3DASE A Novel 3D Strain Measurement Technique Applied to Needle Insertion in Gel Brain Phantom.

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Abstract. We have previously presented the creation and application of the 3DASE method for the measurement of strain profiles in soft transparent gels subjected to indentation. We now present a follow up to that work in which the 3DASE method was used in conjunction with traditional techniques to quantify the differences between 3 needle geometries. It is our aim to provide new information on the strain experienced by gel surrounding the needle, and therefore quantify the volume of strain induced tissue damage during insertion. Results show that insertion behaviour transitions from an initial geometry dependent regime to a friction dominated response that scales with insertion depth. Increasing tip angle leads to higher insertion forces, greater energy dissipation, and increased displacement and strain magnitudes, with deformation effected regions becoming more spatially extensive. Strain localises near the needle shaft and shoulders and evolves into a multi-axial deformation field as insertion progresses. While force responses converge across geometries at depth, 3DASE reveals persistent differences in deformation magnitude and distribution not captured by force data alone. These findings demonstrate that 3DASE provides valuable spatial insight into insertion mechanics and highlights the importance of both strain magnitude and extent when evaluating needle design in order to limit the volume of tissue subjected to damaging strains.

Introduction

Delivering targeted electrical stimulation for neurological disorders such as Parkinson's disease often requires needle or electrode insertion into brain tissue, which can cause mechanical injury due to high strains and inflammation. Understanding the resulting strain distributions is therefore critical, particularly under varying loading conditions and needle geometries [1]. However, accurately measuring three-dimensional strain in soft, transparent tissue analogues remains challenging, as conventional methods require high concentrations of contrast agents that may alter material properties or are limited in volume [2,3]. To address this, the 3DASE method was previously introduced as an alternative approach for three dimensional strain measurement [4]. This study builds on that work by applying 3DASE alongside traditional techniques to examine the influence of needle geometry on strain profiles in soft gels.

Method

3DASE determines displacement and strain by tracking embedded particles in gelatine using information gained from the Shake-the-Box method [5] during needle insertion. A grid of Gaussian kernels defines nodal points of a Hex8 finite element mesh, where accumulated displacements deform the mesh and enable strain calculation at element centres [4]. Three conical needle geometries (20°, 40°, 60° Fig 1a) were inserted into 1 L gelatine samples (50 mm height), with a particle-seeded cylindrical region imaged by four cameras (Fig 1b). Insertions were performed at 1 mm/s, including full-thickness penetration, a 10 s hold, and retraction. The procedure was repeated along the same path to separate cutting and frictional contributions.

Results

Force Displacement. The force response increased linearly between 25% and 90% depth for all geometries, indicating friction-dominated behaviour with minimal dependence on tip angle. Slightly lower forces during second insertions suggest a small, diminishing cutting contribution. Deviations near full insertion were attributed to boundary effects, and variability increased with depth. Relaxation behaviour was consistent across geometries, while energy analysis showed higher work during first insertions, greatest for the 60° needle.

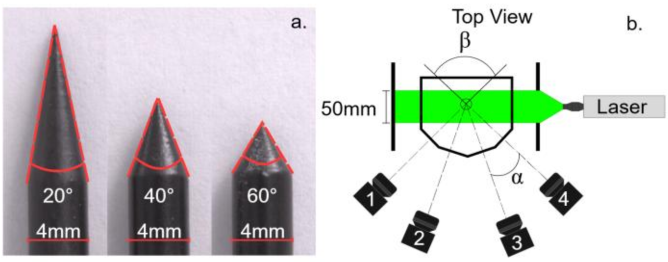

Fig 1a. Shows the different needle tip angles used in both insertion test types. b. Schematic of the indentation setup where the cameras are in an arc (1-4), with angles of α = 26° and β = 78° around the sample. The cameras line of sight is perpendicular to the plane on the chambers viewing window, and the particle infused gel is circled in the centre of the chamber.

Displacement Comparison. As shown in Fig 2, displacement magnitude increased with insertion depth, with the 60° needle producing the largest and most spatially extensive fields, followed by the 40° and 20°. Peak displacements were concentrated along the needle axis, with some peripheral artefacts. The region of maximum displacement progressed deeper with insertion, and at equivalent depths the 60° needle affected a larger volume, while the 20° and 40° responses remained more localised.

Strain Comparison Fig 3 shows peak strain initially located either side of the needle axis, extending along the shaft with insertion. Strain magnitude increased with tip angle, with the highest values at the needle shoulders for the 60° geometry, while the 20° needle exhibited lower, more diffuse strain.

Discussion

Displacement and strain measurements align with force displacement trends, increasing with tip angle and insertion depth (60° > 40° > 20°), consistent with higher forces and work for blunter needles. This demonstrates that 3DASE captures the key mechanics of insertion, though as consistency rather than independent validation. Similar looking fields at shallow depths likely reflects localised, compression dominated deformation and resolution limits. With increasing depth, the divergence in responses highlights the growing influence of needle geometry, consistent with force behaviour.

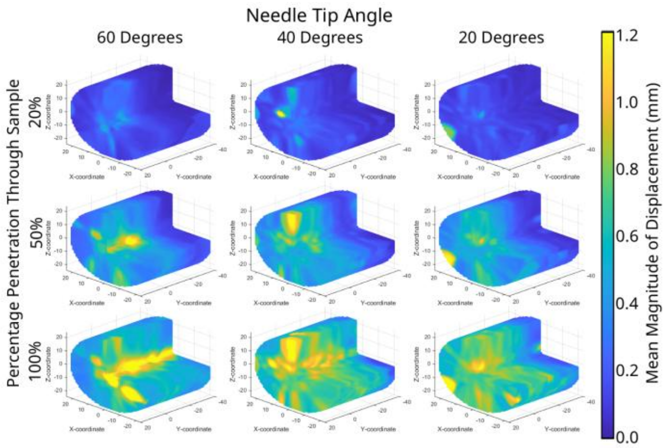

Fig 2 Shows the 3D mean (n=3) displacement magnitude fields produced by the 3DASE method for all three tip angles at 20%, 50% and 100% insertion depths. On quarter of the volume has been removed to better view the internal displacements

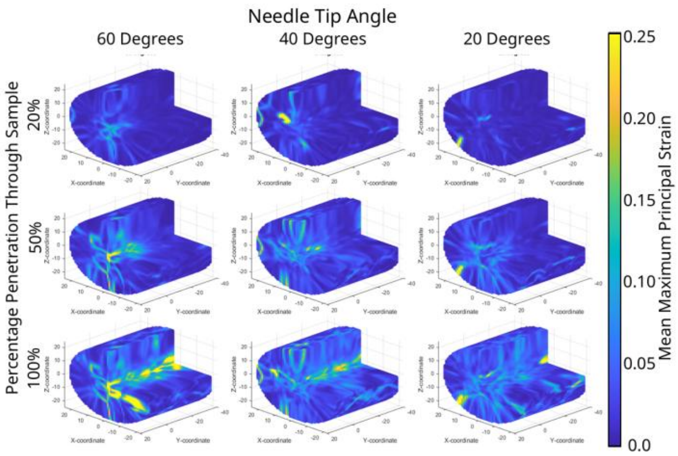

Fig 3. Shows the 3D mean (n=3) maximum principal strain fields produced by the 3DASE method for all three tip angles at 20%, 50% and 100% insertion depths

Conclusion

This study shows that needle insertion is governed by an initial geometry dependent response followed by friction dominated behaviour that scales with depth. Increasing tip angle increases insertion work and deformation, with friction dominating beyond initial cutting. The 3DASE method captures corresponding increases in displacement, strain, and spatial extent, revealing multi-axial deformation and persistent geometry effects not evident from force data alone. Despite limitations in resolution and repeatability, the method provides valuable spatial insight and highlights the importance of both strain magnitude and extent in needle design.

References

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