A novel volumetric measurement technique to measure strain in brain phantoms during needle insertion.

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Abstract

This work focuses on the creation of a novel method which utilizes the shake the box particle tracking algorithm to obtain a 3D strain field within a hydrogel brain phantom. This study includes a finite element model of a ball tip indentation to act as a baseline to validate the shake the box measurement technique. Following this, needle insertion tests are preformed and the strain profile around the needle tip extracted.

Possible Sessions

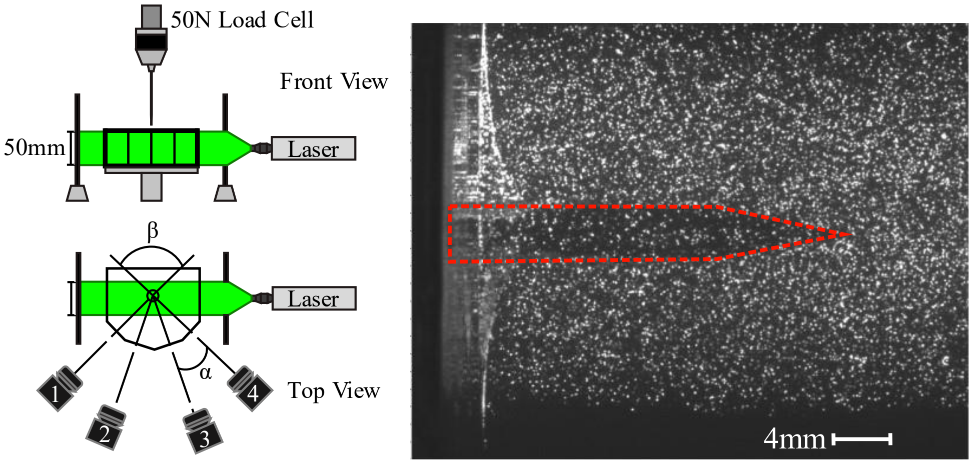
12. Medical Applications, 16. Novel Experimental Techniques, 21. Soft matter

Introduction

One of the main challenges in developing effective treatments for neurological disorders such as Parkinson's disease is to deliver electrical stimulation to specific regions of the brain with minimal damage to the surrounding tissue. This requires the insertion of needles or electrodes into the brain, which can cause mechanical injury and inflammation [1]. To minimize these adverse effects, it is essential to understand the strain profile of the tissue during initial implantation and how these change during different loading conditions and needle geometries. This necessitates the creation of three-dimensional strain profile measurements around these implants. This paper builds off the work of Leibinger *et al* [2] and introduces a new method of obtaining a three-dimensional strain profile, which provides an alternative to digital volume correlation and optical coherence tomography.

Methods

The phantom being used for all tests is a 3.4%wt gelatine gel which has been shown to exhibit similar properties to human brain tissue in the context of needle insertion [2]. It also has the benefit of being naturally transparent allowing fluorescent particles embedded throughout the volume to be illuminated and viewed. A pulsed laser, commonly used in particle image particle image velocimetry, is used to illuminate the volume, causing the embedded particles to fluoresce. The needle is then inserted into the gel. The displacement of the particles is tracked using the four-camera setup shown in Fig. 1a with an example image shown in Fig.1b.



a. b.

Fig 1: Experimental setup – a. schematic of the needle insertion setup where the cameras are in a linear configuration (1-4), with angles of α = 26° and β = 78°; and b. An example raw image taken mid insertion needle outlined in red.

The images are then analysed in the LaVision Shake-the-box software [3] allowing the displacements of individual particles to be tracked. The displacements were assigned to the particles initial position and a uniform voxel grid is overlayed over the measurement domain. The displacements are calculated at the centroids of each of the voxels by multiplying the displacement of each individual particle by a Gaussian weighting function (W) before summing the resultant weighted particle displacement. Here W is based on the particles position relative to the voxel centroid with particles further from the voxel centroid having a lower weighting and therefore a smaller contribution to the summed displacement in that voxel. The method of calculating W is shown in Eq. 1.

$$W = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{D^2}{2\sigma^2}} \tag{1}$$

Where D is the distance between a data point and the bin's centroid and σ is the standard deviation of the Gaussian distribution, controlling the width of the distribution. With the displacement field established the strain field is calculated by implementing a finite element method, where the centroids of the displacement voxels are used as nodes in a Hex 8 finite element mesh. The components of the displacement were applied at each of the centroids and the resulting deformation gradient ($\boldsymbol{F}$) was calculated at the centroid of the finite element. $\boldsymbol{F}$ was then used to calculate the Green strain tensor using the Eq. 2

$$\boldsymbol{E} = \frac{1}{2}(\boldsymbol{F}^T \cdot \boldsymbol{F} - \boldsymbol{I}) \tag{2}$$

The deviatoric component of the green strain tensor was calculated via Eq.3.

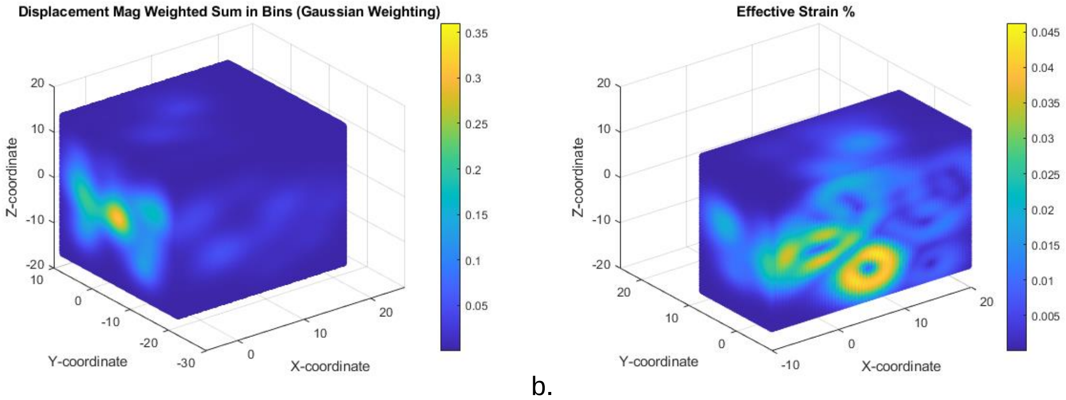
$$\boldsymbol{E}' = \boldsymbol{E} - \left(\frac{tr(\boldsymbol{E})}{3}\right)\boldsymbol{I} \tag{3}$$

Where $tr(\boldsymbol{E})$ is the trace of the strain tensor and $\boldsymbol{I}$ is the identity tensor. The maximum and minimum principal strains were then calculated for each element and the effective strain was calculated as shown in Eq.4:

$$\varepsilon_{eff} = \sqrt{\frac{3}{2}(\boldsymbol{E}' : \boldsymbol{E}')} \tag{4}$$

Results and conclusion

This method allows for the extraction of volumetric strain profiles around needle tips, see Fig. 2. These results demonstrate the feasibility and applicability of this novel technique to quantify volumetric strains. Now various needle tip and device probe designs can be quantitatively assessed for safety and suitability for insertion into brain tissue, relating strain characteristics to tissue damage risk.



a. b.

Fig 2: Displacement and strain fields – a. displacement magnitude extracted from the shake the box particle tracks; and b. a cross section of the extracted volumetric effective strain profile produced by one of the needle tips.

References

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[3] D. Schanz, S. Gesemann, A. Schröder. *Shake-The-Box: Lagrangian particle tracking at high particle image densities*. Experiments in fluids. 2016 May;57:1-27.