Living with diabetes: Development of therapeutic insoles with overload-sensing via electrical impedance tomography of carbon nanotube networks

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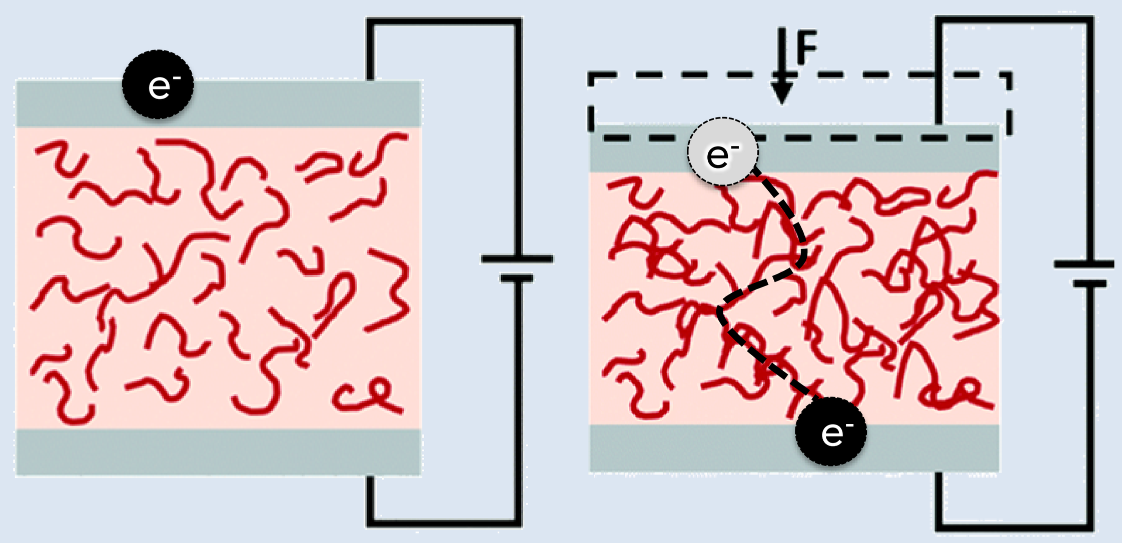
INTRODUCTION

Foot orthoses are available in the market to distribute pressure more evenly across the feet. However, these wear out and eventually lose their functionality. This research aims to develop a low cost, durable and mass producible therapeutic insole from a piezoresistive nanocomposite that would tell patients that functionality has been lost and it needs replacing. Towards this goal, piezoresistive nanocomposites have been made by embedding multi-walled carbon nanotubes (MWCNT) in thermoplastic polyurethane (TPU) and sensing options have been explored.

To simplify the concept, imagine that polyurethane (pink) is a river, carbon nanotubes (red) are unlinked sections of a bridge, and the electrons are cars attempting to cross. Without a bridge, the cars cannot get to the other side. The material is insulating at this point. As the insole is used, it compresses, bringing the carbon nanotubes in contact, eventually forming conductive bridge which allows the movement of the cars across the river. This then makes the material conducting. When the insole wears over time, more bridges are formed, lowering the electrical resistance further. Because of this, the actual insole would serve as the sensor, changing its internal conductivity distribution with wear.

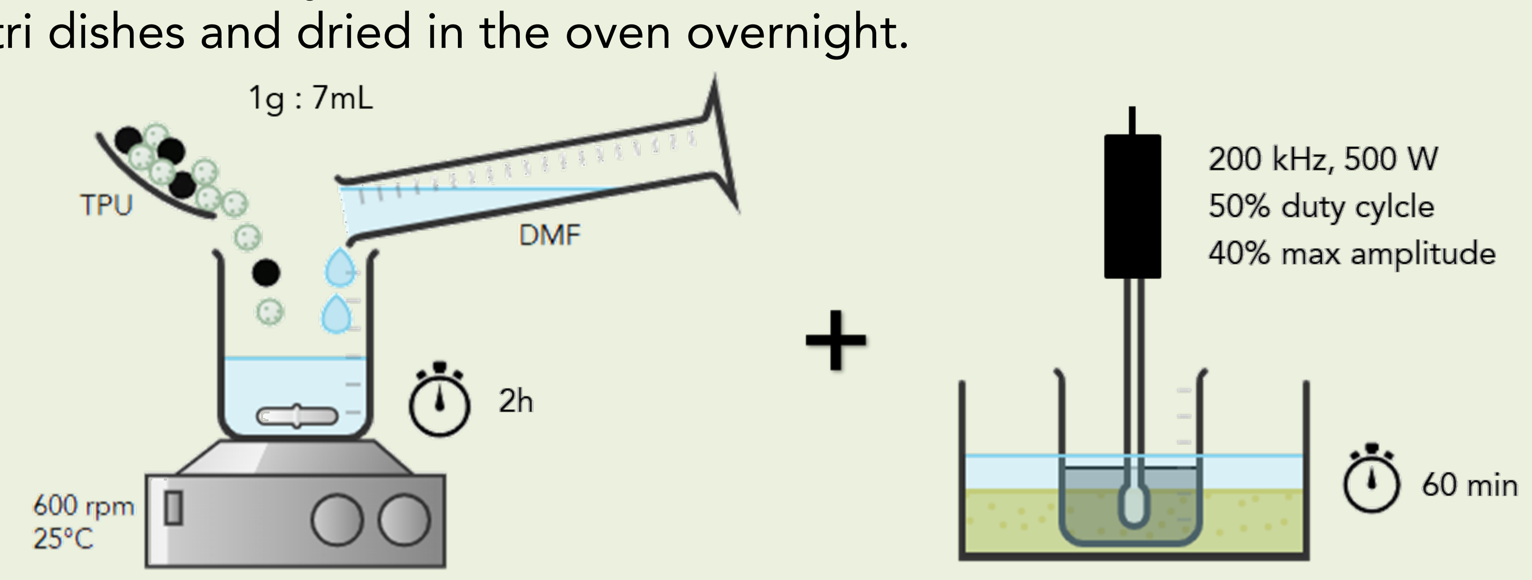


Conductive fillers embedded in insulating matrix in piezoresistive sensors form conductive paths upon the application of pressure.
Image Source: Heikenfeld et al. [1]

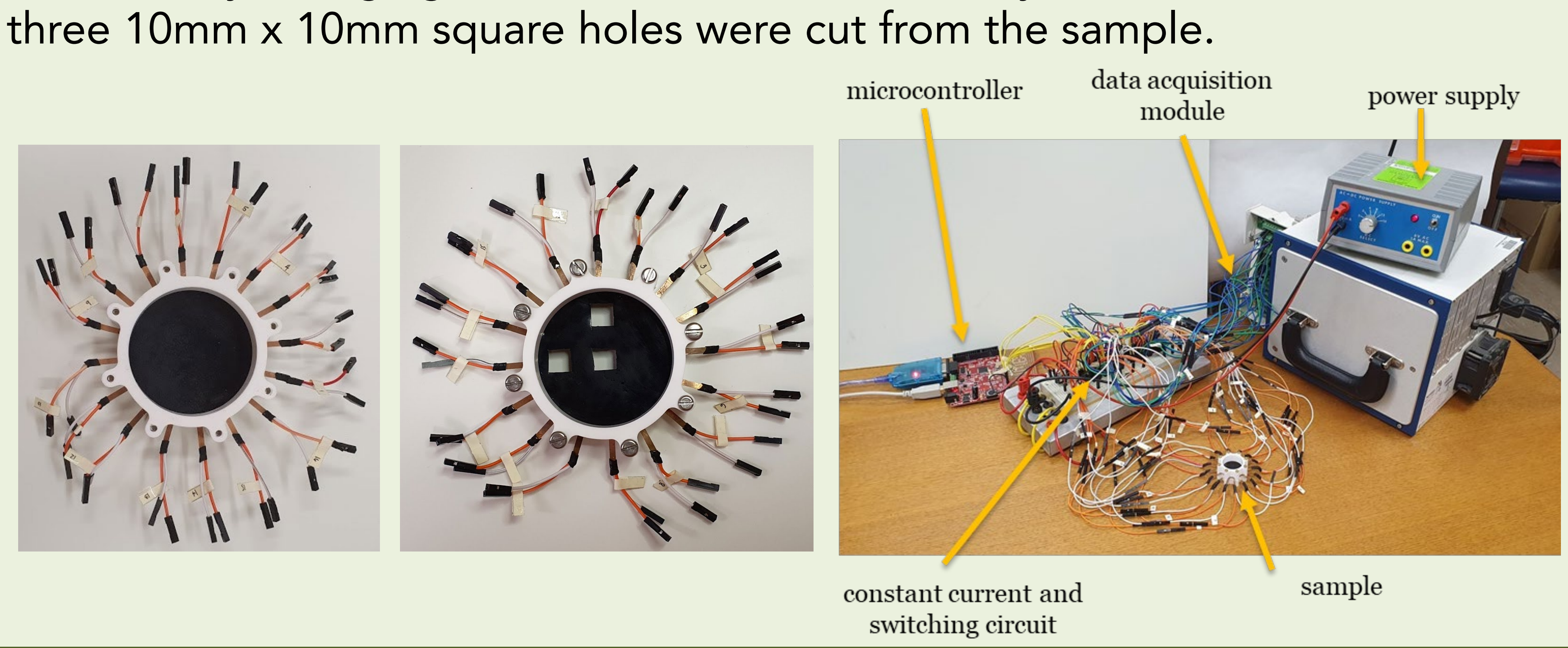
Electrical Impedance Tomography (EIT) is a non-invasive method to image the internal conductivity distribution of a domain bounded by electrodes [2]. The concept, which is initially used in medical and geophysical imaging, has recently gained attention for its potential in structural health monitoring (SHM) as it can potentially be used to detect and spatially map conductivity-changing stimuli [2,3]. For piezoresistive materials, where external stimulus induces localized conductivity change, the conductivity map can specify the extent and location of large strains or damages [4].

METHODOLOGY

Respective amounts of pristine TPU and MWCNT masterbatch pellets were weighed to synthesize 5wt% MWCNT-TPU. The pellets were then dissolved in dimethyl formamide (DMF) for two hours, ultrasonicated, cast on to petri dishes and dried in the oven overnight.

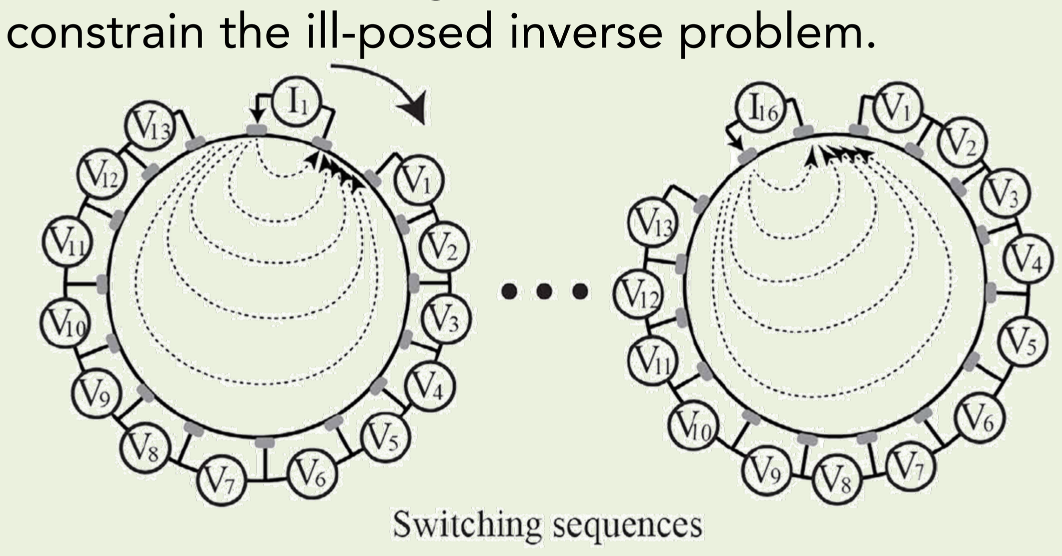


As EIT can be very sensitive to factors such as electrode misplacement and domain shape errors, this research is limited to using time-difference imaging, i.e. calculating the change in conductivity before and after the conductivity-changing event. To test EIT sensitivity based on known defects, three 10mm x 10mm square holes were cut from the sample.



ELECTRICAL IMPEDANCE TOMOGRAPHY

Sheffield protocol, where the current is injected between two adjacent electrodes while simultaneously measuring the voltage at the remaining electrodes, then cycling current stimulation through all electrode pairs – was implemented after each conductivity-changing event. The measured boundary voltages were then inputted in Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software (EIDORS), an open-source software toolbox written mainly in MATLAB. The five most common regularisation techniques namely Tikhonov, Newton One-Step Error Reconstructor (NOSER), Laplace, Automatic Hyperparameter Selection and Total Variation using Primal-Dual Interior Point Method (PDIPM) were used to constrain the ill-posed inverse problem.



Sheffield Protocol - adjacent current stimulation and interface pattern
Image Source: Lee et al., 2017

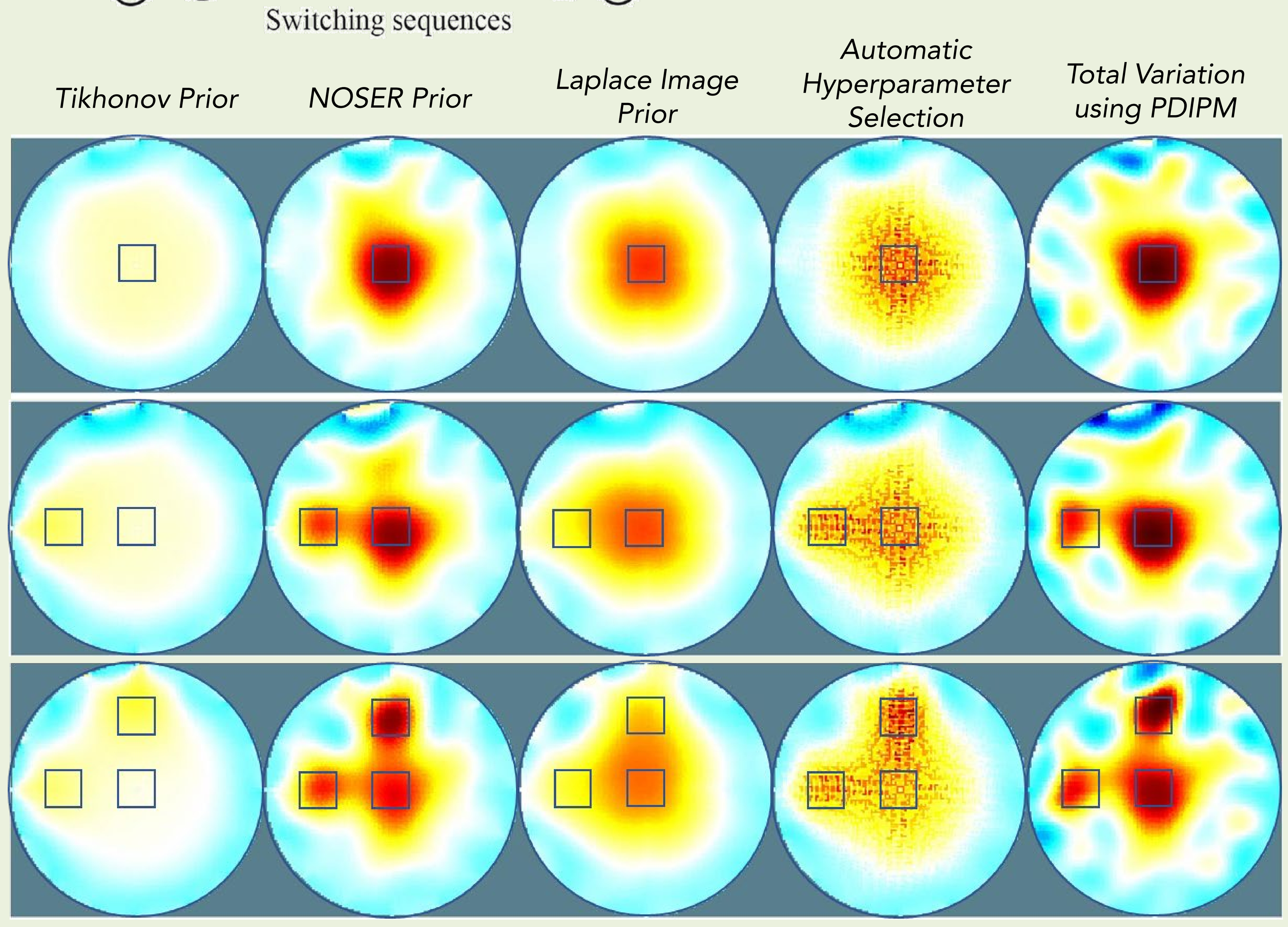
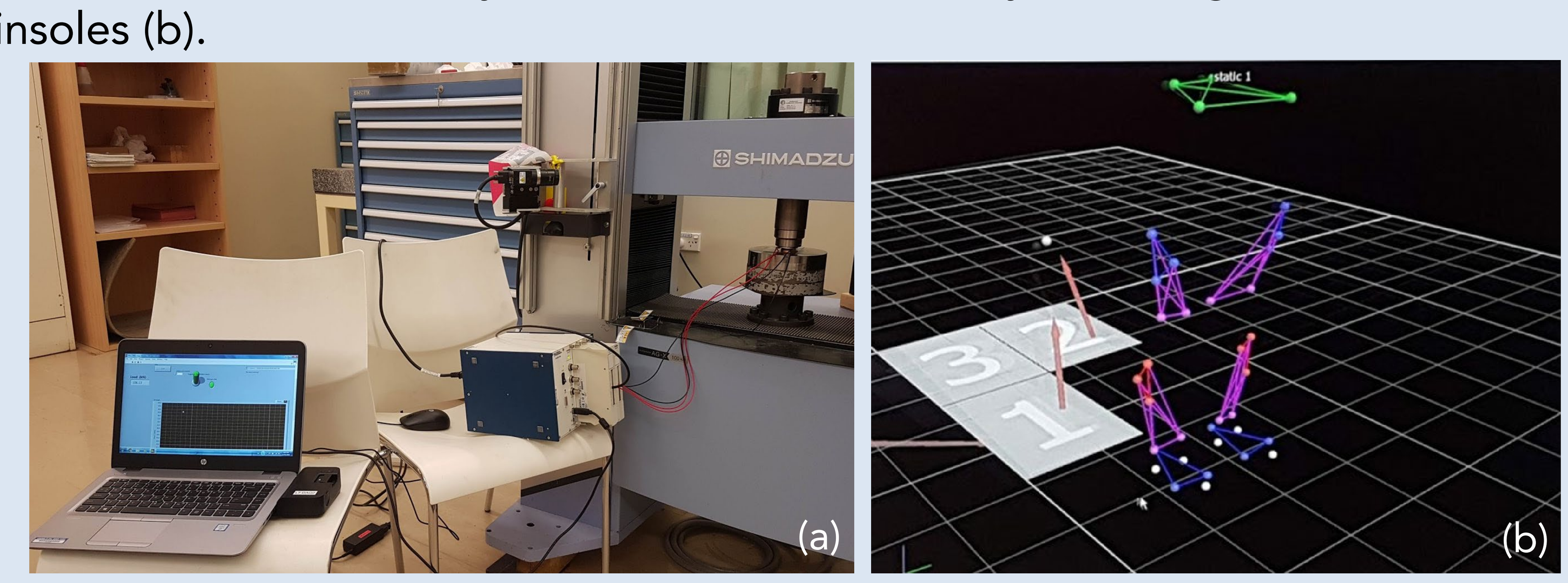


Image processing using ImageJ revealed that for 1 hole damage, Laplace Image Prior gave a normalised area and perimeter closest to the damage. Although NOSER and Total Variation using PDIPM identified the location of all three defects, the size and shape were not represented accurately.

CONCLUSION AND OUTLOOK

Multi-wall carbon nanotubes were homogeneously incorporated in thermoplastic polyurethane to synthesise a piezoresistive material. Reconstructed images from electrical impedance tomography indicate that the location of intentional holes is correctly identified by certain regularisation methods. The Laplace Image prior reproduced the geometry of the damage best. The resolution of the tomographic image may be improved by changing the current stimulation pattern, which is presently being studied.

As part of future work, the gait of a person will be simulated through cyclic compression loading in universal testing machine (a). The gait biomechanics of healthy individuals will be analysed using new and worn insoles (b).



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