Characterization of Strain Mode in Human Ribs Subjected to Anterior-Posterior Loading

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I. INTRODUCTION

The current mission of computational human body models (HBMs) is to develop and maintain high-fidelity finite element (FE) models for crash simulations. Increased biofidelity of HBMs has been proposed to be achieved through various enhancements and new validated models. Ultimately, these improved models may assist with better understanding of injury prediction capabilities. One of the most commonly injured regions in motor vehicle crashes (MVCs) in the United States is the thorax, specifically the ribs [1-2]. However, the failure mechanism of ribs is not completely understood, which may be one of the contributing factors as to why HBMs often underpredict the number of rib fractures [3].

In an effort to increase biofidelity in thoracic FE modelling, rib failure should be defined in terms of bony surface (cutaneous or pleural) and strain mode (i.e. initial failure mechanism). The initial failure mechanism is essential to understanding fracture mechanics and therefore is meaningful data for HBMs to incorporate. Additionally, a more comprehensive understanding of rib injury, through rib fracture characteristics (e.g. fracture location, number of fractures, fracture mechanism, injury severity), is needed to improve injury prediction. Bone is generally understood to be weaker in tension than in compression and therefore has an expected failure strain mode of tension. However, previous studies have shown that the initial failure mechanism of human ribs is not consistently in tension, even under the same controlled loading conditions [4]. The objective of this research was to identify variability in strain mode at fracture initiation in human ribs subjected to repeatable dynamic bending experiments.

II. METHODS

Two hundred human ribs (female = 42, male = 158) from 101 post-mortem human subjects (PMHS) (female = 37, male = 64; 9–95 years old, mean ± standard deviation = 54.5 ± 22.6 years) were included in this study. Whole ribs were loaded to failure in an anterior-posterior dynamic bending scenario, simulating a frontal thoracic impact (for complete experimental details, see [5]). Prior to each experimental test, four uniaxial strain gauges (Vishay Micro-Measurement, CEA-06-062UW-350, Shelton, CT, USA) were affixed to the ribs, two on the cutaneous surface at 30% and 60% of the entire rib length and two on the pleural surface at the same locations opposite to the cutaneous gauges (Fig. 1). The boundary conditions of the test setup dictated that cutaneous gauges experienced tension while pleural gauges experienced compression due to rib bending. Strain data were collected throughout the event at 20k Hz and the raw values were utilized to determine time of initial local failure by identifying the strain immediately preceding the sudden drop-off (see [5] for details regarding data processing) (Fig. 2).

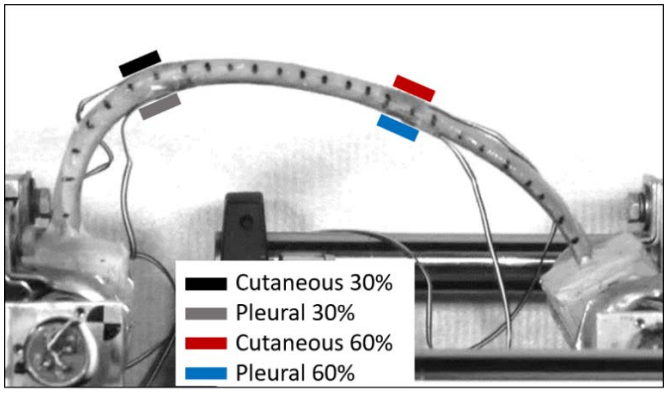

Fig. 1. Exemplar of human rib in experimental fixture with schematic of strain gauge placement.

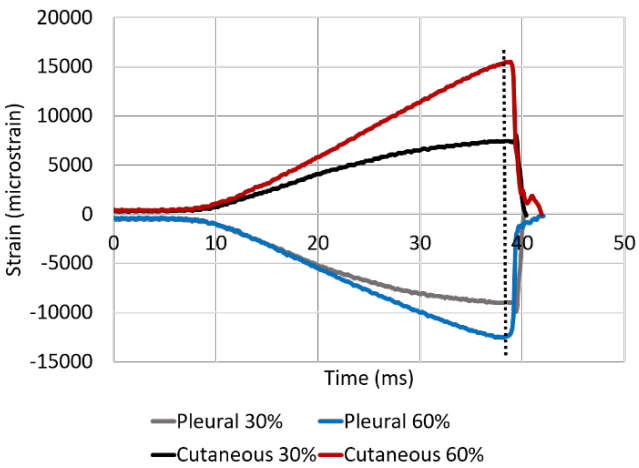

Fig. 2. Exemplar strain-time plot with initial local failure indicated (dotted line).

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Failure strain mode was determined by identifying the gauge and, subsequently, the rib surface associated with the time of initial local failure (cutaneous, pleural, or both [i.e. failure occurred in the cutaneous and pleural surfaces at the same time]). These data were then translated to failure strain mode as: tension, compression, or simultaneous, respectively. Chi-Square tests were used to determine relationships between failure strain mode and sex or rib level. A Kruskal-Wallis test was used to determine if there were any differences in failure strain mode according to age.

III. INITIAL FINDINGS

Failure strain mode was determined for all ribs and frequencies of failure strain mode by rib level, sex, and age are shown in Table I. Of the 200 ribs included in this study, the failure strain modes demonstrated were: tension (n=98, 49%), compression (n=79, 39.5%), or simultaneous (n=23, 11.5%). Chi-Square tests demonstrated no significant relationships between failure strain mode and sex, x^2 *(2, N=200)=1.757, p=0.415*, or failure strain mode and rib level, x^2 *(3, N=196)=4.009, p=0.261*. For the Chi-Square failure strain mode and rib level analysis, compression and simultaneous failure strain modes were combined into one category ("not tension") and rib levels 3 and 8 were excluded due to low expected counts. A Kruskal-Wallis test demonstrated no significant difference in failure strain mode according to age, *H=2.89, p=0.236*, with mean rank values of 99.5 for Tension, 106.6 for Compression, and 83.5 for Simultaneous.

TABLE I
FREQUENCY OF FAILURE STRAIN MODE BY RIB LEVEL, SEX, AND AGE

Failure Strain Mode	**Sex**	**Rib Level**					
		3	*4*	*5*	*6*	*7*	*8*
Tension	F	0	1 (80)	2 (77–79)	17 (11–90)	1 (90)	0
	M	0	16 (16–79)	22 (13-86)	26 (22–95)	13 (16–87)	0
Compression	F	0	2 (77–80)	2 (41–92)	10 (24–93)	0	0
	M	1 (42)	13 (9–88)	9 (20-88)	22 (9–88)	18 (20–87)	2 (9–16)
Simultaneous	F	0	0	1 (25)	5 (10–67)	1 (90)	0
	M	0	4 (29–75)	4 (16–69)	3 (48–55)	4 (16–68)	1 (16)

*Age range in years listed in parenthesis

IV. DISCUSSION

As researchers attempt to develop and validate strain-based rib fracture criteria in HBMs [6], the characterization of specific failure strain mode becomes increasingly important. Fracture initiation of ribs subjected to anterior-posterior bending has previously been estimated to be tension [3], based on first principle strain together with skeletal biology research [3][7-9]. However, human ribs subjected to dynamic anterior-posterior loading do not clearly demonstrate consistent failure strain modes; fractures initiated in tension in only 49% of the current sample. Since age, sex, and mid-thoracic rib level have no relationships with failure strain mode, it is likely these variables can be excluded in predictive models focused on initial failure mechanism. Future research is important to explore more complex variables, such as rib global and cross-sectional geometry, and their relationships with failure strain mode in order to improve rib fracture prediction in HBMs.

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