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Spatial tuning of negative and positive Poisson's ratio in a multi-layer scaffold

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ABSTRACT

While elastic modulus is tunable in tissue engineering scaffolds, it is substantially more challenging to tune the Poisson's ratio of scaffolds. In certain biological applications, scaffolds with a tunable Poisson's ratio may be more suitable for emulating the behavior of native tissue mechanics. Here, we design and fabricate a scaffold, which exhibits simultaneous negative and positive Poisson's ratio behavior. Custom-made digital micro-mirror device stereolithography was used to fabricate single- and multiple-layer scaffolds using polyethylene glycol-based biomaterial. These scaffolds are composed of pore structures having special geometries, and deformation mechanisms, which can be tuned to exhibit both negative Poisson's ratio (NPR) and positive Poisson's ratio (PPR) behavior in a side-to-side or top-to-bottom configuration. Strain measurement results demonstrate that analytical deformation models and simulations accurately predict the Poisson's ratios of both the NPR and PPR regions. This hybrid Poisson's ratio property can be imparted to any photocurable material, and potentially be applicable in a variety of biomedical applications.

1. Introduction

Elastic modulus and Poisson's ratio of a tissue engineering scaffold directly reflect its ability to handle various loading conditions, and must be tailored to match the attributes of the target tissue [1,2]. Ideally, the elastic response of a biomaterial should be optimized for the intended application; this requires control over pore size and architecture, while ensuring optimal environmental accessibility and interconnectedness of the pore network. Although stiffness of biomaterials themselves can be tuned by modifying properties such as cross-link density and swelling ratio [3,4], it is substantially more challenging to tune the Poisson's ratio of scaffolds. Poisson's ratio, which essentially describes the deformations in the transverse direction, is an important parameter, determining the complete elastic response of any biomaterial. While stiffness measurements alone do not fully characterize a scaffold's elastic behavior, no attempt has been made to tune the Poisson's ratio, and all the biomaterials used in the field exhibit a fixed positive Poisson's ratio (PPR). A PPR scaffold contracts in the transverse direction with axial loading. On the other hand, a tunable negative Poisson's ratio (NPR) scaffold would expand in both the axial and transverse directions simultaneously, the magnitude depending on the deformation geometry and mechanics of the scaffold. A scaffold with NPR or "auxetic" property would allow a biomaterial to expand or compress uniformly or non-uniformly in the axial and transverse directions. For naturally occurring materials that exhibit auxetic behavior [5–20], the unusual NPR behavior seems to be an intrinsic property of the material and cannot be tuned according to specific applications.

In some tissue engineering applications, scaffolds having a tunable hybrid NPR-PPR property may better mimic the elastic behavior of the native tissue [21–28]. For example, the sub-endothelial axially aligned fiber layer of bovine carotid arteries was observed to thicken in response to a circumferential strain, indicating a NPR or auxetic behavior [29]. Recently, it has been demonstrated that injection of new heart cells to repair damaged heart tissue resulted in premature death of implanted cells due to the mechanical biaxial squeezing action of the contracting myocardium [30]. A hybrid scaffold with NPR/PPR properties may be ideally suited for tissue engineering applications which require biaxial expansion; the NPR nature of the scaffold would cause concurrent deformations with the beating of the heart [31]. In tissue engineering, one must have the capability to precisely tune the magnitude and polarity (positive or negative) of Poisson's ratio to match the properties of the specific tissue being regenerated. In the past, NPR behavior has been achieved in polyurethane foams by annealing the foams in a compressed state, which naturally causes a re-organization in their cellular microstructure. These techniques, however, cannot be utilized to exercise a fine degree of control over the magnitude of the Poisson's ratio. Man-made NPR materials can be constructed by patterning materials with an artificial lattice of rib-containing unit cells (pores), which tune Poisson's ratio by their shape and

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