 0.280$, $\lambda_{\alpha-MPS} = 0.128$ $\lambda_{\omega-MAS} = 0.256$, $\lambda_{\alpha-MAS} = 0.119$ MPS: RMSE=0.023 SSE=0.054 MAS: RMSE=0.014 SSE=0.019

IV. DISCUSSION

Several scaling approaches were used in this study to translate the head kinematic data between pig and human. The optimal scaling factor resulted in the most similar axonal and brain tissue deformation responses between pig and human. The optimal scaling approach takes into consideration the geometry and brain tissue material behaviour differences between these two species. The scaling factors determined in this study can be used to translate the head rotational kinematic findings in pig model of TBI, which is one of the closest available animal models to mimic the mechanism and neurological outcomes of human TBI, for different applications for human, such as TBI risk assessments and helmet design criteria. Future work will include other unidirectional rotations as well as multidirectional head loadings in order to provide more comprehensive translational recommendations for future pig TBI studies.

V. REFERENCES

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