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High-Speed Biplane X-Ray Head Impact Experiments in the Göttingen Minipig

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ABSTRACT – Traumatic brain injury is a persistent problem in the United States. To develop a head injury metric that relates underlying damage found *in vivo* to impact kinematics, scaling from the minipig to a human is required. The methods and results presented here describe the high-speed biplane x-ray experiments that will be used for finite element model development. Göttingen minipigs underwent surgery to implant radiopaque markers into the brain, and to attach markers to the skull. During the non-penetrating, impact induced injury, a high-speed biplane x-ray system and a visible light camera captured the event. Relative brain/skull motion displayed similar figure-eight/looping patterns as during cadaver testing, similarities between live and recently deceased impacts, and that a higher input leads to larger brain motion, but similar motion patterns. Data from these tests will be used to validate a minipig finite element model.

INTRODUCTION

Traumatic brain injury is a persistent problem in the United States, with an estimated 2.5 million incidences in 2013 (Taylor et al., 2017). Current injury metrics do not relate an impact to underlying damage. A novel injury device has been developed for use with the Göttingen minipig. *In vivo* injury testing for up to 24 hours was characterized using immunohistochemistry and proton magnetic resonance spectroscopy. To develop a new head injury metric that relates the underlying damage and biochemical cascades found *in vivo* to the input impact kinematics, scaling from the minipig to a human is required. This will be accomplished by comparing minipig and human head FE model responses. The methods and results presented here describe the high-speed biplane x-ray experiments that will be used for model development.

METHODS

Six female Göttingen minipigs underwent surgery to implant tin markers (1 mm) and a pressure transducer into the brain, to attach lead markers to the skull (2 mm), and to adhere strain gages to the sides of the skull. Surgical head preparation, as described in Fievisohn et al., 2014, was also done to ensure rigid attachment between the animals and the injury device. Then, animals were bolted into the combined translation and rotation input injury device and dropped at either a low or high speed. During the non-penetrating, impact induced injury, a high-speed biplane x-ray system and a visible light camera captured the event. Data were collected from two linear accelerometers, one angular accelerometer, and one angular rate sensor. Animals were euthanized immediately after impact. A second impact was performed after euthanasia for four of the animals to make live versus recently deceased comparisons. The animal protocols were approved by the Virginia Tech Institutional Animal Care and Use Committee under protocols 014-069 and 17-088.

Marker motion in the two x-ray planes was tracked and relative brain-skull motion was reconstructed in three dimensions. Multiple skull marker configurations were used to double-check the marker motion patterns. Final marker motion was transformed to midway between the base of the occiput.

Here, comparisons were made between low and high-speed impacts, minipig and cadaver brain marker motion patterns, using different skull marker locations to define the body fixed basis for coordinate transformations, and between live and recently deceased impacts.

RESULTS

Figure 1 shows an example of the linear acceleration, angular speed, and angular acceleration of a low and high-speed impact. Higher input corresponds to larger brain motion, but similar figure-eight/looping patterns relative to lower input (Figure A.1) and similar patterns compared to cadaver impacts from Hardy et al., 2001 and 2007 (Figure A.2).

Brain marker motion with different body fixed basis definitions are shown in Figures A.2 and A.3.

Finally, Figure A.4 displays similar motion from a live versus a recently deceased animal exposed to the same impact level.

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DISCUSSION

This preliminary analysis of data expresses five important points to consider when looking at brain marker motion.

A recently deceased animal (within an hour) compared to a live test does not show significant brain marker motion differences. This is beneficial in case the animal dies or needs to be euthanized during surgery. Figure 5 also supports that the brain markers return to their initial position after impact.

Skull markers used to define the body fixed basis should be checked for accuracy using different skull markers to ensure the marker motion is real.

Marker motion from the minipig exhibits similar figure-eight/looping patterns shown in cadavers from Hardy et al., 2001 and 2007. This supports the minipig as a human surrogate as the brain behaves mechanically similar.

Finally, a higher input results in larger amounts of brain motion, but shows similar shapes.

Future research will include developing and validating a finite element model of the minipig. Once this is completed, the minipig model will be compared to a human model to develop a transfer function. Ultimately, this research will lead to the development of an injury metric that relates an impact to underlying damage/impairment.

CONCLUSION

The minipig model was supported by similar figure-eight/looping patterns as those observed in cadavers. This preliminary study provides the experimental data necessary to develop and validate a finite element model of the minipig to then be compared to a human head model.

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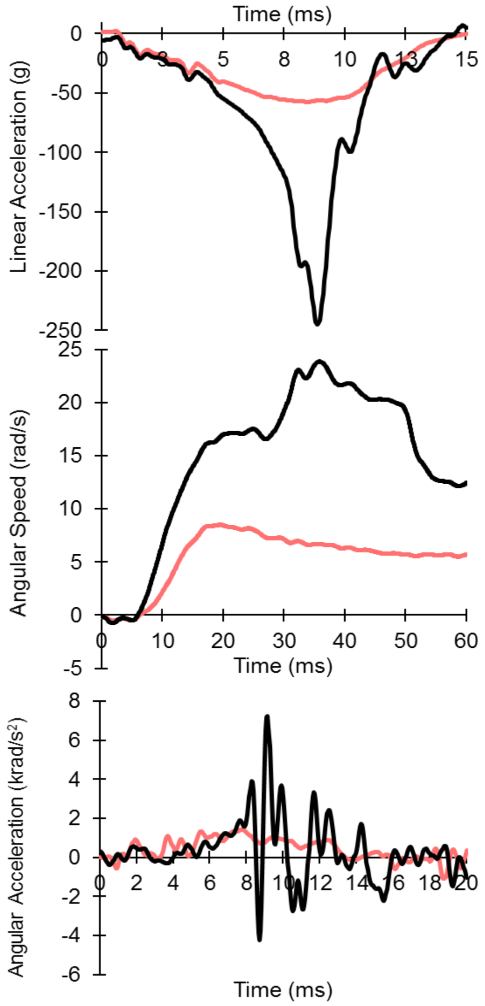

Figure 1. Linear acceleration (top), angular speed (middle), and angular acceleration (bottom) of the high and low speed impacts (black and gray, respectively).

Appendix A

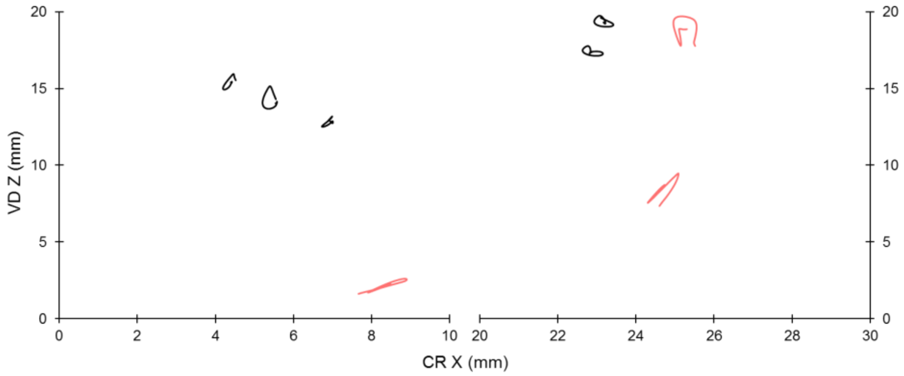

Figure A.1. Relative brain/skull motion in low speed (black) and high speed (red) impact severities.

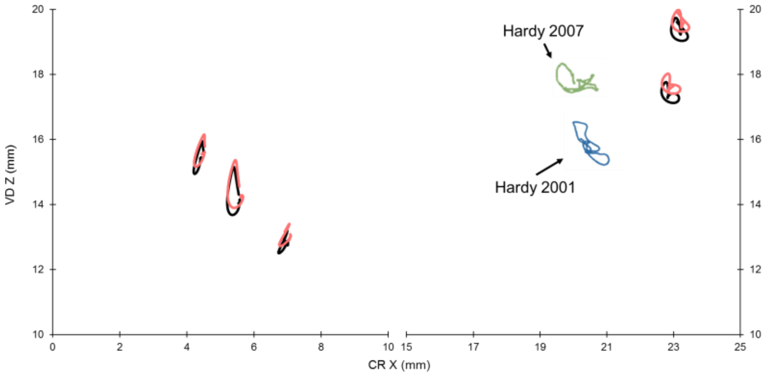

Figure A.2. Comparisons between different skull marker configurations (black vs. red). Blue and green markers are cadaver brain motion patterns from Hardy et al., 2001 and 2007, respectively.

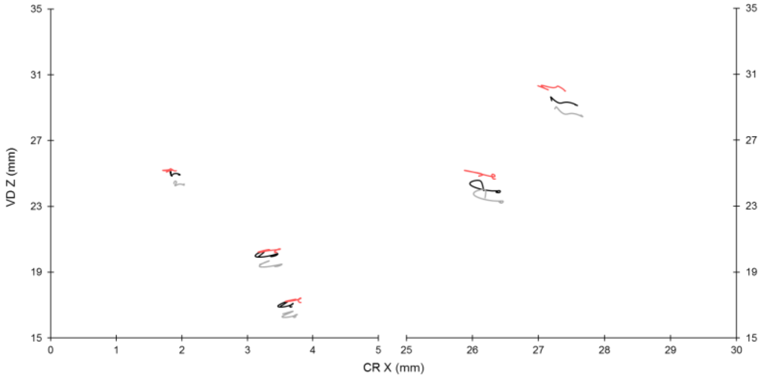

Figure A.3. Additional comparisons between different skull marker configurations as the definition of the body fixed basis from the same test.

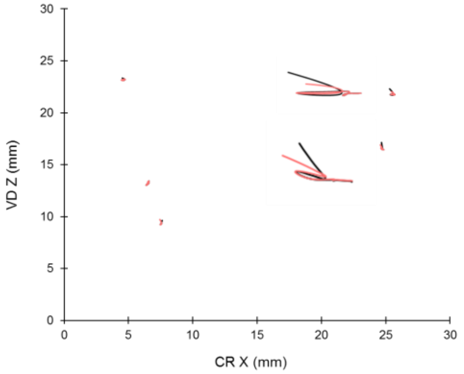

Figure A.4. Live (red) versus recently deceased (black) brain marker motion patterns. The two zoomed in markers are not to scale.