The Dynamic Response of FlexiForce Sensors for use in Injury Risk Assessments

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I. INTRODUCTION

Impact protection systems (automotive, sport, ballistic) are regularly assessed using Anthropomorphic Test Devices (ATDs), designed to provide repeatable injury predictors during safety testing. ATDs rely on instrumentation placed at discrete locations for injury risk assessments; however, regions such as the upper extremity and chest currently lack this instrumentation and thus may not predict injury adequately. Furthermore, ATD instrumentation within the 'skeleton' contrasts with impactor-mounted load measurements on the exterior of post-mortem human subjects (PMHS), as is frequently done during development of injury limits. This reduces the transferability of PMHS-derived injury limits to ATDs.

Load cells, commonly used in ATDs, are generally heavy and stiff, and risk altering the impact conditions. Piezoresistive force sensors (FSRs) are cost-effective, flexible force transducers that can conform to irregular geometries, such as the human body's surface, making them a potential candidate for external force measurement. These light-weight sensors could be placed at any location of interest and applied equally to PMHS and ATDs for improved injury limit transfer. Previous investigations into using FSRs for dynamic injury assessment are limited, with one previous study using them for helmet tests where the sensors had low root meet square errors (RMSE) at a single energy level [1]. While appealing for their potential use for the field, a comprehensive evaluation was required to investigate whether force readings would be affected by substrate curvature or compliance, two factors that vary dramatically across PMHS/ATD and anatomical locations.

II. METHODS

Three FlexiForce A502 (Tekscan Inc., Norwood, MA) thin film sensors were selected for their high force sensing range (45 kN) and large sensing area (2-in x 2-in). Each was conditioned per manufacturer specifications by loading to 110% of the target force range (11 kN) using a materials testing machine. Dynamic impacts were applied using a pneumatic impacting apparatus (Fig. 1a) equipped with a 663 g projectile with a vulcanised rubber impact cap. A PCB 200C20 (PCB Piezotronics Inc, Depew, NY) was used as the reference force sensor, to which a 2-in x 2-in 3D-printed PLA mount was secured. Each FlexiForce was secured to this mount using double-sided tape and covered with a thin piece of vinyl (0.12-in) for sensor protection (Fig. 1a). Dynamic calibration was performed using a flat PLA mount, and forces applied across the desired force range (0-10 kN). Lines of best fit were calculated for each sensor, and calibration accuracy assessed via R^2 (> 0.95 considered good) and RMSE (< 5% of force range (500 N) considered good) of the lines of best fit.

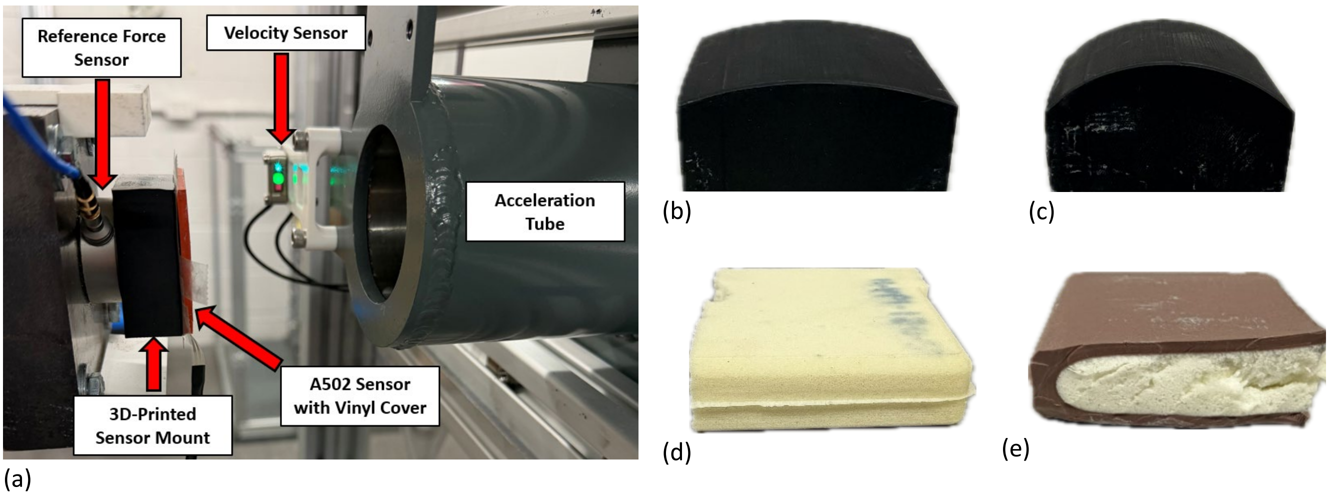

Figure 1: (a) Impact chamber of pneumatic impacting apparatus with the initial calibration setup shown. (b) The shallow curved impact surface, (c) the deep curved impact surface, (d) foam, (e) vinyl-foam composite.

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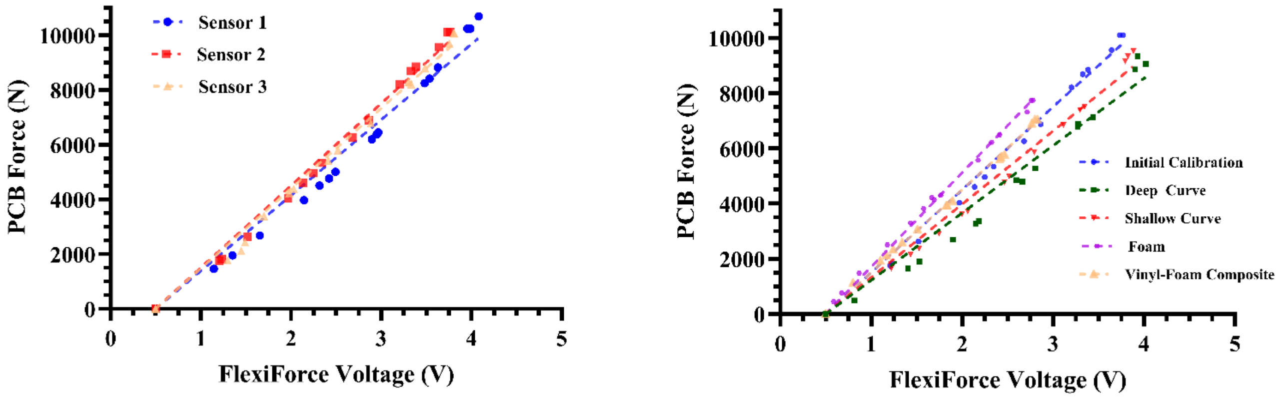
Dynamic impacts were then applied to each sensor over the desired force range to assess the effects of curvature and substrate stiffness on sensor performance. Deep radius of curvature (3-in, based on the forearm) and shallow radius of curvature (1.5-in) sensor mounts were 3D-printed (Fig. 1b-c) and the sensor edges taped to conform to the desired curve. To represent softer surfaces, foam and vinyl-foam composite samples (Humanetics Group, Farmington Hills, MI) were also used in turn (mounted in front of vinyl covering) (Fig. 1d-e). Sensor accuracy was similarly characterised, and for each sensor the slope of each line of best fit was compared to the initial calibration.

III. INITIAL FINDINGS

Impact velocity ranged from 2.3 to 10.8 m/s, with peak impact forces between 301 and 10,688 N, and impact durations of 1.8 – 10.1 ms. Initial calibration testing yielded highly linear lines of best fit ($R^2 > 0.98$, RMSE < 450 N) (Fig. 2a). Sensor sensitivity during base calibration was between 2763 N/V and 3001 N/V. Sensor response remained highly linear for the four other conditions tested ($R^2 > 0.97$, RMSE < 586 N) but did vary with loading conditions (Fig. 2b). Increasing impact surface curvature increased sensor sensitivity, while the foam (most compliant surface) decreased sensor sensitivity. This resulted in errors up to 20%; for sensor three an applied force of 5 kN would have been measured as a load of 5954 N using the deep curvature, and the foam condition would have resulted in a measured load of 3948 N (based on the base calibration curve). Errors were less pronounced for the shallow and vinyl-foam composite conditions.



(a) (b)

Figure 2: (a) Comparison of the initial calibration for the three A502 force sensors. (b) Comparison of Sensor 2's initial calibration to the four alternative impact conditions.

IV. DISCUSSION

This study evaluated the performance of FlexiForce A502 sensors under high-rate loading at varying impact conditions to assess their potential use for injury risk assessments. Initial dynamic calibration was successful, with each sensor producing a highly accurate linear response across a 10 kN target force range, at speeds relevant to the injury biomechanics field. The sensors had substantially different sensitivities, such that a 4 V reading would correspond to sensor 1 measuring 9,670 N and sensor 2 measuring 10,504 N. As a result, individual calibration is needed for each sensor as one general calibration curve does not appear feasible.

The sensors maintained their linear response under curvature, but force values deviated from the initial calibration. This indicates that scenario-specific calibration may be required when used on certain anatomical regions (such as the forearm) to ensure accurate data. The response of the sensors was not substantially impacted by moving to a medium compliance mount (the vinyl-foam), which suggests they may be suitable for use for tests against ATDs. However, the deviation when impacts were applied over low-stiffness material (foam) may necessitate scenario-specific calibration for softer impacts (*e.g.* PMHS, certain anatomical regions). Future work should identify when this may be needed. Ongoing work will investigate the repeatability of the sensors and long-term consistency. The accuracy of these sensors under dynamic loading provides confidence in their use for future injury risk assessments for both PMHS and ATDs, when calibrated appropriately.

V. REFERENCES

[1] R. Ouckama *et al.*, J. Biomech., 2011.