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COMPUTATIONAL SIMULATION OF A MEMS-BASED MICROACTUATOR FOR TISSUE ENGINEERING APPLICATIONS

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INTRODUCTION

The relationship between the 3D microstructure of tissue-engineered constructs (TECs) and their resulting mechanical and biological function is critical in providing TECs with clinically meaningful mechanical properties in reasonable incubation times. We hypothesize that the next generation of TECs must incorporate a controllable and optimized microstructure (and resulting mechanical properties) if they are to mechanically and biologically mimic tissue function. While the development of a robustly engineered tissue replacement will undoubtedly require simultaneous biochemical and biomechanical stimulation, this paper will focus on the development of a device to impose localized micro-mechanical stimulation.

In this paper a MEMS-based device is introduced that can differentially stimulate the mechanical microenvironment of TECs using a noninvasive magnetic actuation mechanism. The device consists of a bed of micro-flaps (MFs) that are doped with a para/ferromagnetic material. Since the fabrication of such a device can be costly, the purpose of the current work is to develop a computational tool that can aid in device design. Finite element models (FEMs) are introduced to determine the relationship between MF/magnet size/properties and horizontal MF deflection. Towards this end, a 2D magneto-structural model was created to guide the development of a microdevice with a desired MF deflection.

MATERIALS AND METHODS

Computational Simulation of Microflaps

Figure 1 shows the stretching concept. The MFs are made of polydimethylsiloxane (PDMS) doped with iron filings. The tissue engineered construct (TEC) sits on the top of the MFs. As the magnets (light blue, with coersive force vector applied in the vertical dimension) are brought close to the four MFs (red), the MFs will move, straining the TEC. The actual straining occurs between the two center MFs. This setup was simulated using the commercially available magneto-structural finite element program ANSYS Version 10.

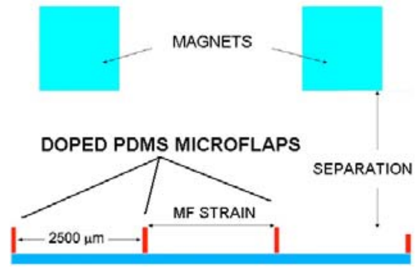

Figure 1: Stretching concept

The mechanical properties of the PDMS in the computational model were taken from the literature [1]. The magnetic properties of the doped-PDMS MFs were assumed to be close to other materials that do not exhibit high susceptibility to magnetic fields (μrH1) [2]. The mechanical properties were assumed to be homogeneous, isotropic, and the magnetic properties assumed to be in the unsaturated, linear portions of their respective B-H curves.

A 500 μm high by 100 μm thick arrangement of MFs with a separation of 2500 μm provided the geometric baseline. A sensitivity study was performed on the following system parameters: magnet size, magnet-to-MF separation, and magnetic particle density within the PDMS. An optimal magnetic particle density for mixing was first determined, after which the geometry of the small magnets were optimized to obtain a deflection at the top of the two central MFs in the x-direction of 175 μm. This value would correspond to 7% strain in the TEC.

Magnetic and structural FEMs were solved sequentially using 8-node quadrilateral elements. Infinite boundary elements were used at the boundary of the air elements. The model had 8,568 nodes with a refinement ratio of 3.0 from the air edge to areas with high magnetic field density or deflection areas of interest around the MFs [3]. Once the magnetic forces were obtained in the magnetic FEM, these were saved and exported to a structural analysis, where they were used to cause MF deflection. The structural model was constrained at the top of the magnet, around the end boundaries of the air elements, and at the bottom of the un-doped PDMS in all degrees of freedom.

Experimental Validation

To confirm these simulations resulted in meaningful MF deflection, a doped-PDMS flap was created on a larger scale. MF deflection was observed through a microscope when an 1/8" cube permanent magnet was brought to within 1.65 mm of the MF. This was confirmed computationally via the same process as the four-MF analysis. A 1:10 ratio of catalyst to PDMS base was mixed by mass, then mixed with iron filings to a .119:1 by volume ratio, and finally vacuum pumped for degassing to create the doped-PDMS mixture. After the mixture cured on a microscope slide, the thickness of the PDMS was measured with calipers all across the slide. The section that exhibited the smallest change in thickness (±13 μm) over an area of 25 mm^2 was removed from the mold and cut with a razor blade to result in dimensions of 0.28 mm thick by 4.39 mm high by 2.44 mm wide.

RESULTS

The first investigated parameter was the magnetic permeability of the PDMS MF (related to the density of the particles of iron filings in the MF). Baseline models with the same dimensions as the one in Figure 1 were used, however, with just one flap. The magnet was moved toward and away from the MF, and peak nodal forces were exported by using nine different models. A notable detail of these results is that with a specific magnet to MF separation the applicable magnetic force on the MF will saturate at a specific point. This point actually occurs at relatively low permeabilities compared to the permeability of iron [4]. This means that with the expected location of the magnet in the final analysis, mixtures greater than ~.119:1 of iron filings to PDMS will not increase the force on the MF. This in turn means that iron filings need not be wasted, and the density of the iron filings may remain low in order for the MF to better retain the mechanical properties of the PDMS.

Next, a model was developed with different magnet positions and four MFs (Figure 2, permanent magnets not shown). Four separate models were run with varying magnet size and magnet separation. An exponential equation was determined relating MF deflection and magnet separation. In order to isolate the appropriate magnet separation, the desired MF displacement was inserted and back solved for separation. This separation was 1.92 mm from the bottom of the magnet to the top of the MFs. A model was created with this separation and solved non-linearly, large deflection, with 50 iterations for the magnetic analysis and 1000 iterations structurally. As seen in Figure 2, the deflection between the two central MFs was 180 μm, which resulted in 7.2% strain between the tip of adjacent MFs.

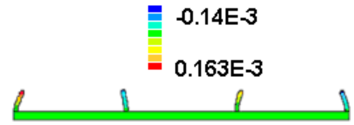

Figure 2: FEM MF displacement results (in meters)

The same computational scheme was applied to simulate the physical model using geometries from the experiment (Figure 3). The error between the displacements of the two models was 5.9 percent. The relatively small error between the scaled up physical experiment and its resulting computational simulation serves as a preliminary validation of the computational scheme.

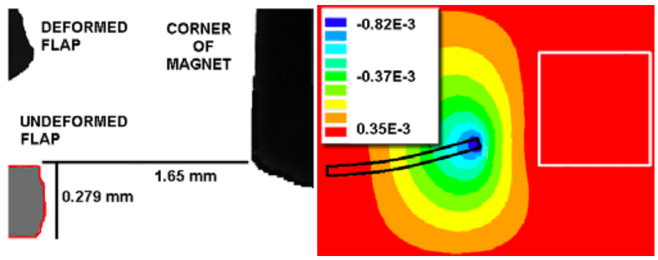

Figure 3: Experimental test (left) and computational validation (right). FEM displacement (in meters)

DISCUSSION

This study demonstrates that a magnetically actuated MEMS-based microdevice can be constructed and should allow for the differential stimulation of tissue-engineered constructs. While other groups have investigated methods of manipulating cells using magnetic actuation [2], the application of MEMS magnetic microactuation for noninvasive TEC manipulation has yet to be reported. Ongoing research with our laboratory includes investigating the degree to which MF deflection transmits into TEC strain.

The present study concluded that magnetically doped-polydimethysilxone magneto-structural characteristics can be simulated in a computational environment. Such analysis will aid in microdevice development, which will eventually lead to systems capable of stimulating tissue engineered constructs at appropriate length scales and in preferred directions.

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