Achieving Total-Implant Bone-Matched Modulus with 3D-Printed Soft Titanium® in Spinal Interbody Fusion

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Abstract

Transference of load onto bone is essential for healthy bone growth and post-operative recovery. Existing low-modulus spine implants are traditionally bio-inert PEEK or solid titanium structures; even cutting-edge 3D printed devices maintain solid-structure form factors resulting in high stiffness implants. To fill this need, Soft Titanium® is developed as a low-modulus, load-bearing structure for use in implants. Primarily, the mechanical performance of lumbar implants manufactured with this structure are assessed in static and dynamic modes—with a lifespan over 5 million cycles—and includes a discussion of the impact of device design on implant stiffness. The total achieved modulus of a tested implants comprised of Soft Titanium is 3.1 GPa. To achieve load transfer, the structure is also designed as a scaffold for bone growth, with 67% porosity and pores for in-growth in the range of 300-600µm. Clinically, this device may improved bone formation at the fusion site and reduce the risk of subsidence resulting from the reduced device modulus.

Keywords: Low Stiffness, Low Modulus, Wolff's Law, 3D Printing, Titanium, Spine Implant, Bone Growth

Intro

Accomplishing spine fusion is reliant on a delicate balance between stability and biomechanical environment experienced at the surgical level. Addition of instrumentation to the fusion has been shown to increase stiffness and fusion rates compared to uninstrumented fusions [1]. However, a construct that is too stiff may have negative impact on fusion with collapse of osteoporotic bone and could potentially affect the healing process.

Mechanical loading of bone can influence the speed and efficacy of tissue regeneration and the healing process. Bone tissue consistently requires a baseline loading; essentially a minimum effective strain it must experience or otherwise undergo resorption [2]. Loading of bone has been shown across the body to improve strength through:

- physical exercise [3],
- increasing bone density in mice [4],
- osteoblast and osteocyte recruitment via PGE and PGI [5, 6].

Trabeculae formation—volume, quantity, thickness, spacing—in an ovine model also demonstrate an exceedingly precise relationship to peak loading and direction [7].

This process is also an active biological control system [8] in which bone cells are known to communicate via mechanotransduction [9, 10], relaying information of loading which has been shown to be essential for skeletal growth [11]. These cells are further shown to respond optimally to high strains (magnitude, frequency, rate) and when strains are presented in unusual distributions [2, 12-19].

Critically, the stiffness of the extracellular environment surrounding bone tissue has been shown to impact a primary growth factor in bone (TGF-β) [20]. This mechanosensitive growth factor in turn has a direct impact on the strength of forming bone tissue [21].

It is also necessary to develop materials which do not over-load the surrounding tissue, which may result in subsidence or adjacent injury after or during the healing process.

Implant Design

When applied to design, it is essential to account for the impact of loading to improve future devices. The factors impacting lumbar interbody fusion healing with a cage overall are complex but can be simplified to three categories including tissue ingrowth, surface characteristics, and mechanical compatibility. Orthopedic implants are primarily a mechanical support but can also become active participants in tissue regeneration.

Utilizing advanced 3D printing technology in combination with implant grade titanium offers unique advantages in creating structures that can have greatly reduced stiffness to allow bone loading as compared with subtractively manufactured titanium implants. Such methods also enable porous volumes to allow permeability to bone for tissue ingrowth, surface modification, better mechanical compatibility and enhanced radiographic properties. Titanium is particularly well suited as an implant material with surface characteristics including a bioactive oxide layer which actively engages in the promotion of osteogenesis.

In the following, we discuss the mechanical compatibility of 3D-printed Soft Titanium® with bone tissue in spine and the resultant clinical benefits.

Background

Advocates for PEEK devices recognized the need for reduced stiffness as compared to subtractively manufactured titanium implants; however, PEEK lacks the beneficial material characteristics of titanium. Well-processed titanium surfaces where manufacturers can control tissue interaction to the nano-scale propose to offer even greater advantages.

Previous 3D printed implants rely on rigid framing structures, shells, and solid noses and tails to bear the loads required for rigorous mechanical performance demands. The result reduces load to the porous volume with less area for bone formation around the construct.

Alternate approaches to internal porosity utilize randomly generated structures prone to unknown failure points, inconsistent or reduced bone loading, and choke points for fluid flow. Truss structures are prone to loss of graft material, particularly during insertion, and do not provide substantial surface area to support tissue during healing.

Our goal was to design a device which once implanted in the disc space prepared for fusion, offers a powerful feature set, including:

- a supporting scaffold for bone growth,
- ideal pore characteristics for ingrowth,
- maximal surface for bone to attach,
- intraoperative visibility,
- and mechanical compatibility.

As a result, we target the design of a homogeneous scaffold with an overall modulus

of elasticity below that of PEEK and a volume of ingrowth above 60%.

Mechanical performance testing for spine implants is conducted in accordance with ASTM F2077 for evaluation of the axial strength and stiffness of the tested device.

Solution

At the confluence of these physiological demands sits Soft Titanium. With a repeating unit-cell structure, this 3D printed scaffold provides a uniform modulus of elasticity matched to that of bone tissue. This uniformity of the scaffold dramatically improves the consistency pore size for bone in-growth, in mechanical performance to reduce the risk of device failure, and in transportability to a wide range of devices, bone health, and anatomy.

Critically, Soft Titanium exists as the only structural member in the implant thus maximizing load sharing with regenerating tissue as it forms in parallel with the scaffold and creating an environment of continuous stiffness for tissue integration.

Soft Titanium Structure

At its core, the Soft Titanium scaffold comprises the load bearing body of the implant with no requirement for other non-porous solid support structures in the device design. Identical, repeated unit cells provide known and predictable mechanical properties which permeate the body of the device.

As compared with other unit cell structures, Soft Titanium provides increased strength and fatigue resistance for a given porosity.

Device Design

Employing Soft Titanium as the complete structure of the device body, we have designed the NanoHive™ (Figure 1) lines of interbody devices. Design features serve to soften the edges of the scaffold and protect tissue during insertion, as well as to improve manufacturability of the device and lend to other intraoperative and clinical features. Specifically:

- Interbody teeth are designed to minimally restrict permeability to the scaffold while maximizing purchase.
- Upper and lower surfaces distribute load across the body and minimize stress shielding.
- Inserter features are robust and integrated into the scaffold but shaped to reduce impact on device axial stiffness and minimize impact on overall bone ingrowth volume.
- Nose features are smooth to protect tissue and Soft Titanium during insertion but

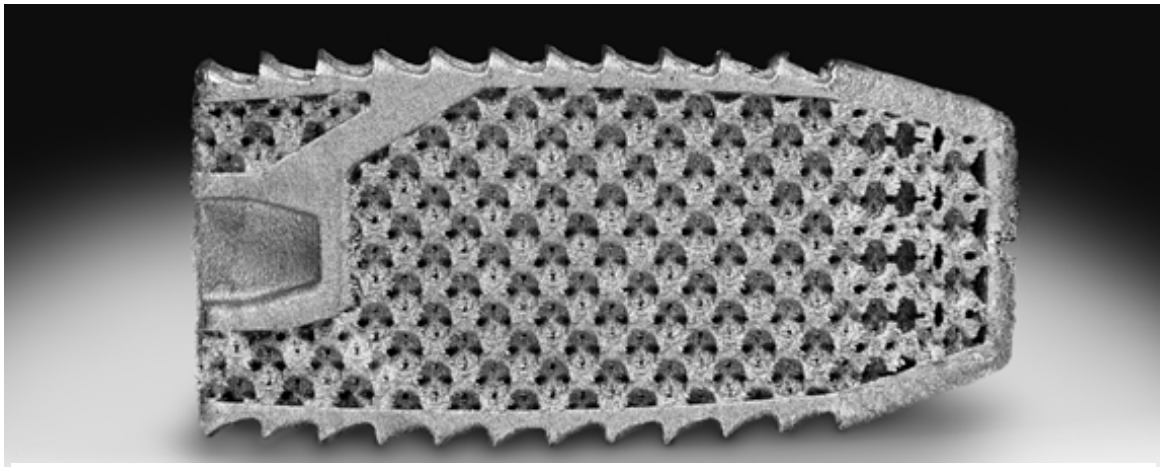

Figure 1 - Example HD LifeSciences NanoHive™ interbody comprised of Soft Titanium®; device as utilized in this study.

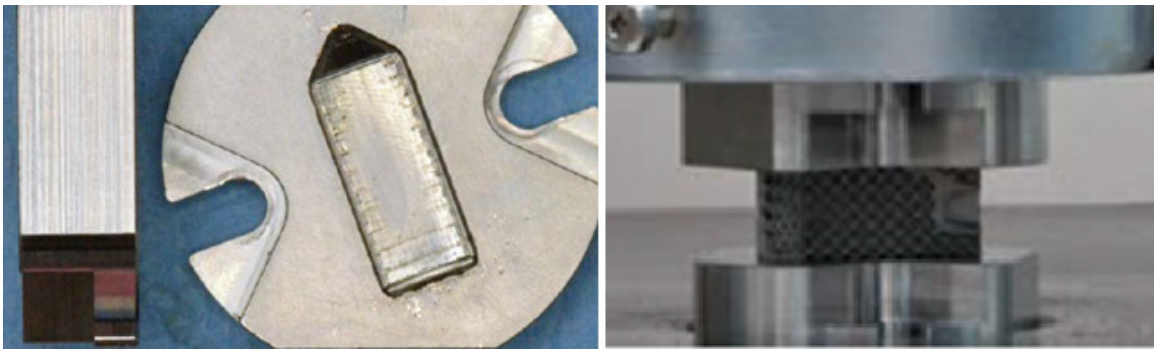

Figure 2 - Implant in mechanical testing with Implant test blocks (left) demonstrating recessed cavity for containing implant during test, and as loaded configuration (right) with an implant in the mechanical test stand between blocks.

remain disconnected axially to avoid increases in device axial stiffness.

Implant Porosity

The network of interconnected pores is designed for an optimal bone ingrowth pore size of 300-600µm [22].

Larger pores up to 1.2mm support angiogenesis, osteogenesis, neurogenesis, fluid commutation, and load sharing throughout the structure.

As designed, the scaffold is 67% porous.

Mechanical Performance

Mechanical testing is performed on implants constructed with Soft Titanium per ASTM F2077 for spinal interbody fusion devices. Implants undergo both static testing to verify stiffness, modulus of elasticity, and yield strength, and dynamic testing to verify the lifecycle of the device under load. Twenty-four implants are tested for this study.

Implant Testing Methods

Devices are tested in both Static and Dynamic Axial Compression. In the test configuration, production devices are loaded in compression as they would be loaded In vivo between two vertebral bodies, and the deformation of the device is measured along the axis of the device.

Device loading is achieved by containing the implants in test blocks (Figure 2, left), each with a recess matching the shape of the implant top and bottom surfaces. The test blocks and device are mounted in a test stand (Figure 2, right) which can apply loads up to 25kN.

Implants are then tested to exceed 5 million cycles while undergoing loads beyond physiological limits.

Stiffness

As the device is loaded, we measure the force applied and the deformation of the device, e.g. it's change in height or displacement. Stiffness is calculated during axial compression testing as the slope of the initial linear elastic region of this compression and represents the effective elasticity of the overall implant (Figure 3).

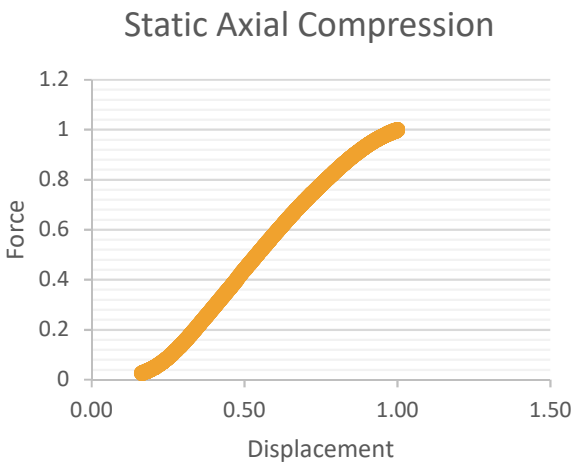

Figure 3 - Normalized Force/Displacement curve for an implant in Static Axial Compression.

As alluded to in the device design, the overall device stiffness is inextricably linked to the geometric as well as material properties of each device.

- Stiffness will increase with **larger device area**.
- Stiffness will increase with **shorter heights**.
- Stiffness will increase with **greater modulus** material.

In this way, even materials traditionally thought of as a desirable low-stiffness can result in a problematic high-stiffness device.

Modulus of Elasticity

To determine the achieved modulus of elasticity, we utilize these force and displacement measurements combined with the average cross-sectional area of the tested device footprint to calculate the implant Modulus of Elasticity. The resultant modulus observed in the testing of this device is 3.1GPa.

Discussion and Conclusion

Soft Titanium achieves a bone-like modulus of elasticity of 3.1GPa—thirty-six times lower than that of solid titanium—while retaining strength capable of bearing the loads experienced by a spine implant.

This overcomes challenges in traditional over-stiff titanium devices and bio-inert lower-stiffness devices. It also suppresses shortcomings of modern 3D printed devices which rely on supplemental structures for mechanical integrity, reducing the load on newly forming bone which may have an impact on the healing of the fusion.

Further, this technology combines these mechanical loading advantages with additional leading advancements in bone ingrowth, surface topography, and improved radiographic evaluation.

It is important to keep in mind that bone growth will vary across the skeleton and throughout the lifespan of an individual [23], and that in discussing bone growth relative to the spine, we aggregate work conducted across many bone structures, animal models, and clinical experiences.

Clinical Impact

Properties of this technology, with modulus of elasticity and stiffness that is matched closer to normal bone, have two potential advantages for obtaining solid fusion after spine surgery. One advantage is the potential benefit of allowing some elastic deformation during regular activities, which in turn will place more loading on the healing fusion without destabilizing the construct and may influence improved bone formation at the fusion site. The second advantage of a lower stiffness of the cage is lower risk of subsidence especially in osteoporotic patients, which may prevent compromised fixation and loss of correction. This loss of correction can impact alignment and indirect decompression subsequently decreasing outcomes. Lower stiffness of the cage is less likely to violate the endplates on insertion, which can also prevent subsidence.

AUTHOR CONTRIBUTIONS

This work was conducted, analyzed, and authored by CJ, with additional clinical assessment and provided by BW and JT.

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Follow-Up

For further information on Soft Titanium and HD LifeSciences NanoHive interbodies, please visit HDLifeSciences.com or contact info@HDLifeSciences.com.

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