A hitchhiker's guide to size effects in metamaterial implants.

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Abstract

Metamaterial implants – rationally designed cellular bone-reconstruction devices – have recently emerged as promising alternatives to common clinical solid implants (1,2). While researchers can nowadays design personalized implants replicating patient's morphology (3), these bulky metal structures suffer from mechanical failure occurring mainly due to stress shielding - a mismatch in the mechanical properties of an implant and adjacent bones that leads to a loss in bone density followed by loosening of the implant. In contrast, the mechanical properties of metamaterial implants can be tuned to bone-like behavior that promises to minimize implant failure (4). For this, the solid parts of a metal implant are replaced with a porous microstructure optimally distributed for applied muscular-driven loads (1).
The dimensions of a metamaterial implant can however be very limited, to ensure the implant's fit that leads to size effects – the dependence of the mechanical properties of a metamaterial on the number of constitutive building blocks (unit cells) under different types of loading. It occurs if the characteristic lengths of an implant and unit cells are comparable and results in the failure of classical approximation techniques, e.g. first-order homogenization, to provide adequate approximations for the mechanical behavior (5).

In this study, we propose a procedure to estimate and model size effects through full-scale and effective medium FE simulations. We exemplified our findings by analyzing auxetic, beam-type, and surface-type unit cells under all relevant loading conditions and identified that size effects occur in every structure containing less than 5 unit cells. These findings were confirmed in full-scale experimental tests on additively manufactured polymer prototypes. To properly capture the size effects within an effective continuum, we applied a higher-grade continuum theory which allowed us to develop a toolkit for efficiently modeling and optimizing different types of metamaterial implants. The outcomes of our study are especially relevant for implants with intrinsically limited dimensions, including mandibular, cranial,

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and pelvis implants (3, 6).

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