VDASE a Novel Volumetric Strain Measurement Technique Based on Shake the Box Particle Tracking.

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Abstract. This work introduces the creation and implementation of a novel volumetric strain measurement technique which can be applied to large volumes using displacement information gained from the Lagrangian particle tracking technique known as Shake the Box. The method relies on gaussian weighted binning of measured three-dimensional particle displacements to an imposed voxel grid. These points become the nodes of a hex8 finite element mesh which is used to calculate the volumetric strain.This method is verified using synthetic particle datasets to measure error and any bias before being applied to real experimental particle image sets. The resultant volumetric displacement and strain profiles were then compared with those of a finite element model created by inverse parameter identification. It was found that this model gives a representative strain distribution up to a point which is highly reliant on the particle density and size of the local displacement gradient.

Possible Sessions

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

Introduction. Quantifying the volumetric strain within gels experiencing complex loading can be challenging due to the lack of natural internal contrast required for digital volume correlation leading to high concentrations of particles having to be embedded to measure volumetric strain [1,2]. This may impact mechanical properties of the gel and has currently only been applied to small volumes. There is a requirement for a method which allows strain in large volumes to be measured with a reduced particle concentration.

Method

Volumetric Displacement and Strain Extraction (VDASE) Method. Information about the particles position over time is extracted from the outputs of the Shake the Box particle tracking method [3]. The displacement of individual particles within the measurement domain is measured over a single timestep. A voxel grid is applied over the entire measurement domain and the displacement information is binned to the voxel centroid. The particle's displacement is then calculated for the next timestep and added to the voxel centroid; this continues for the entire dataset. The voxel centroids then form the nodes of a Hex8 finite element grid, and the displacements accumulated in each of the voxel centroids is applied deforming the mesh. Using the finite element method the strain in each of the elements is calculated at the element centre.

Synthetic Particle Testing. In order to quantify the performance of the method under idealised conditions a synthetic particle dataset was created. Randomly generated particles were displaced according to there initial cartesian coordinates. This was fed into the VDASE method, and the imposed particle displacement field was compared with that of the measured. Techniques such as Bayesian optimisation and Bland-Altman plot analysis were employed to assess the effect of number of particles, bin size and weighting function on the measurement results.

Experimental Testing. In order to check the effectiveness of the method on a real dataset, a macro scale indentation test was performed on a gel embedded with fluorescent particles. The indentation was performed with a 4mm radius ball indenter up to a depth of 5mm at a speed of 1mm/s, the indentation was repeated twice for each of the seven samples. The gel being tested in this case is 3.7%wt gelatine as this is naturally transparent allowing the particles to be illuminated and tracked. The volume is illuminated with a pulsed laser and the volume captured by an array of four cameras shown in Fig 1. Shake the Box particle tracking was then used to extract the particle's cartesian coordinates at each timestep, this data was fed into the VDASE method and the displacement and strain output compared to results obtained from a finite element model.

FEA Comparison. A finite element model matching the indentation process was created to act as a baseline for comparison with the experimental data. Inverse parameter identification used the force displacement data from the indentation to fit a first order Ogden model to the gel for each of the samples. The outputs of this model were compared to the outputs from the VDASE model.

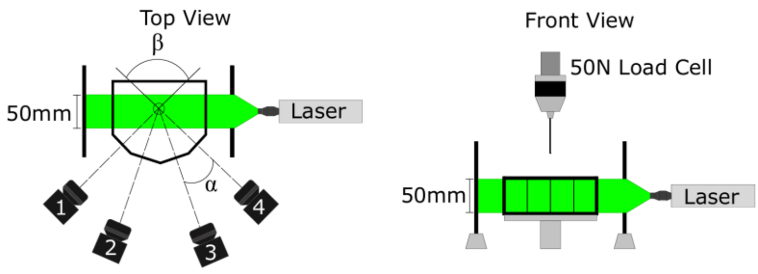

Fig 1 Left: Schematic of the indentation setup where the cameras are in an arc (1-4), with angles of α = 26° and β = 78° around the sample. Right: Shows the front view where a 4mm diameter ball indenter is attached to a 50N load cell.

Results

Synthetic Particle Testing. These tests show a decrease in the RMSE and P-infinity norm with increasing number of tracked particles (100-10000). The RMSE decreased from 0.35 mm (7%) to 0.06 mm (1.2%), with 90% of that decrease occurring before 5000 particles. The P-infinity norm also decreased with increasing particle numbers going from 0.02mm to 0.005mm. Bland-Altman plot analysis showed that the VDASE method gave a slight underestimation of displacement in areas of sharp displacement gradients.

Experimental Testing. This showed consistent displacement and strain measurements between samples. However, maximum magnitude of the displacement is significantly lower than expected at the point of indentation, 1.5mm compared to the 5mm imposed by the indenter. The result of this is an underestimation of the strain in these high displacement gradient regions. See Fig 2.

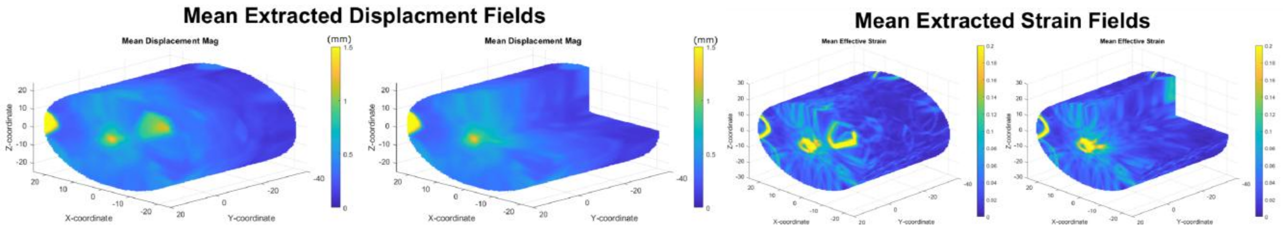

Fig 2 Mean results (n=7) Left: Volumetric experimental displacement magnitude. Right: Effective strain. These profiles were extracted from the STB datasets using the following parameters: bin size 0.5mm, sigma size 1.5mm and minimum track cutoff 3000 particles.

FEA Comparison. When comparing the FEA results to those extracted from the experimental data it was found that as the maximum displacement gradient increased so did the RMSE. As the displacement increased from 0.2 to 1.2 the RMSE increased from under 0.1 to 1.2mm. When the Person's Rank correlation was calculated it constantly had values between 0.8 and 1. When displacement and strain fields are compared side by side it is clear that the disparity lies around the indenter point while displacements further away are more representative see Fig 3.

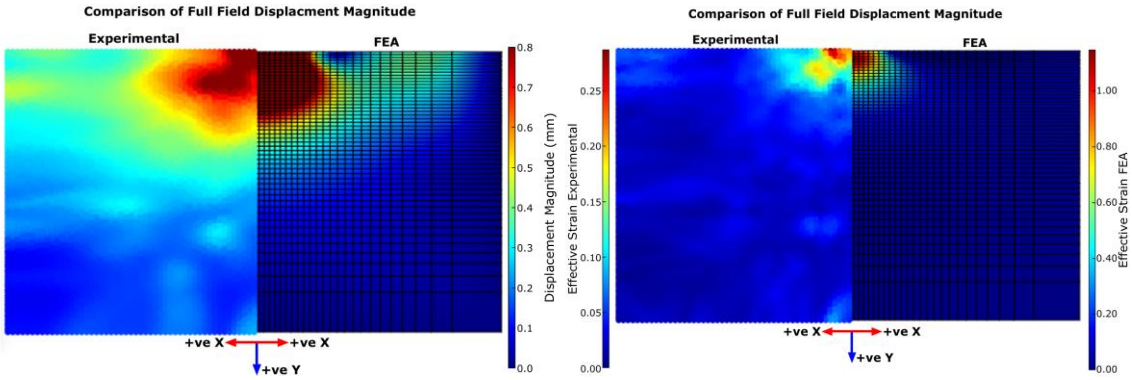

Fig 3 Left: Comparison of full field displacement magnitude results of the FEA models and the VDASE model, scaled to the output of the experimental data. Right: Comparison of full field results for effective strain of the FEA models and the VDASE model. Experimental profiles extracted from the STB datasets using bin size 0.5mm, sigma size 1.5mm and minimum track cutoff 3000 particles.

Discussion and Conclusion

This work shows a novel method of measuring volumetric strains from particle tracking datasets. This method differs from previous methods as it allows the displacement and strain in a large volume of gel to be measured. Under synthetic ideal conditions RMSE's as low as 1.2% over an imposed 5mm point displacement were observed. The accuracy of results is highly dependant on the quality of the extracted particle data, in experimental datasets particle loss due to aggregation in high compression regions is believed to be the cause of displacement underestimation, along with areas of high displacement gradients. Despite this, areas with relatively small displacement gradients showed accurate displacement and strain profiles. This method could be employed in a variety of loading conditions such as needle/medical instrument loading to tissue phantoms and impact loading of ballistic gel phantoms.

References

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