Comprehensive Characterization of Soft Tissue and Surrogate Materials Across Varied Loading Methods

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Introduction: The upper extremity is vulnerable to injury in numerous fields such as automotive, defence, or sports. These impacts may be blunt or focal and occur over a broad range of speeds. Injury risk in industry is typically assessed based on internal sensors in an Anthropomorphic Test Device (ATD). However, the loads measured will depend greatly on the properties of the soft tissue analogue used to transmit them (typically vinyl/foam composites). Very little is known about the impact response of natural soft tissue (adipose and muscle) or how well ATD 'flesh' represents these. The purpose of this study was to characterize human soft tissues and analogues' responses over a range of impact conditions, to characterize the material properties. These data may be used to develop novel soft tissue representations in future ATDs.

Methods: Soft tissue samples were extracted from the mid-length of eight cadaveric forearms, taken from the anterior and posterior aspects. Samples consisted of 8 mm diameter cores and 18x18x10 mm cubes, extracted using a coring tool and scalpel, respectively, 1.5 hours after removing from a freezer. Core samples were loaded in unconfined compression (UC) (to represent blunt loading) using a flat-ended platen at 1) a quasi-static strain rate of $0.001s^{-1}$ and 2) a moderate strain rate of $1s^{-1}$ until 50% strain. Indentation tests were conducted on the cubic samples (to represent focal loading) using a 6 mm diameter indenter at the same quasi-static and medium strain rates, until 20% strain. For both unconfined compression and indentation testing a 60s displacement hold was set at the maximum displacement to evaluate the material's stress relaxation response. A custom-built drop tower was used to perform unconfined compression tests on the cubic samples post-indentation testing at a high strain rate of $\sim 200s^{-1}$, to 50% strain. Current ATD foam and vinyl-foam composites were similarly tested in triplicate.

Results: The ATD modulus values were consistently higher than those of the soft tissue samples across all testing scenarios (Table 1). Soft tissues exhibited higher stress relaxation responses over the 60s period compared to ATD samples; ATD samples showed 7.7% (± 0.3) and 11.3% (± 0.3) for quasi and moderate rates, while soft tissues demonstrated 64.4% (± 13.6) and 83.4% (± 9.4) for the same rates, respectively. Force-deflection curves were substantially affected by the muscle/adipose proportions of tissues, and ongoing work is modelling this to identify target properties to represent each.

Discussion: This study underscores the need for more accurate soft tissue analogues in ATDs to better predict injury risk in various impact scenarios. By characterizing the mechanical properties of both soft tissues and current ATD materials, these data can inform the development of novel materials that can find a greater balance between bio-fidelity and reusability in modern ATDs. The general agreement between unconfined compression and indentation suggests that it may be unnecessary to conduct both testing types for future studies, allowing future researchers to apply this coring methodology to increase sample size within the constrained availability of soft tissues.

Table 1. The mean +- SD moduli values for the three testing rates and two experiment types. All values in kPa and up to 20% strain.

	Quasi-static rate		**Moderate rate**		**High rate**
	Unconfined	**Indentation**	**Unconfined**	**Indentation**	**Unconfined**
Soft tissues	6.94 ± 4.35	7.47 ± 3.76	16.62 ± 8.86	14.35 ± 7.66	118.62 ± 56.5
ATD foam	234.80 ± 2.81	114.25 ± 2.81	272.80 ± 4.16	134.84 ± 1.79	339.92 ± 38.65
ATD vinyl-foam composite	345.92 ± 14.31	344.34 ± 16.83	405.03 ± 16.13	436.47 ± 26.41	342.63 ± 26.35