Investigating Design Parameters and Accuracy of Embedded Markers Used in Tracking PMHS Brain Motion

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I. INTRODUCTION

Measuring displacement in soft tissues as a result of impulsive acceleration loads is necessary for the validation of finite element models used in traumatic brain injury studies [1-5]. Much of the validation data used presently has been derived from the motion of tissue-embedded radiographic markers or sonomicrometry crystals (SMCs) in post-mortem human subjects (PMHSs) [6-10]. The quality of this data is critical in order to ensure that models accurately represent the domain under investigation. Notably, when the same data is used to calibrate different models, different responses are produced, despite identical input conditions [11]. While differences in model boundaries and geometries may contribute to these response variations, the accuracy of the tissue motion used for validation is also a contributing factor. Despite this, a thorough understanding of how embedded tracking markers interfere with the accuracy of the natural response of the tissue has not been discussed. Technological advances have improved measurement precision, but precision is often conflated with accuracy. While measurement systems may precisely identify the position of markers within tissue, a loss of accuracy in the displacement field may exist due to the inclusion of the markers themselves. To further the understanding of the effects of embedded markers on the surrounding matrix, we performed two related studies. Each study subjected tissue simulating gel blocks to a one-dimensional impact load via drop tower. First, a parametric sensitivity study was performed to examine how marker properties of stiffness, density, and spacing, relate to variations in peak displacement measurements. The results of this study were used to develop a new marker, the Carleton Elastomeric Marker (CEM). The second study compared the Maximum Principal Strain (MPS) response computed from gel blocks containing previously published marker designs (NDT, SMC, Tin), as well as the CEM.

II. METHODS

For each investigation, contrast markers were cast into thermoplastic gel (Humimic #4) blocks measuring 152x152x47 mm. Blocks were prepared using an elastomeric mould (1:1 Sylgard 184/527), which was also used as a protective encasement during drop testing. Within each test block, markers were cast in a central plane to minimise boundary effects. In the parametric study, marker spacing was varied. In the comparison of published marker types, spacing was constant at 20 mm.

To evaluate the effect of marker properties on the measured impact response, nine different marker designs were developed. Each design varied in stiffness, density, and pattern spacing, per a Taguchi L9 array. All markers contained a powdered contrast agent ($BaSO_4$) mixed into an elastomeric binder. Ratios between the powder and the binder produced differences in density (1.05, 1.45, 1.85 g/mL). Variations in stiffness were achieved with different binding agents [12]: 1:1 Sylgard 184:527 (830 kPa), 1:5 Sylgard 184:527 (130 kPa), Humimic #4 (9 kPa). Spacing was varied during the casting process (10, 15, 20 mm). As the thermoplastic gel set, blocks were degassed in a vacuum oven to remove air bubbles. A 10th sample, containing a massless (ink-based) marker was prepared providing a response baseline for the neat gel material. Impact videos were recorded using HSXR, excluding the massless (non-attenuating) marker, which was captured optically.

A similar process was used for the preparation of the marker comparison samples. Comparison markers were reproduced from published descriptions [6-10]. Neutral Density Targets (NDTs) were made from polyethylene tubes, 5 mm in length and 1.5 mm diameter, each with a tin granule placed inside. Tube ends were sealed with cyanoacrylate adhesive. SMCs were prepared by dip-coating a twisted pair signal cable (34 AWG, PTFE Jacket, Daburn Electronics) in epoxy (3M DP 420, Dow Inc.) until a 1.5 mm bulb formed at the tip. Wire-free SMCs were prepared the same way, with the wire clipped post-cure. Tin granules of 1.5 mm diameter were produced from 99.97% tin solder. To vary the orientation of markers with non-uniform shapes, NDTs and wired SMCs were tested in both vertical and horizontal orientations. An additional NDT block was prepared with markers cast in the transverse orientation. Due to batch differences between these specimens and those used in the parametric study, a new neat specimen was prepared as a baseline comparison. Impact videos were captured using an optical high-speed camera.

Drop tests for each specimen were conducted using a custom table-top drop tower. For the parametric study,

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specimens were dropped from a height of 76 cm and for the comparison study from a height of 84 cm. These impacts produced a strain rate similar to those found in head impact studies of interest [9], approximately $10s^{-1}$. Drops were repeated three times. Resultant video frames were analysed using an in-house sparse particle tracking code following image distortion corrections and contrast adjustments. Markers were not found to migrate through the gel material, returning to their original positions following impacts.

III. INITIAL FINDINGS

Results from the parametric study revealed that differences in marker properties contribute to a deviation in the response when compared to a neat matrix with a massless marker. Fig. 1 presents the vertical displacement of embedded markers following an impact for markers with specific properties. Medium stiffness and/or density markers appear to provide a more accurate response than those with high density and/or stiffness.

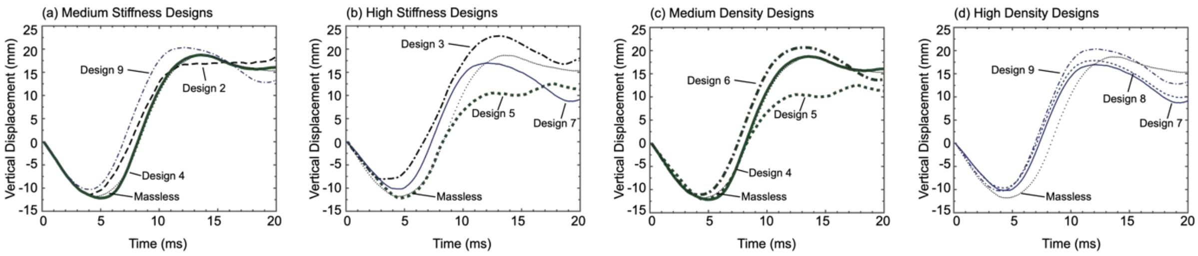

Fig. 1. Mean vertical displacement of markers with respect to material properties, as compared to massless markers. a) Medium stiffness. b) High stiffness. c) Medium density. d) High density.

The comparison of published markers and the CEM (12 kPa, 1.6 g/mL) (Fig. 2) shows the average MPS for a central group of triangular elements. In the initial compressive phase, Massless markers indicated that the neat material experienced an average compressive strain of 3.1%. The subsequent tensile phase resulted in 7.0% MPS. None of the blocks with embedded markers performed identically to the neat material, but the tuned CEM provided the best comparison at 3.0% and 6.7% respectively. Strain calculated from blocks containing markers with non-uniform shapes or wiring caused directional deviations from the natural deformation of the matrix.

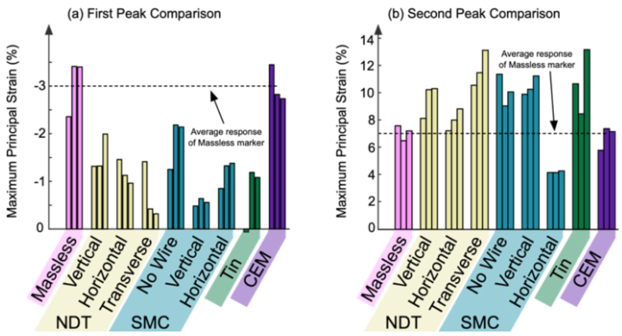

Fig. 2. MPS at block centre for (a) first (compressive) and (b) second (tensile) phase of deformation. Each bar represents one repeated drop test. Mean response from massless markers is highlighted with dashed line.

IV. DISCUSSION

The parametric study presents the sensitivity of marker properties and their ability to reproduce the impact displacement response of a neat, marker-free, material. Marker density, stiffness, and spacing all play a role in achieving an accurate measured response, independent of tracking precision. Using this information, a tunable elastomeric marker was produced and compared to published marker designs in a drop-test configuation. This comparison shows that the process of tuning a marker for impact studies is feasible and beneficial, yielding minimal interference in the MPS response of the neat material. In addition, it is clear that non-unity aspect ratios and wired sensor designs present a significant orientation biased interference, making their use in model validation challenging. Further discussion and analysis will be the subject of future publications.

V. REFERENCES

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