Loading Rate Dependency of Cervical Spine Ligaments Assessed using Statistical Parametric Mapping

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I. INTRODUCTION

Cervical spine ligaments play a key role in the head and neck kinematics and have been implicated as a source of pain in whiplash-associated disorders. Characterisation of ligaments is critical for human body models to predict responses such as ligament distraction, rupture, and associated injury risk [1]. Published research has suggested that the mechanical responses of ligaments exhibit loading rate dependence [2]; however, statistical assessments of mechanical responses are inherently limited by the need to simplify force-displacement responses to single-value scalar metrics, limiting analysis to specific features such as peak force without capturing differences in displacement or response shape. In this paper, the rate dependence of the cervical spine capsular ligament was assessed with a new statistical technique coupling statistical parametric mapping (SPM) [3-4] with arc-length re-parameterisation [5] to perform hypothesis testing between loading rates considering variability across the length of the response, providing a general approach to analysis shape differences between test conditions.

II. METHODS

Force-displacement data of cervical spine capsular ligaments tensile experiments at three different loading rates (quasi-static, medium, and high) were investigated from an experimental study [2]. Hypothesis testing was carried out to determine if there was a statistically significant difference in ligament response with loading rate using the arc-length-based SPM methodology, leading to three pairwise tests between all rates. A significance, α, of 0.05 was selected, with a Sidak correction applied to correct for the family-wise error rate, resulting in each pairwise t-test using a significance of α=0.017. For comparison, traditional scalar t-tests were undertaken on the peak force of each response.

The arc-length-based SPM methodology consisted of two main processes (Fig. 1). First, all responses across all test conditions (loading rates in the case of this study) were re-parameterised with respect to normalised arc-length, $\hat{s}$, to ensure that all responses had the same number of points equally spaced along a common sampling parameter intrinsically tied to the shape of the response. Arc-length re-parameterisation also removed issues wherein force-displacement responses terminated at different displacements and forces. Next, signal registration was performed to align shared features in all responses with respect to $\hat{s}$ without changing the shape of the responses to accurately capture variability in both force and displacement axes simultaneously [5]. Details of arc-length re-parameterisation and registration are covered in [5].

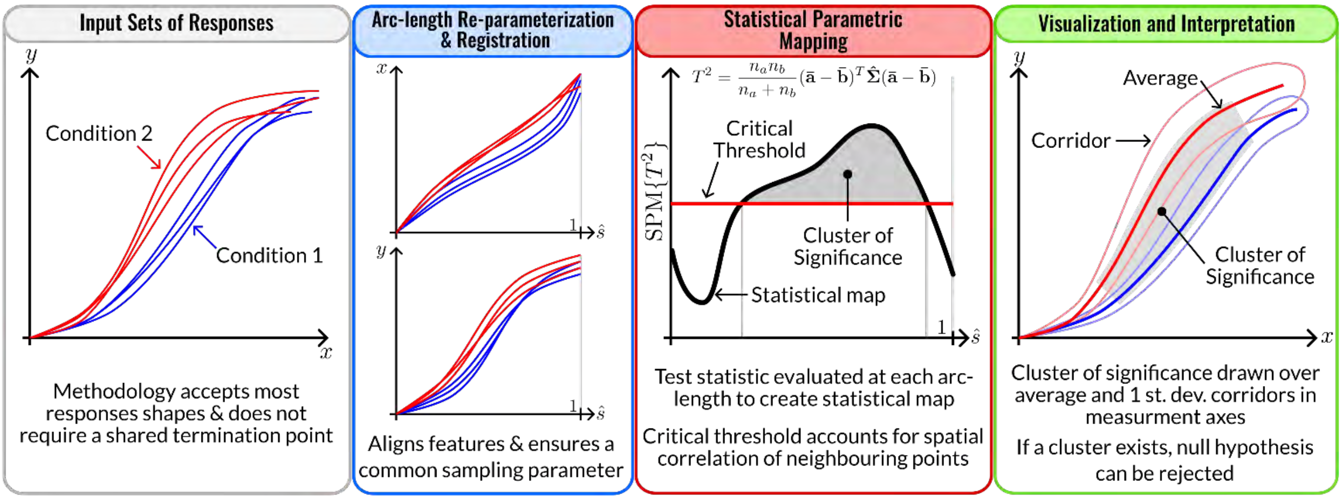

Fig 1. A graphical overview of the arc-length-based SPM methodology.

Statistical analysis was performed on the re-parameterised responses using SPM. First, a test statistic was computed at each $\hat{s}$ across all responses to create what is known as a statistical map. The statistical map captured

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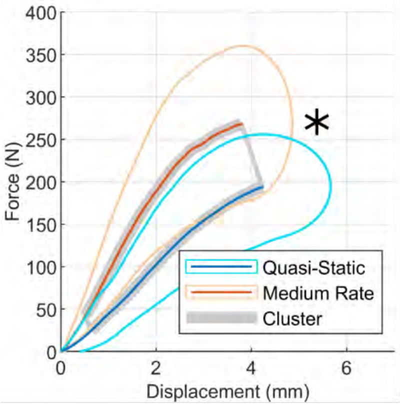
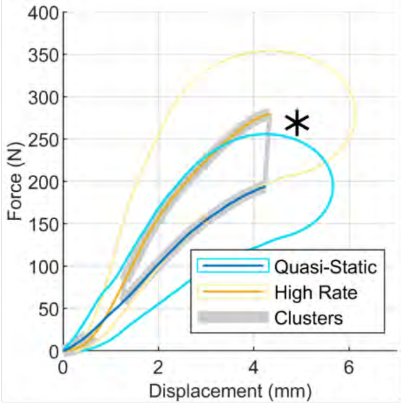
variability throughout the responses. A Hotelling's T^2 test statistic was used to assess variability in force and displacement simultaneously. Next a critical threshold for the statistical map was computed for a desired significance level using random field theory [4]. The threshold calculation was akin to a critical value for scalar t-tests but accounted for the correlation between neighbouring points in the statistical map rather than treating each point as independent. Regions of the map above the critical threshold indicated areas where the two sets of responses were significantly different. These regions, also known as clusters, were then plotted over the average and ± 1 standard deviation corridors of each set of responses to visualise clusters in the context of the original responses.

III. INITIAL FINDINGS

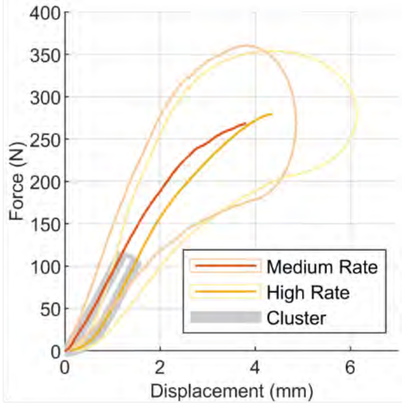
Pairwise tests using arc-length-based SPM agreed with scalar tests for the first two pairs of tests while also highlighting significant differences in the shape and slope of the responses (Fig. 2a,b). Furthermore, the arc-length-based SPM approach was able to infer differences between the response of ligaments tested at medium and high rates owing to differences in the initial shape of the force-displacement responses (Fig. 2c). Pairwise scalar t-tests on peak force inferred statistically significant differences in the peak force between capsular ligaments tested quasi-statically and at medium loading rates (p=0.002) and between quasi-statically and at high rates (p<0.001). However, a scalar t-test did not infer a difference in peak force between medium and high rates.



(a) Quasi-static to Medium Rate



(b) Quasi-static to High Rate



(c) Medium to High Rate

Fig 2. Pairwise statistical inferences between all rates using the arc-length-based SPM approach (α=0.017). Solid lines are the average responses of each dataset, with the lighter bounding loop representing ± 1 standard deviation. Regions or features of responses that produce statistical differences (known as clusters) are highlighted in grey, and asterisks indicate where scalar t-tests showed significant differences in peak force (p<0.017).

IV. DISCUSSION

The arc-length-based SPM approach detected differences in the responses by accounting for variability in both force and displacement throughout the entire response, while scalar t-tests on peak force could not infer differences between medium and high loading rates. The ability to capture variability in both measurement axes simultaneously allowed the arc-length SPM approach to capture differences in the slope and shape of ligament response between loading rates that could contribute to the prediction of injury risk. However, SPM-based approaches can be more conservative and require more repeats for sufficient resolving power.

While scalar statistical tests are the established method of analysing continuous responses like force-displacement behaviour, scalar metrics for testing must be carefully selected. As demonstrated, peak force was effective for inferring differences in some loading rates but could not account for differences in slope and stiffness between loading rates. The selection of scalar summary metrics inherently introduced some bias into testing. By considering the entire response, the arc-length-based SPM methodology provided a framework for statistical analysis that reduced the need to carefully select response features to analyse, reducing the chance of bias in testing.

V. REFERENCES

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