Leveraging Abdominal Pressure Sensors in the THOR-05F Finite Element Model to Predict the Onset of Lap-Belt Submarining

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I. INTRODUCTION

Anthropomorphic test devices (ATDs) are the primary tools used in regulatory and consumer crash testing to capture human response in real-world loading scenarios. While limitations have been identified in these devices [1], recent developments in advanced ATDs, such as the Test device for Human Occupant Restraint (THOR), have improved biofidelity and instrumentation capability, particularly in the pelvic, thoracic and abdominal regions [2–3]. One such advancement in instrumentation is the twin abdominal pressure sensors positioned in the THOR-05F, which allows for the detection of pressure change in the abdominal region during testing.

Submarining is defined as the occurrence of the lap-belt sliding over the iliac crest of the occupant with lap-belt forces effecting the internal abdominal organs during forward displacement of the lower torso [4]. As multi-step detection methods are recommended for identifying the onset of lap-belt submarining [5], the development of submarining criterion, especially in the abdominal region, proves beneficial to the continued support of research and ATD use in this field. The objectives of this study were to leverage the THOR-05F abdominal pressure sensors to observe changes in pressure during submarining and non-submarining scenarios, quantify the predictive capabilities of this metric, and identify a preliminary threshold of submarining.

II. METHODS

A finite element (FE) model of the THOR-05F v1.5.2 ATD (Humanetics, Farmington Hills, MI) was performed in a 200 simulation test series of frontal impacts varying seven literature derived, influential factors of submarining: seatback recline angle, seat cushion angle, buckle anchor position, knee bolster presence, pulse severity (delta-v), load limiting, and pretensioning. A uniform distribution was applied to discrete variables while Latin Hypercube Sampling was used to adequately sample the space of the continuous variables. A custom FE test sled was developed around an OEM seat [6] to accommodate variations in all desired boundary conditions. Figure 1 presents the THOR-05F in the test sled at an upright posture and 3° seat cushion angle.

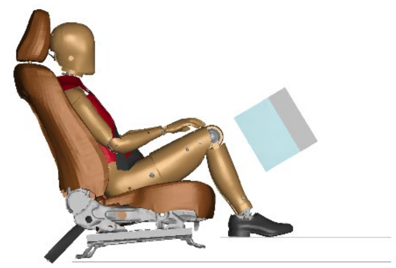

Fig. 1: THOR-05F in custom test sled

Submarining in all 200 simulations was first identified through code and confirmed visually as the lower edge of the lap-belt passing over the most anterior/superior portion of the model's ASIS load cells. After submarining classification (yes or no), abdominal pressure was extracted from both of the twin pressure sensors. Maximum abdominal pressure was used for analysis and was computed as the maximum pressure reading in either sensor. Taking abdominal pressure results and submarining response of the 200 simulations, a Mann-Whitney U test was first performed on abdominal pressure readings between submarining and non-submarining cases to assess statistically significant differences in pressure based on model response. Then, a Receiver Operating Characteristic (ROC) analysis was performed to quantify the ability of abdominal pressure to identify submarining using the area under the ROC curve (AUC), and determine thresholds of submarining using Youden's J statistic to select the optimal predicted probability cut off. Finally, a multivariable linear regression with a 95% confidence interval incorporating inboard/outboard lap-belt force, shoulder-belt force, seatback recline angle, and thoracic flexion represented as standardised beta coefficients was incorporated to statistically address whether or not changes in abdominal pressure were influenced by external factors other than belt loads. Variance inflation factors (VIFs) were calculated alongside the regression to quantify the extent to which the variance of each regression coefficient was inflated due to relationships among other predictors.

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III. INITIAL FINDINGS

Out of 200 simulations, the THOR-05F submarined in 108 cases and alternatively did not submarine in 92 cases with an average submarining time of 55.75 ± 8.86 ms. Figure 2 shows two simulations; one where submarining was not identified (left) and one where submarining was identified (right).

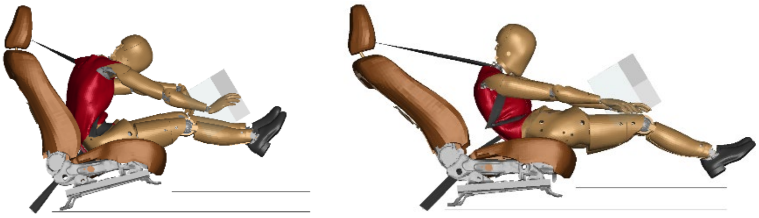

Fig. 2: Non-submarining (left) and submarining (right) simulations

The relatively equal distribution of submarining and non-submarining scenarios allows for sufficient data sets to observe trends in abdominal pressure changes. The Mann-Whitney U test indicated that submarining cases had a statistically significant increase in abdominal pressure compared to non-submarining cases. The average abdominal pressure in non-submarining cases was 134.7 ± 28.2 kPa while the average abdominal pressure in submarining cases was 198.6 ± 40.6 kPa.

The ROC analysis found that changes in abdominal pressure were highly predictive of submarining response as it received an AUC of 0.922. Youden's J statistic also determined that the threshold for the onset of submarining was 164.1 kPa. Figure 3 presents the ROC curve of THOR-05F abdominal pressure.

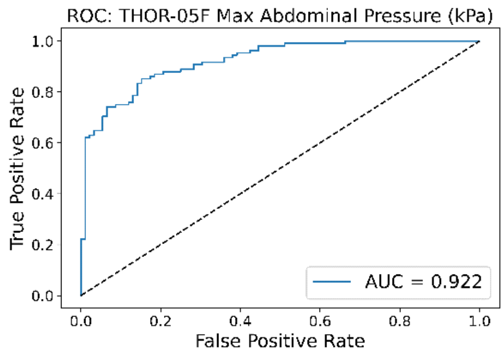

Fig. 3: ROC curve for THOR-05F abdominal pressure

The multivariable linear regression found that while belt forces were significantly associated with changes in abdominal pressure, the seatback recline angle and thoracic flexion were not. A VIF calculation showed that there was moderate collinearity between inboard and outboard belt forces but the other factors maintained relatively low scores indicating that no predictors showed enough collinearity to consider merging predictors.

IV. DISCUSSION

As the lap-belt loses its interaction with the pelvis during a frontal impact, it begins directly loading the abdomen of the occupant. The results of this study indicate this action increases abdominal pressure in the THOR-05F and this rise in pressure is correlated with submarining. This study quantified this association and proposes a preliminary submarining criterion (threshold) for the THOR-05F based on this pressure sensor. As submarining identification in physical testing has shown to occasionally be ambiguous [5], the introduction of an objective abdominal pressure metric to detect submarining further aids in classification. This metric will also assist in large-scale computational test series, such as the one presented in this study, as objective metrics are useful for quickly identifying submarining in post-hoc data analysis without requiring direct observation of the simulation results.

Additionally, when analysing the external effects of abdominal pressure changes while accounting for others through a multivariable linear regression, it was found that belt forces were more strongly associated with changes in abdominal pressure than seatback recline angle or thoracic flexion. The purpose of this analysis was to show that changes in abdominal pressure were not due to the forward flexion of the body during impact (i.e. thorax crushing down on the sensors) but rather the loading of the three-point belt system on the abdomen. Future work will focus on corroborating these findings in Human Body Models and verifying these findings in physical experimentation.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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