Optimization of Structural Properties of 3D printed Poly (Propylene Fumarate) and Poly (Caprolactone Fumarate) Blend Scaffolds for Improved Bone Regeneration Using Finite Element Analysis

Areonna Schreiber, Asghar Rezaei, Ph.D., Lichun Lu, Ph.D.
Mayo Clinic, Rochester MN

Introduction

On a daily basis, a **staggering 65 million people** in the United States experience the burden of chronic lower back pain due to degenerative spinal conditions such as herniated disc disease or spinal arthritis. Within lower back pain management, lumbar spinal fusion surgery stands as the primary recourse – an intervention where two lumbar vertebrae are fused together to provide stability after the excision of affected tissue. Presently, titanium or poly (ether ether ketone) (PEEK) screws, cages, and plates, in conjunction with bone grafts are used in spinal fusion surgeries. A successful bone implant hinges on two criteria: mechanical and biological factors. Mechanical success requires closely replicating natural bone's flexibility and mechanical strength, which is highly dependent on the scaffold microstructures, including pore geometry, size, interconnectivity, and material properties and distribution. Environmental success involves achieving biocompatibility, facilitating osteogenic cell migration, and promoting cell differentiation and bone matrix formation. Unfortunately, the currently employed **titanium and PEEK implants fall short in at least one of these pivotal attributes,** consequently this can lead to painful health complications such as brittle bones or failed spinal fusion.

To address the pitfalls of the current implants, this study used an advanced polymer blend comprising of poly (propylene fumarate) (PPF) and poly (caprolactone fumarate) (PCLF) that is specially tailored for the precise 3D printing of spinal cage implants. Previous research from our laboratory has confirmed that PPF and PCLF are biocompatible, biodegradable, and, when combined, exhibit mechanical strength and flexibility akin to bone. When coupled with this polymer blend, the optimization of scaffold microstructures through the application of Finite Element Analysis (FEA) computational modeling will substantially elevate implantability.

Methods

In this study, we synthesized and formulated a resin blend with varying amounts of poly (propylene fumarate) (PPF) (mw = ~1200 kDa) and poly (caprolactone fumarate) (PCLF) (mw = ~ 4000 kDa), specifically 5%, 10%, or 20% PCLF to PPF ratio (wt %). Hydroxyapatite (HA) was added to the polymer ink (5%, 10%, 20%) to increase printed scaffold strength and enhance contrast for post-operative imaging. Additionally, we used finite element analysis (FEA) computational modeling to find the optimum scaffold geometry. Using FEA, stress and strain distributions were compared for all the geometries and pore distributions to find the best candidate for 3D printing. The scaffolds had consistent pore size of 1 mm cylindrical pores, and varying shapes (rectangular box and cylinder with orthogonal pores and a cylinder with radially oriented pores). To obtain the FEA model, a computer aided design built in SolidWorks was uploaded, a tetrahedral mesh applied with a mesh size of approximately 0.07 mm, material properties assigned, and a load applied in ANSYS Mechanical APDL software. Then, scaffolds were printed using a digital light processing LumenX Cellink printer from the same computer aided design built using SolidWorks software.

Results

FEA analysis of the cylinder with orthogonally oriented pores had a von Mises stress ranging from .8 MPa to 141 MPa with the highest stress points located inside the pores. FEA analysis of the rectangular box with orthogonally oriented pores had a Von Mises stress ranging from 1.3 MPa to 159 MPa with the highest stress points located inside the pores. The overall stress was higher when compared with the orthogonally oriented cylinder model. FEA analysis of the cylinder with radially oriented pores had a von Mises stress up to 675 MPa with the highest stress points located inside the pores. Comparing all these geometries and pore distributions, the cylindrical scaffold with orthogonally oriented pores had smaller stress concentrations, with a more uniform distribution of stress, and therefore was the most suitable candidate for our study. All three PCLF-to-PPF ink ratios were successfully printed with 1mm pore size. Resins with HA levels of 5% and 10% were printable in all PCLF-to-PPF ink ratios, however, only 100% PPF and 5% PCLF-to-PPF resins with 20% HA were successfully printed.

Discussion

The FEA computational model developed in this study has shown it can be a strong tool for predictive tailoring of implantable scaffold microstructures for advanced mechanical outcomes based on stress distribution data. The next step is to perform thorough compressive mechanical testing on the 3D printed implantable scaffold samples and control groups comprised of pure PPF and PCLF materials. This mechanical analysis was aimed at extracting critical data, such as elastic modulus and failure strength, and was crucial for validating the FEA computational models. The FEA models can then be employed to predict and optimize scaffold parameters tailored to specific tissue requirements.

Relevance

Clinical: Lumbar spinal fusion imposes a substantial annual economic burden on the healthcare system, quantified at approximately **14.1 billion dollars**. A significant portion of this financial burden originates from pro-longed in-patient hospitalization stays, a problem that is further exacerbated by the necessity for **repeat spinal fusions** due to the suboptimal outcomes of initial attempts. Considering these challenges, the introduction of a **novel implant** presents a **promising avenue** for **mitigating the financial burden** on the health care system.
The introduction of this polymer for spinal implantation holds the potential to not only **elevate the quality of life** for individuals afflicted by chronic lower back pain but also to **propel** the **field of biomaterial bone implants** to **new heights**. The versatility of the PPF/PCLF blend extends beyond lumbar intervertebral fusion applications, encompassing **multiple other bone implant applications** such as hip arthroplasty or addressing critical-size bone defects.
Scientific: The integration of **FEA computational modeling** stands as a pivotal component in optimizing the geometric parameters of the PPF/PCLF for the **precise application** of lumbar interbody fusion. This computational framework harnesses stress distribution data to **predict the most favorable** pore size, quantity, configuration, and inter-pore spacing, with the overarching objective of augmenting cellular migration, integration, and differentiation – Thereby **expediting and enhancing the healing process**.

> **Commented [RP1]:** you need to mention the pore size... the size per volume like 70%...
> if you have space, you can also mention that the pore size were the same for all the geometries in this study, but we are expanding our FEA to also optimize pore size.