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Inventor(s)

Prawel; David et al.

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### Methods and Devices for Improving Bone Healing

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#### Abstract

A method for treating a bone defect extending between a proximal bone structure and a distal bone structure of a patient may include resecting a region of bone between the proximal bone structure and the distal bone structure and encompassing the bone defect, positioning a biodegradable osteogenic scaffold within a biodegradable sleeve, coupling the biodegradable sleeve to a fixation member, positioning the biodegradable sleeve between the proximal bone structure and the distal bone structure, and attaching the fixation member to each of the proximal bone structure and the distal bone structure.

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**Inventors:** Prawel; David (Loveland, CO), Seguin; Bernard (Fort Collins, CO), Witt; Connor (Colorado Springs, CO)

**Applicant:** Colorado State University Research Foundation (Fort Collins, CO)

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 17/541,121, filed Dec. 2, 2021, which claims the benefit of, and priority to, U.S. Provisional Patent Application No. 63/120,675, filed on Dec. 2, 2020, and titled “Methods and Devices for Improving Bone Healing,” the disclosures of which are expressly incorporated herein by reference in their entirety.

### FIELD OF THE DISCLOSURE

[0002] The present disclosure relates generally to healing bone defects and more particularly to methods and devices for treating bone defects, such as a critical-sized bone defects, of human or veterinary patients.

### BACKGROUND

[0003] Critical bone defects occur with unfortunately high frequency in both human veterinary patients, due to cancer and trauma. Poor healing of critical-sized bone defects remains one of the biggest challenges in human and veterinary orthopedic medicine, often resulting in clinical complications, reoperations, poor functional outcomes, and ultimately limb loss, causing significant clinical and economic cost. Researchers have worked on this problem for decades using a wide variety of bone regeneration techniques and biomaterials, often involving 3D printed scaffolds to enhance bone growth, also referred to as bioactivity (osteoconduction, osteoinduction, and osseointegration). Scaffolds made with biomaterials like hydroxyapatite (HA  $\rho$ ), beta-tri-calcium phosphate ( $\beta$ -TCP) and numerous other forms of calcium phosphates and derivatives thereof are highly osteogenic but are too brittle to enable any practical load bearing. Contrarily, enhancing the load-bearing capability of these osteogenic materials results in scaffolds with reduced osteogenic character. To date, no one has overcome this paradox for critical, load-bearing bone defects. The current standard of care for limb-sparing uses permanent fixation with large metal plates and endoprostheses that remain in the patient for lifetime.

[0004] Eighty-five percent of all skeletal tumors in dogs are osteosarcomas (see Vail, D. M. et al. Withrow & MacEwen's Small Animal Clinical Oncology. Elsevier Saunders; 2013.), most often affecting the proximal humerus and distal radius. Limb-sparing procedures are considered the standard of care in humans. In dogs, limb sparing is indicated in dogs with significant concurrent orthopedic or neurologic disease but is also often performed because the owners are strongly opposed to amputation. These procedures involve ostectomy of the cancerous and surrounding tissue, typically from the diaphysis through and including the epiphysis of the bone, followed by implantation of a large locking fixation plate and endoprosthesis. See Mitchell K E et al. Outcomes of Limb-Sparing Surgery Using Two Generations of Metal Endoprosthesis in 45 Dogs With Distal Radial Osteosarcoma. A Veterinary Society of Surgical Oncology Retrospective Study: Limb Sparing Endoprosthesis for Canine Radial Osteosarcoma. Veterinary Surgery 2016;45:36-43; Liptak J M et al. Cortical Allograft and Endoprosthesis for Limb-Sparing Surgery in Dogs with Distal Radial Osteosarcoma: A Prospective Clinical Comparison of Two Different Limb-Sparing Techniques. Vet Surgery 2006;35:518-33. This approach presents complications such as screw loosening, plate fracture, infection, and significant metal remaining in the body for the remainder of the animal's life. These challenges are also experienced in human medicine. Poor healing of these critical-sized bone defects remains one of the biggest challenges in human and veterinary orthopedic surgery, often resulting in limb loss (see Liptak J M et al.), leading to poor long-term

outcomes with complication rates as high as 48% in humans (see Vidal L et al. Reconstruction of Large Skeletal Defects: Current Clinical Therapeutic Strategies and Future Directions Using 3D Printing. *Front Bioeng. Biotechnol.* 2020;8:61.) and over 90% in dogs (see Mitchell K E et al.), reoperations, and poor functional outcomes, resulting in significant negative clinical and economic impact. Other strategies such as autografts, allografts and xenografts also have major drawbacks, including shortage of available tissue, thus there is a critical need to address this challenge. Tissue engineering solutions have emerged that use synthetic scaffolds to provide structure for new growing bone. Countless materials have been considered for scaffold development.

[0005] Hydroxyapatite (HA  $\rho$ ), beta-tri-calcium phosphate ( $\beta$ -TCP), and numerous other forms of calcium phosphates and derivatives thereof are widely studied for bone regeneration scaffolds. See Bose S et al. Additive manufacturing of biomaterials. *Progress in Materials Science* 2018;93:45-111; Vondran et. al. 3D printing of ceramic implants. *MRS Bulletin* 2016;41:71; Suwanprateeb J et al. Mechanical and in vitro performance of apatite-wollastonite glass ceramic reinforced hydroxyapatite composite fabricated by 3D-printing. *J Mater Sci: Mater M ed* 2009;20:1281. These materials are bioreplaceable by new, native bone. They release calcium during degradation, which supports bone formation, resulting in excellent osteoconductivity. See Vondran et al. Despite excellent bone regeneration properties, success of these scaffolds is hampered by inadequate structural strength and stiffness required for acceptable load-bearing. See Bose S et al. This is especially challenging in critical defects. Polycaprolactone (PCL) is widely used polymeric biomaterial (see Lu L et al. Biocompatibility and biodegradation studies of PCL/ $\beta$ -TCP bone tissue scaffold fabricated by structural porogen method. *J Mater Sci: Mater M ed* 2012;23:2217-26.) due to its excellent biocompatibility, and is FDA approved for medical use. PCL is popular in bone tissue engineering due to its slow degradation and high stiffness. See Eshraghi S et al. Mechanical and microstructural properties of polycaprolactone scaffolds with one-dimensional, two-dimensional, and three-dimensional orthogonally oriented porous architectures produced by selective laser sintering. *Acta Biomaterialia* 2010;6:2467-76; Brunello G et al. Powder-based 3D printing for bone tissue engineering. *Biotechnology Advances* 2016;34:740-53. PCL is also radiolucent, enabling real-time radiographic assessment. See Choi S et al. New clinical application of three-dimensional-printed polycaprolactone/ $\beta$ -tricalcium phosphate scaffold as an alternative to allograft bone for limb-sparing surgery in a dog with distal radial osteosarcoma. *The Journal of Veterinary Medical Science* 2019;81:434-9.

[0006] 3D printing (3DP) has emerged as a popular method to fabricate complex shaped structures with high precision. 3DP enables creation of patient-specific scaffolds directly from CT scans, ensuring the scaffolds precisely fit the defect site, improving outcomes because the morphology of each bone and the percentage of bone removed varies between patients, depending on the size of the tumor. See Harrysson OLA et al. Applications of Metal Additive Manufacturing in Veterinary Orthopedic Surgery n.d.: 8; Seguin B et al. Limb-sparing in dogs using patient-specific, three-dimensional-printed endoprosthesis for distal radial osteosarcoma: A pilot study. *Vet Comp Oncol* 2020;18:92-104. Patient-specific implants allow the implants to fit as perfectly as possible for each patient thereby enabling loads to be transmitted through the limb. Interrelated parameters such as porosity, permeability, pore size, shear stress, bulk material, and shape (topology) dictate the success of a scaffold. See Montazerian H et al. Longitudinal and radial permeability analysis of additively manufactured porous scaffolds: Effect of pore shape and porosity. *Materials & Design* 2017;122:146-56; Rodríguez-Montaña Ó et al. Comparison of the mechanobiological performance of bone tissue scaffolds based on different unit cell geometries. *Journal of the Mechanical Behavior of Biomedical Materials* 2018;83:28-45; Aueid D W et al. Mechanical properties of 3D printed polymeric Gyroid cellular structures: Experimental and finite element study. *Materials & Design* 2019;165:107597; Melchels FPW et al. Effects of the architecture of tissue engineering scaffolds on cell seeding and culturing. *Acta Biomaterialia* 2010;6:4208-17. Advanced, structurally-optimized scaffold topologies such as Gyroids (see Montazerian H et al.; Melchels F P W et al.

Mathematically designed tissue engineering scaffold architectures prepared by stereolithography. *Biomaterials* 2010;31:6909-16.) are enabling 3D printing of stiffer, stronger scaffolds (see Rodríguez-Montañó Ó et al.; A bueidda D W et al.; Yuan L et al. Additive manufacturing technology for porous metal implant applications and triple minimal surface structures: A review. *Bioactive Materials* 2019;4:56-70.).

[0007] Recombinant human bone morphogenetic protein-2 (rhB M P-2) is one of the most widely used growth factors in both human (see Lissenberg-Thunnissen S N et al. Use and efficacy of bone morphogenetic proteins in fracture healing. *International Orthopaedics (SICOT)* 2011;35:1271-80.) and veterinary (see Pinel C B, Pluhar G E. Clinical application of recombinant human bone morphogenetic protein in cats and dogs: A review of 13 cases n.d.; 53:8; Boudrieau, R. Initial Experience With rhBMP-2 Delivered in a Compressive Resistant Matrix for Mandibular Reconstruction in 5 Dogs. *Vet Surg* 2015;44:443-58.) orthopedic surgery because of its powerful osteoinductive properties. A suitable carrier is required for sustained and local delivery of rhBM P-2. See E I Bialy I et al. Formulation, Delivery and Stability of Bone Morphogenetic Proteins for Effective Bone Regeneration. *Pharm Res* 2017;34:1152-70. Various forms of calcium phosphate have proven successful in numerous BM P delivery systems for large defect bone healing. Despite some reports of hypertrophy observed in some experimental (see Minier K et al. BM P-2 delivered from a self-cross-linkable CaP/hydrogel construct promotes bone regeneration in a critical-size segmental defect model of non-union in dogs. *Vet Comp Orthop Traumatol* 2014;27:411-21.) and clinical (see Pinel C B et al.; Boudrieau R et al.) cases treated with rhB M P-2, recent studies counter that RhB M P-2 can have anti-neoplastic effects against osteosarcoma (see Xiong Q et al. B M P-2 inhibits lung metastasis of osteosarcoma: an early investigation using an orthotopic model. *OTT* 2018;Volume 11:7543-53; Rici R E G et al. Combination therapy of canine osteosarcoma with canine bone marrow stem cells, bone morphogenetic protein and carboplatin in an in vivo model n.d.:11; Grassi Rici R et al. Mesenchymal stem cells with rhBM P-2 inhibits the growth of canine osteosarcoma cells. *B M C Vet Res* 2012;8:17.).

[0008] Although existing techniques for treating bone defects may be suitable in certain applications, there remains a need for improved methods and devices for treating bone defects, such as a critical-sized bone defects, of human or veterinary patients, which may overcome one or more of the drawbacks associated with existing techniques

#### SUMMARY OF THE DISCLOSURE

[0009] The present disclosure provides methods and devices for treating bone defects, such as a critical-sized bone defects, of human or veterinary patients. In one aspect, a method for treating a bone defect extending between a proximal bone structure and a distal bone structure of a patient is provided. In one embodiment, the method may include resecting a region of bone between the proximal bone structure and the distal bone structure and encompassing the bone defect, positioning a biodegradable osteogenic scaffold within a biodegradable sleeve, coupling the biodegradable sleeve to a fixation member, positioning the biodegradable sleeve between the proximal bone structure and the distal bone structure, and attaching the fixation member to each of the proximal bone structure and the distal bone structure.

[0010] In some embodiments, coupling the biodegradable sleeve to the fixation member may include sliding the biodegradable sleeve onto the fixation member. In some embodiments, positioning the biodegradable sleeve between the proximal bone structure and the distal bone structure may include inserting a distal end portion of the proximal bone structure into a proximal end of the biodegradable sleeve such that the distal end portion contacts the biodegradable osteogenic scaffold, and inserting a proximal end portion of the distal bone structure into a distal end of the biodegradable sleeve such that the proximal end portion contacts the biodegradable osteogenic scaffold. In some embodiments, attaching the fixation member to each of the proximal bone structure and the distal bone structure may include attaching the fixation member to the proximal bone structure using a first plurality of screws, and attaching the fixation member to the

distal bone structure using a second plurality of screws. In some embodiments, the method also may include treating the biodegradable osteogenic scaffold with one or more bioactive agents to facilitate bone growth or angiogenesis. In some embodiments, the method also may include treating the biodegradable sleeve and the fixation member with an antibiotic to inhibit infection. In some embodiments, the method also may include obtaining computed tomography scans of the patient, and fabricating the biodegradable osteogenic scaffold and the biodegradable sleeve based at least in part on the computed tomography scans. In some embodiments, the method also may include fabricating a cutting guide based at least in part on the computed tomography scans, and resecting the region of bone between the proximal bone structure and the distal bone structure and encompassing the bone defect may include resecting the region of bone using the cutting guide. In some embodiments, the biodegradable osteogenic scaffold may be formed of a calcium phosphate-based material or a composite comprising a calcium phosphate and a polymer, and the biodegradable sleeve may be formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone. In some embodiments, the method also may include detaching the fixation member from the proximal bone structure and the distal bone structure and removing the fixation member from the patient after the bone defect has healed and the biodegradable osteogenic scaffold and the biodegradable sleeve have degraded.

[0011] In another aspect, a device for treating a bone defect extending between a proximal bone structure and a distal bone structure of a patient is provided. In one embodiment, the device may include a biodegradable sleeve configured for positioning between the proximal bone structure and the distal bone structure, a biodegradable osteogenic scaffold configured for positioning within the biodegradable sleeve, and a fixation member configured for coupling to the biodegradable sleeve and attaching to each of the proximal bone structure and the distal bone structure.

[0012] In some embodiments, the biodegradable sleeve may include a first passage extending from a proximal end to a distal end of the biodegradable sleeve and configured for receiving the biodegradable osteogenic scaffold therein, and a second passage extending from the proximal end to the distal end of the biodegradable sleeve and configured for receiving a portion of the fixation member therein. In some embodiments, the biodegradable sleeve also may include support ribs disposed between the first passage and the second passage and extending from the proximal end to the distal end of the biodegradable sleeve, and the first passage may be in communication with the second passage through a gap defined between the ribs. In some embodiments, a portion of the biodegradable osteogenic scaffold may extend into the gap when the biodegradable osteogenic scaffold is positioned within the biodegradable sleeve. In some embodiments, the first passage also may be configured for receiving a distal end portion of the proximal bone structure and a proximal portion of the distal bone structure therein. In some embodiments, the biodegradable sleeve also may include a plurality of apertures disposed along one or more sides of the biodegradable sleeve and extending from an outer surface of the biodegradable sleeve to the first passage, and the apertures may be configured for controlling transcortical perfusion. In some embodiments, the biodegradable sleeve also may include a plurality of openings disposed along a side of the biodegradable sleeve and extending from an outer surface of the biodegradable sleeve to the second passage, and the openings may expose respective portions of the fixation member when the fixation member is coupled to the biodegradable sleeve and may be configured for receiving respective collagen sponges carrying an antibiotic therein. In some embodiments, the biodegradable osteogenic scaffold may include a central passage extending from a proximal end to a distal end of the biodegradable osteogenic scaffold and configured for receiving a collagen sponge carrying rhB M P-2 or vascular endothelial growth factor (VEGF) therein. In some embodiments, the fixation member may include a proximal portion configured for extending beyond the proximal end of the biodegradable sleeve when the fixation member is coupled to the biodegradable sleeve, a distal portion configured for extending beyond the distal end of the biodegradable sleeve when the fixation member is coupled to the biodegradable sleeve, and an intermediate portion configured for

positioning within the second passage when the fixation member is coupled to the biodegradable sleeve. In some embodiments, the biodegradable osteogenic scaffold may be formed of a calcium phosphate-based material or a composite comprising a calcium phosphate and a polymer, and the biodegradable sleeve may be formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone.

[0013] These and other aspects and improvements of the present disclosure will become apparent to one of ordinary skill in the art upon review of the following detailed description when taken in conjunction with the several drawings and the appended claims.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1A is a top view radiograph of a current standard of care for treating a critical bone defect in a limb-sparing procedure, showing a metal locking plate.

[0015] FIG. 1B is a side view radiograph of a current standard of care for treating a critical bone defect in a limb-sparing procedure, showing a metal locking plate, screws, and an endoprosthesis spacer.

[0016] FIG. 2A is an exploded perspective view of an example device for treating a bone defect in accordance with embodiments of the disclosure, showing a biodegradable sleeve, a biodegradable osteogenic scaffold, a fixation member, and a plurality of biodegradable cuffs of the device.

[0017] FIG. 2B is a perspective view of the device of FIG. 2A, showing the biodegradable sleeve, the biodegradable osteogenic scaffold, the fixation member, and the biodegradable cuffs in an assembled state.

[0018] FIG. 2C is a detailed side view of a portion of the biodegradable osteogenic scaffold, showing a gyroid topology of the scaffold.

[0019] FIG. 3A is a perspective view of an example device for treating a bone defect in accordance with embodiments of the disclosure, showing a biodegradable sleeve, a fixation member, and a plurality of screws of the device in relation to a proximal bone structure and a distal bone structure in accordance with an example use of the device.

[0020] FIG. 3B is a perspective view of the device of FIG. 3A, showing the biodegradable sleeve, the fixation member, and the screws in relation to the proximal bone structure and the distal bone structure.

[0021] FIG. 3C is a perspective view of a portion of the device of FIG. 3A, showing the fixation member coupled to the biodegradable sleeve.

[0022] FIG. 3D is a perspective view of a portion of the device of FIG. 3A, showing the fixation member coupled to the biodegradable sleeve.

[0023] FIG. 3E is a perspective view of a portion of the device of FIG. 3A, showing a biodegradable osteogenic scaffold of the device positioned within the biodegradable sleeve.

[0024] FIG. 3F is a perspective view of a portion of the device of FIG. 3A, showing the fixation member coupled to the biodegradable sleeve and the biodegradable osteogenic scaffold positioned within the biodegradable sleeve.

[0025] The detailed description is set forth with reference to the accompanying drawings. The drawings are provided for purposes of illustration only and merely depict example embodiments of the disclosure. The drawings are provided to facilitate understanding of the disclosure and shall not be deemed to limit the breadth, scope, or applicability of the disclosure. The use of the same reference numerals indicates similar, but not necessarily the same or identical components. Different reference numerals may be used to identify similar components. Various embodiments may utilize elements or components other than those illustrated in the drawings, and some elements and/or components may not be present in various embodiments. The use of singular terminology to

describe a component or element may, depending on the context, encompass a plural number of such components or elements and vice versa.

## DETAILED DESCRIPTION OF THE DISCLOSURE

[0026] In the following description, specific details are set forth describing some embodiments consistent with the present disclosure. Numerous specific details are set forth in order to provide a thorough understanding of the embodiments. It will be apparent, however, to one skilled in the art that some embodiments may be practiced without some or all of these specific details. The specific embodiments disclosed herein are meant to be illustrative but not limiting. One skilled in the art may realize other elements that, although not specifically described here, are within the scope and the spirit of this disclosure. In addition, to avoid unnecessary repetition, one or more features shown and described in association with one embodiment may be incorporated into other embodiments unless specifically described otherwise or if the one or more features would make an embodiment non-functional. In some instances, well known methods, procedures, and/or components have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

### Overview

[0027] Embodiments of methods and devices for treating a bone defect, such as a critical-sized bone defect, extending between a proximal bone structure and a distal bone structure of a patient are provided. As described herein, example methods generally may include resecting a region of bone between the proximal bone structure and the distal bone structure and encompassing the bone defect, positioning a biodegradable osteogenic scaffold within a biodegradable sleeve, coupling the biodegradable sleeve to a fixation member, positioning the biodegradable sleeve between the proximal bone structure and the distal bone structure, and attaching the fixation member to each of the proximal bone structure and the distal bone structure. In this manner, the fixation member may provide fixation of the proximal bone structure and the distal bone structure across the bone defect to enable normal load bearing, the biodegradable osteogenic scaffold may facilitate new bone growth between the proximal bone structure and the distal bone structure, and the biodegradable sleeve may protect the biodegradable osteogenic scaffold while new bone grows and also contain the new bone growth. Over time, the biodegradable osteogenic scaffold and the biodegradable sleeve may degrade, the new, natural bone growth may provide complete bone healing between the proximal bone structure and the distal bone structure, and the fixation member may be removed from the patient, leaving only endogenous bone. As described herein, example devices generally may include a biodegradable sleeve configured for positioning between the proximal bone structure and the distal bone structure, a biodegradable osteogenic scaffold configured for positioning within the biodegradable sleeve, and a fixation member configured for coupling to the biodegradable sleeve and attaching to each of the proximal bone structure and the distal bone structure. Various configurations of the device components may be used in different embodiments.

[0028] The present disclosure provides endoprosthetic designs and surgical procedures that can be used in veterinary and human orthopedic medicine. As discussed above, HA  $\rho$ ,  $\beta$ -TCP, and numerous other forms of calcium phosphates and derivatives thereof are excellent and widely used biomaterial for bone regeneration but provide insufficient mechanical support for acceptable load bearing. Many researchers are succeeding at strengthening such scaffolds using a wide variety of additives and infiltration techniques, but thus far at the cost of reductions in bioactivity. The methods and devices described herein leverage the fixation member to support the load, as it already functions in the current standard of care, and as a means to connect to and protect an osteogenic calcium-phosphate-based scaffold so that the scaffold can enable new bone growth and bioactivity. A critical-sized, patient-specific, biodegradable endoprostheses may be 3D printed to protect the scaffold and augment its poor mechanical properties, while working alongside the fixation member. The scaffold may be treated with rhB M P-2 to enhance bone healing, as recently demonstrated for large bone defects (see Grassi Rici R et al. Mesenchymal stem cells with rhB M

P-2 inhibits the growth of canine osteosarcoma cells. BM C Vet Res 2012;8:17; Franch J et al. Use of three-dimensionally printed  $\beta$ -TCP synthetic bone graft combined with recombinant human bone morphogenetic protein-2 to treat a severe radial atrophic nonunion in a Yorkshire terrier. Veterinary Surgery 2020: vsu.13476.). As described, the present techniques in limb sparing treatment of a bone defect, based on current standard of care, use bioreplaceable endoprostheses to enable a highly osteogenic scaffold to support healthy bone growth under normal loads. Ultimately, the techniques can enable complete bone healing and removal of fixation, leaving the patient with endogenous bone as in the Franch study (see Franch J et al.), after the endoprostheses degrades safely in the body.

[0029] Although initial development of the disclosed methods and devices has been performed in dogs, the methods and devices translate to human medicine fairly easily. The dog is a highly suitable model for human bone from a biological standpoint, in many ways better than sheep (see Bae) et al. Development and Assessment of a 3D-Printed Scaffold with rhB M P-2 for an Implant Surgical Guide Stent and Bone Graft Material: A Pilot Animal Study. Materials 2017;10:1434.), with similarities in microstructure and remodeling. Large dogs weigh as much as a small to mid-sized human. Furthermore, the techniques described herein depend on structural design improvements rather than complex physiological or biological approaches, that translate more readily to human medicine. Medical devices for canine orthopedics are often identical to those for humans, making possible translation of devices. Materials used for the scaffold and endoprostheses have been thoroughly studied and known to be biocompatible for implantation in live animals and FDA approved for many applications. The disclosed methods and devices can significantly improve patient outcomes in limb-sparing procedures, for animals and humans alike.

[0030] FIGS. 1A and 1B illustrate one instance of a standard of care for treating a bone defect, specifically an epiphyseal defect in a limb of a canine patient being treated for osteosarcoma. In this case, as shown, a distal portion of the patient's radius encompassing the tumor may be removed, along with a distal portion of the patient's ulna. Fixation of the limb may be provided by a metal locking plate **110** that is attached via screws **120** to each of a proximal bone structure and a distal bone structure. As shown, a proximal end portion of the locking plate **110** may be attached to the remaining host radius, and a distal end portion of the locking plate **110** may be attached to the third metacarpal. An endoprosthesis **130** may be positioned between the proximal bone structure and the distal bone structure to act as a spacer for limiting movement of the proximal bone structure relative to the distal bone structure to inhibit loosening of the locking plate **110**. As shown, the endoprosthesis **130** may be positioned between the remaining host radius and the radial carpus. Although the depicted example shows the locking plate **110**, the screws **120**, and the endoprosthesis **130** being used to treat an epiphyseal defect, these components similarly may be used to treat a segmental defect in a limb of a patient. As discussed above, the standard of care approach may present certain complications, including screw loosening, plate fracture, infection, and significant metal remaining in the body for the remainder of the patient's life.

#### Example Devices and Methods for Treating a Bone Defect

[0031] FIGS. 2A-2C illustrate an example device **200** for treating a bone defect, such as a critical-sized bone defect, of a veterinary or human patient. In some instances, the device **200** may be used to treat an epiphyseal defect. In other instances, the device **200** may be used to treat a segmental defect, a mandibular defect, or other type of bone defect. As shown, the device **200** may include a biodegradable sleeve **210**, a biodegradable osteogenic scaffold **230**, a fixation member **240**, and a plurality of biodegradable cuffs **250**. It will be appreciated that the size and shape of the respective components of the device **200** may be varied to accommodate a particular patient and the particular defect being treated. As discussed below, in some embodiments, the biodegradable sleeve **210**, the biodegradable osteogenic scaffold **230**, and the biodegradable cuffs **250** may be fabricated as patient-specific components. For example, these components may be 3D printed based on CT scans of the patient's limb. In some embodiments, the fixation member **240** may be a commercially-



available component used in accordance with the standard of care, with the size of the fixation member **240** being selected to accommodate the patient and defect to be treated.

[0032] As shown, the biodegradable sleeve **210** may be formed as an elongate structure having a proximal end **212** and a distal end **214** disposed opposite one another along the longitudinal axis of the biodegradable sleeve **210**. In some embodiments, as shown, the proximal end **212** may be shape-matched to a distal portion of the proximal bone structure of the patient, and the distal end **214** may be shape matched to a proximal portion of the distal bone structure of the patient. For example, for an epiphyseal defect, the proximal end **212** may be shape-matched to the remaining host radius, and the distal end **214** may be shape-matched to the radial carpus. In some embodiments, as shown, the biodegradable sleeve **210** may have a generally C-shaped cross-sectional shape (i.e., taken perpendicular to the longitudinal axis of the biodegradable sleeve **210**), with a gap extending along one side of the biodegradable sleeve **210**. In this manner, the biodegradable sleeve **210** may include a passage configured for receiving the biodegradable osteogenic scaffold **230** therein during use of the device **200**. In some embodiments, as shown, the biodegradable sleeve **210** may include a plurality of screw holes **216** extending therethrough and spaced apart from one another along the length of the biodegradable sleeve **210**. As discussed below, the screw holes **216** may facilitate connection of the biodegradable sleeve **210** to the fixation member **240** and the biodegradable cuffs **250**. In some embodiments, as shown, the biodegradable sleeve **210** may include a plurality of ribs **218** each extending from the proximal end **212** to the distal end **214**. As discussed below, the ribs **218** may facilitate connection of the biodegradable sleeve **210** to the biodegradable cuffs **250** and load sharing therebetween. In some embodiments, as shown, the biodegradable sleeve **210** may include a plurality of apertures **222** extending therethrough and spaced apart from one another along the length of the biodegradable sleeve **210**. The apertures **222** may be configured for controlling transcortical perfusion during use of the device **200**. In some embodiments, the apertures **222** may be omitted to prevent transcortical perfusion through the biodegradable sleeve **210**. In some embodiments, the biodegradable sleeve **210** may be formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone. Other suitable biocompatible and biodegradable materials may be used for the biodegradable sleeve **210** in other embodiments.

[0033] The biodegradable osteogenic scaffold **230** may be formed as an elongate structure having a proximal end **232** and a distal end **234** disposed opposite one another along the longitudinal axis of the biodegradable osteogenic scaffold **230**. In some embodiments, as shown, the biodegradable osteogenic scaffold **230** may have a gyroid topology, with a plurality of interconnected pores **236**. Other porous topologies of the biodegradable osteogenic scaffold **230** may be used in other embodiments. In some embodiments, the biodegradable osteogenic scaffold **230** may have a porosity of 70%. In some embodiments, the biodegradable osteogenic scaffold **230** may include a hollow canal configured for allowing intracortical perfusion. As shown, the length of the biodegradable osteogenic scaffold **230** may be less than the length of the biodegradable sleeve **210**. In this manner, the biodegradable osteogenic scaffold **230** may be positioned entirely within the biodegradable sleeve **210** during use of the device **200**. In some embodiments, the biodegradable osteogenic scaffold **230** may be formed of a calcium phosphate, such as HA  $\rho$  or  $\beta$ -TCP. In some embodiments, the biodegradable osteogenic scaffold **230** may be formed of a calcium phosphate-based material or a composite comprising a calcium phosphate and a polymer. Other suitable biocompatible, biodegradable, and osteogenic materials may be used for the biodegradable osteogenic scaffold **230** in other embodiments.

[0034] The fixation member **240** may be formed as an elongate structure having a proximal end **242** and a distal end **244** disposed opposite one another along the longitudinal axis of the fixation member **240**. According to various embodiments, the fixation member **240** may be a fixation plate, a fixation rod, a locking plate, a locking rod, or other type of suitable structure for fixation of bone structures. In some embodiments, as shown, the fixation member **240** may have a curved cross-

sectional shape (i.e., taken perpendicular to the longitudinal axis of the fixation member **240**). As discussed below, the fixation member **240** may be coupled to the biodegradable sleeve **210** such that the fixation member **240** covers the open side of the biodegradable sleeve **210**, thereby containing the biodegradable osteogenic scaffold **230** between the fixation member **240** and the biodegradable sleeve **210**. In some embodiments, as shown, the fixation member **240** may be inserted into the gap of the biocompatible sleeve **210**. As shown, the fixation member **240** may include a plurality of screw holes **246** extending therethrough and spaced apart from one another along the length of the fixation member **240**. As discussed below, some of the screw holes **246** may be used to facilitate connection of the fixation member **240** to the biodegradable sleeve **210** and the biodegradable cuffs **250**, while other screw holes **246** may be used to facilitate connection of the fixation member **240** to a proximal bone structure and a distal bone structure during use of the device **200**. The fixation member **240** may be formed of any suitable biocompatible, non-biodegradable material such that the fixation member **240** may be removed from the patient after the bone defect has healed and the biodegradable sleeve **210** and the biodegradable osteogenic scaffold **230** have degraded. According to various embodiments, the fixation member **240** may be formed of a metal, a polymeric material, a ceramic material, a composite material, or other suitable material for fixation of bone structures.

[0035] As shown, each of the biodegradable cuffs **250** may be formed as ring-shaped members configured for sliding over the biodegradable sleeve **210** and the fixation member **240**. In some embodiments, as shown, edges of the biodegradable sleeve **210** and the fixation member **240** may be rounded to ease sliding of the biodegradable cuffs **250** onto the biodegradable sleeve **210** and the fixation member **240** as well as to minimize tissue trauma. In some embodiments, as shown, each of the biodegradable cuffs **250** may include a pair of screw holes **256** extending therethrough and disposed opposite one another. The screw holes **256** may facilitate connection of each of the biodegradable cuffs **250** to the biodegradable sleeve **210** and the fixation member **240**. In some embodiments, as shown, for each of the biodegradable cuffs **250**, a screw may be inserted through one of the screw holes **256** of the biodegradable cuff **250**, through one of the screw holes **246** of the fixation member **240**, through the biocompatible osteogenic scaffold **230**, through one of the screw holes **216** of the biodegradable sleeve **210**, and through the other screw hole **256** of the biodegradable cuff **250**. This configuration may distribute load through the biodegradable cuff **250** into the fixation member **240**, which may maintain the integrity and minimize mobility of the biocompatible osteogenic scaffold **230** as new bone develops. In some embodiments, as shown, each of the biodegradable cuffs **250** may include a plurality of protrusions **258** extending radially inward and configured for mating with the ribs **218** of the biodegradable sleeve **210**. As shown, the mating engagement between the protrusions **258** and the ribs **218** may facilitate alignment of the screw holes **256** of the biodegradable cuff **250** with the screw holes **216** of the biodegradable sleeve **210** and the screw holes **246** of the fixation member **240**. In some embodiments, the biodegradable cuffs **250** may be formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone. Other suitable biocompatible and biodegradable materials may be used for the biodegradable cuffs **250** in other embodiments.

[0036] As noted above, the biodegradable sleeve **210**, the biodegradable osteogenic scaffold **230**, and the biodegradable cuffs **250** may be fabricated as patient-specific components. In some embodiments, CT scans of the patient's limb may be used to fabricate the biodegradable sleeve **210**, the biodegradable osteogenic scaffold **230**, and the biodegradable cuffs **250** for the patient. In some embodiments, a series of two-dimensional DICOM images of the full extent of the limb may be imported (e.g., using InVesalius) and segmented to create high-resolution digital models of the radius, ulna, manus, and metacarpals of the patient. The images then may be segmented based on Hounsfield attenuation values, and surface representations of the bone may be generated and then imported (e.g., into Fusion **360**) where 3D models of the components may be created for 3D printing. In some embodiments, finite element analysis (FEA) may be used to investigate the ideal

design parameters of the biodegradable sleeve **210** and the biodegradable cuffs **250** and the overall device **200**, with and without the fixation member **240**, to determine optimal geometry of the components and features thereof. Parameters such as rib height and thickness and mechanical properties such as structural modulus may be simulated to optimize the design of the device **200** prior to fabrication. In some embodiments, the CT scans also may be used to fabricate cutting guides to assure accurate surgical resections to match the geometry of the device **200**.

[0037] The biodegradable osteogenic scaffold **230** may be 3D printed using existing methods. See Lopez Ambrosio, Katherine V. HYDROXY APATITE STRUCTURES CREATED BY ADDITIVE MANUFACTURING WITH EXTRUDED PHOTOPOLYMER. Master's Thesis, Ft. Collins, CO: Colorado State University; 2019; 2019. In some embodiments, a photopolymer comprised of ethylene glycol dimethacrylate (EDGM A) and other polymers may be mixed with hydroxyapatite (HA  $\rho$ ) particles into a shear-thinning slurry using a planetary ball mill. Slurries of 41 vol % HA  $\rho$  may be transferred to a syringe and 3D printed on 3D printer, such as a HyRel Engine SR printer with a 0.413 mm nozzle inner diameter, using a combination of viscous extrusion and photopolymer processes. The photopolymerization reaction may be initiated by continuous exposure of the deposited roads to a near-UV light source (405 nm wavelength), causing polymerization and hardening of the continuous phase, layer-by-layer. The sintered biodegradable osteogenic scaffold **230** may be non-cytotoxic. After printing, the biodegradable osteogenic scaffold **230** may undergo a two-step sintering process to eliminate the polymeric content and consolidate the HA  $\rho$  particles. In some embodiments, the printed biodegradable osteogenic scaffold **230** may be heated at 5° C./min up to 500° C. and held for 1 h, and then sintered at a heating rate of 15° C./min, up to 1150° C. and held for 5 h. This process may confer the sintered HA  $\rho$  structures with suitable mechanical properties. In some embodiments, the biodegradable sleeve **210** and the biodegradable cuffs **250** may be fabricated using a thermal process on a melt extrusion 3D printer (e.g., Prusa i3-M K 3, Budapest, Hungary). PCL filament may be extruded by regulated ram pressure through a Flexion head. The extruded PCL may cool on a build plate to fabricate the components, which then may cool to room temperature. Prints may be oriented to maximize part strength and minimize support material.

[0038] The device **200** may be used to treat a bone defect, such as a critical-sized bone defect, extending between a proximal bone structure and a distal bone structure of a patient. In some embodiments, the bone defect may be an epiphyseal defect. In some embodiments, the bone defect may be a segmental defect. A method of using the device **200** for treating the bone defect generally may include resecting a region of bone between the proximal bone structure and the distal bone structure and encompassing the bone defect, positioning the biodegradable osteogenic scaffold **230** within the biodegradable sleeve **210**, coupling the biodegradable sleeve **210** to the fixation member **240**, positioning the biodegradable sleeve **210** between the proximal bone structure and the distal bone structure, and attaching the fixation member **240** to each of the proximal bone structure and the distal bone structure.

[0039] In some embodiments, the region of bone may be resected using one or more cutting guides fabricated based on CT scans of the patient's limb. For an epiphyseal defect, approximately 40% of the distal radius may be removed, along with a slightly larger section of the ulna to enable insertion of the device **200**. In some embodiments, the biodegradable osteogenic scaffold **230** may be treated with one or more bioactive agents to facilitate bone growth or angiogenesis before positioning the biodegradable osteogenic scaffold **230** within the biodegradable sleeve **210**. For example, the biodegradable osteogenic scaffold **230** may be treated with rhB M P-2 to facilitate bone growth and/or vascular endothelial growth factor (VEGF) to facilitate angiogenesis. In some embodiments, the biodegradable osteogenic scaffold **230** may be positioned within the biodegradable sleeve **210** such that the proximal end **232** of the biodegradable osteogenic scaffold **230** is offset from the proximal end **212** of the biodegradable sleeve **210**, and a distal portion of the proximal bone structure may be inserted into the biodegradable sleeve **210** and in contact with the proximal end

**232** of the biodegradable osteogenic scaffold **230**. For an epiphyseal defect, a distal portion of the remaining host radius may be inserted into the biodegradable sleeve **210** and in contact with the proximal end **232** of the biodegradable osteogenic scaffold **230**. In some embodiments, the biodegradable osteogenic scaffold **230** may be positioned within the biodegradable sleeve **210** such that the distal end **234** of the biodegradable osteogenic scaffold **230** is flush with the distal end **214** of the biodegradable sleeve **210**, and a proximal portion of the distal bone structure may be positioned in close contact with the distal end **234** of the biodegradable osteogenic scaffold **230** and the distal end **214** of the biodegradable sleeve **210**. For an epiphyseal defect, the proximal end of the carpus may be positioned in close contact with the distal end **234** of the biodegradable osteogenic scaffold **230** and the distal end **214** of the biodegradable sleeve **210**. In some embodiments, the biodegradable osteogenic scaffold **230** may be positioned within the biodegradable sleeve **210** such that the distal end **234** of the biodegradable osteogenic scaffold **230** is offset from the distal end **214** of the biodegradable sleeve **210**, and a proximal portion of the distal bone structure may be inserted into the biodegradable sleeve **210** and in contact with the distal end **234** of the biodegradable osteogenic scaffold **230**.

[0040] In some embodiments, the biodegradable sleeve **210** may be coupled to the fixation member **240** before the biodegradable sleeve **210** is positioned between the proximal bone structure and the distal bone structure. In some embodiments, the biodegradable sleeve **210** may be coupled to the fixation member **240** by inserting the fixation member **240** into the gap of the biodegradable sleeve **210**. In some embodiments, a proximal end portion of the fixation member **240** may be attached to the proximal bone structure using a first plurality of screws, and a distal end portion of the fixation member **240** may be attached to the distal bone structure using a second plurality of screws. For an epiphyseal defect, the proximal end portion of the fixation member **240** may be attached to the remaining host radius, and the distal end portion of the fixation member **240** may be attached to the third metacarpal.

[0041] In some embodiments, the biodegradable cuffs **250** may be slid over the biodegradable sleeve **210** and the fixation member **240** after the fixation member **240** is attached to the proximal bone structure but before the fixation member **240** is attached to the distal bone structure. One of the biodegradable cuffs **250** may be slid over the biodegradable sleeve **210** and the fixation member **240** from the distal ends **214**, **244** toward the proximal ends **212**, **242** thereof, aligned with the proximal-most screw hole **216** of the biodegradable sleeve **210**, and connected to the biodegradable sleeve **210** and the fixation member **240** using a screw. The screw may pass through the biodegradable cuff **250**, the fixation member **240**, and the bone cortex of the proximal bone structure on the cis side and through the bone cortex of the proximal bone structure, the biodegradable sleeve **210**, and the biodegradable cuff **250** on the trans side. In this manner, the screw may lock the proximal end of the device **200** into position. The screw should not protrude exceedingly far from the biodegradable cuff **250** to minimize risk of collateral tissue trauma. Each of the remaining biodegradable cuffs **250** then may be slid over the biodegradable sleeve **210** and the fixation member **240** from the distal ends **214**, **244** toward the proximal ends **212**, **242** thereof, aligned with one of the remaining screw holes **216** of the biodegradable sleeve **210**, and connected to the biodegradable sleeve **210** and the fixation member **240** using a respective screw. Each of these screws may pass through the biodegradable cuff **250**, the fixation member **240**, the biodegradable osteogenic scaffold **230**, the biodegradable sleeve **210**, and the biodegradable cuff **250**. After connecting the biodegradable cuffs **250**, the distal end **214** of the biodegradable sleeve **210** and the distal end of the biodegradable osteogenic scaffold **230** may be positioned in close contact with a proximal portion of the distal bone structure, and the distal end portion of the fixation member **240** may be attached to the distal bone structure. For an epiphyseal defect, the distal end **214** of the biodegradable sleeve **210** and the distal end of the biodegradable osteogenic scaffold **230** may be positioned in close contact with the proximal end of the carpus, and the distal end portion of the fixation member **240** may be attached to the third metacarpal.

[0042] FIGS. 3A-3F illustrate another example **300** for treating a bone defect, such as a critical-sized bone defect, of a veterinary or human patient. In some instances, the device **300** may be used to treat an epiphyseal defect. In other instances, the device **300** may be used to treat a segmental defect or a mandibular defect. Because components of the device **300** may be 3D printed according to patient anatomy, they can be appropriately configured to any surgical case. FIGS. 3A and 3B show the device **300** positioned relative to a proximal bone structure PBS and a distal bone structure DBS for treating an epiphyseal defect. As shown, the device **300** may include a biodegradable sleeve **310**, a biodegradable osteogenic scaffold **330**, a fixation member **340**, and a plurality of screws **360**. It will be appreciated that the size and shape of the respective components of the device **300** may be varied to accommodate a particular patient and the particular defect being treated. As discussed below, in some embodiments, the biodegradable sleeve **310** and the biodegradable osteogenic scaffold **330** may be fabricated as patient-specific components. For example, these components may be 3D printed based on CT scans of the patient's limb. In some embodiments, the fixation member **340** may be a commercially-available component used in accordance with the standard of care, with the size of the fixation member **340** being selected to accommodate the patient and defect to be treated.

[0043] As shown, the biodegradable sleeve **310** may be formed as an elongate structure having a proximal end **312** and a distal end **314** disposed opposite one another along the longitudinal axis of the biodegradable sleeve **310**. In some embodiments, as shown, the proximal end **312** may be shape-matched to a distal portion of the proximal bone structure PBS of the patient, and the distal end **314** may be shape matched to a proximal portion of the distal bone structure DBS of the patient. For example, for an epiphyseal defect, the proximal end **312** may be shape-matched to the remaining host radius, and the distal end **314** may be shape-matched to the radial carpus. In some embodiments, as shown, the biodegradable sleeve **310** may have a generally circular cross-sectional shape (i.e, taken perpendicular to the longitudinal axis of the biodegradable sleeve **310**). The biodegradable sleeve **310** may include a first passage **316** extending from the proximal end **312** to the distal end **314** and configured for receiving the biodegradable osteogenic scaffold **330** therein. As shown, the shape and size of the first passage **316** may correspond to the shape and size of the biodegradable osteogenic scaffold **330**. The biodegradable sleeve **310** also may include a second passage **318** extending from the proximal end **312** to the distal end **314** and configured for receiving a portion of the fixation member **340** therein. As shown, the shape and size of the second passage **318** may correspond to the shape and size of the fixation member **340**. In some embodiments, as shown, the biodegradable sleeve **310** may include a pair of support ribs **322** disposed between the first passage **316** and the second passage **318** and extending from the proximal end **312** to the distal end **314** of the biodegradable sleeve **310**. As shown, a gap **324** may be defined between the ribs **322** such that the first passage **316** is in communication with the second passage **318** through the gap **324**. In some embodiments, as shown, the biodegradable sleeve **310** may include a plurality of apertures **326** disposed along one or more sides of the biodegradable sleeve **310** and extending from an outer surface of the biodegradable sleeve **310** to the first passage **316**. In this manner, the apertures **326** may be configured for controlling transcortical perfusion during use of the device **300**. In some embodiments, the apertures **326** may be omitted to prevent transcortical perfusion through the biodegradable sleeve **310**. In some embodiments, as shown, the biodegradable sleeve **310** may include a plurality of openings **328** disposed along a side of the biodegradable sleeve **310** and extending from an outer surface of the biodegradable sleeve **310** to the second passage **318**. The openings **328** may expose respective portions of the fixation member **340** when the fixation member **340** is coupled to the biodegradable sleeve **310** and may be configured for receiving respective collagen sponges carrying one or more bioactive agents therein, such as an antibiotic to inhibit infection, during use of the device **300**. In some embodiments, the biodegradable sleeve **310** may be formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone. Other suitable biocompatible and

biodegradable materials may be used for the biodegradable sleeve **310** in other embodiments.

[0044] The biodegradable osteogenic scaffold **330** may be formed as an elongate structure having a proximal end **332** and a distal end **334** disposed opposite one another along the longitudinal axis of the biodegradable osteogenic scaffold **330**. In some embodiments, the biodegradable osteogenic scaffold **330** may have a gyroid topology (similar to that depicted in FIG. 2C), with a plurality of interconnected pores. Other porous topologies of the biodegradable osteogenic scaffold **330** may be used in other embodiments. In some embodiments, the biodegradable osteogenic scaffold **330** may have a porosity of 70%. In some embodiments, as shown, the biodegradable osteogenic scaffold **330** may include a central passage **338** extending from the proximal end **332** to the distal end **334** and configured for receiving a collagen sponge carrying rhB M P-2 therein to facilitate bone growth during use of the device **300**. In some embodiments, the length of the biodegradable osteogenic scaffold **330** may be less than the length of the biodegradable sleeve **310**. In this manner, the biodegradable osteogenic scaffold **330** may be positioned entirely within the biodegradable sleeve **310** during use of the device **300**. As discussed above, the biodegradable osteogenic scaffold **330** may be received within the first passage **316** of the biodegradable sleeve **310**. In some embodiments, as shown, a portion of the biodegradable osteogenic scaffold **330** may extend into the gap **324** of the biodegradable sleeve **310**. In some embodiments, the biodegradable osteogenic scaffold **330** may be formed of a calcium phosphate, such as HA  $\alpha$  or  $\beta$ -TCP. In some embodiments, the biodegradable osteogenic scaffold **330** may be formed of a calcium phosphate-based material or a composite comprising a calcium phosphate and a polymer. Other suitable biocompatible, biodegradable, and osteogenic materials may be used for the biodegradable osteogenic scaffold **330** in other embodiments.

[0045] The fixation member **340** may be formed as an elongate structure having a proximal end **342** and a distal end **344** disposed opposite one another along the longitudinal axis of the fixation member **340**. According to various embodiments, the fixation member **340** may be a fixation plate, a fixation rod, a locking plate, a locking rod, or other type of suitable structure for fixation of bone structures. In some embodiments, as shown, the fixation member **340** may have a rectangular cross-sectional shape (i.e., taken perpendicular to the longitudinal axis of the fixation member **340**). As discussed below, the fixation member **340** may be coupled to the biodegradable sleeve **310** by sliding the biodegradable sleeve **310** onto the fixation member **340** such that the fixation member **340** extends through the second passage **318**. As shown, the fixation member **340** may include a plurality of screw holes **346** extending therethrough and spaced apart from one another along the length of the fixation member **340**. As discussed below, the screw holes **346** may be used to facilitate connection of the fixation member **340** to the proximal bone structure PBS and the distal bone structure DBS using the screws **360**. The fixation member **340** may include a proximal end portion **352**, a distal end portion **354**, and an intermediate portion **356**. As shown, when the fixation member **340** is coupled to the biodegradable sleeve **310**, the proximal end portion **352** may extend beyond the proximal end **312** of the biodegradable sleeve **310**, the distal end portion **354** may extend beyond the distal end **314** of the biodegradable sleeve **310**, and the intermediate portion **356** may be positioned within the second passage **318** of the biodegradable sleeve **310**. As shown, the proximal end portion **352** may include a plurality of the screw holes **346** to facilitate connection of the fixation member **340** to the proximal bone structure PBS, and the distal end portion **354** may include a plurality of the screw holes **346** to facilitate connection of the fixation member **340** to the distal bone structure DBS. In some embodiments, the intermediate portion **356** may be devoid of any screw holes **346**. In some embodiments, the intermediate portion **356** may include a plurality of the screw holes **346**, which may be filled with respective plugs to prevent bone growth therein during use of the device **300**. The fixation member **340** may be formed of any suitable biocompatible, non-biodegradable material such that the fixation member **340** may be removed from the patient after the bone defect has healed and the biodegradable sleeve **310** and the biodegradable osteogenic scaffold **330** have degraded. According to various embodiments, the

fixation member **340** may be formed of a metal, a polymeric material, a ceramic material, a composite material, or other suitable material for fixation of bone structures.

[0046] As noted above, the biodegradable sleeve **310** and the biodegradable osteogenic scaffold **330** may be fabricated as patient-specific components. In some embodiments, CT scans of the patient's limb may be used to fabricate the biodegradable sleeve **310** and the biodegradable osteogenic scaffold **330** for the patient. In some embodiments, a series of two-dimensional DICOM images of the full extent of the limb may be imported (e.g., using InVesalius) and segmented to create high-resolution digital models of the radius, ulna, manus, and metacarpals of the patient. The images then may be segmented based on Hounsfield attenuation values, and surface representations of the bone may be generated and then imported (e.g., into Fusion **360**) where 3D models of the components may be created for 3D printing. In some embodiments, finite element analysis (FEA) may be used to investigate the ideal design parameters of the biodegradable sleeve **310** and the overall device **300**, with and without the fixation member **340**, to determine optimal geometry of the components and features thereof. Parameters such as wall thickness and mechanical properties such as structural modulus may be simulated to optimize the design of the device **300** prior to fabrication. In some embodiments, the CT scans also may be used to fabricate cutting guides to assure accurate surgical resections to match the geometry of the device **300**.

[0047] The biodegradable osteogenic scaffold **330** may be 3D printed using existing methods. In some embodiments, a photopolymer comprised of ethylene glycol dimethacrylate (EDGM A) and other polymers may be mixed with hydroxyapatite (HA  $\rho$ ) particles into a shear-thinning slurry using a planetary ball mill. Slurries of 41 vol % HA  $\rho$  may be transferred to a syringe and 3D printed on 3D printer, such as a HyRel Engine SR printer with a 0.413 mm nozzle inner diameter, using a combination of viscous extrusion and photopolymer processes. The photopolymerization reaction may be initiated by continuous exposure of the deposited roads to a near-UV light source (405 nm wavelength), causing polymerization and hardening of the continuous phase, layer-by-layer. The sintered biodegradable osteogenic scaffold **330** may be non-cytotoxic. After printing, the biodegradable osteogenic scaffold **330** may undergo a two-step sintering process to eliminate the polymeric content and consolidate the HA  $\rho$  particles. In some embodiments, the printed biodegradable osteogenic scaffold **330** may be heated at 5° C./min up to 500° C. and held for 1 h, and then sintered at a heating rate of 15° C./min, up to 1150° C. and held for 5 h. This process may confer the sintered HA  $\rho$  structures with suitable mechanical properties. In some embodiments, the biodegradable sleeve **310** may be fabricated using a thermal process on a melt extrusion 3D printer (e.g., Prusa i3-M K 3, Budapest, Hungary). PCL filament may be extruded by regulated ram pressure through a Flexion head. The extruded PCL may cool on a build plate to fabricate the components, which then may cool to room temperature. Prints may be oriented to maximize part strength and minimize support material.

[0048] The device **300** may be used to treat a bone defect, such as a critical-sized bone defect, extending between a proximal bone structure PBS and a distal bone structure DBS of a patient. In some embodiments, as shown in FIGS. 3A and 3B, the bone defect may be an epiphyseal defect. In some embodiments, the bone defect may be a segmental defect. A method of using the device **300** for treating the bone defect generally may include resecting a region of bone between the proximal bone structure PBS and the distal bone structure DBS and encompassing the bone defect, positioning the biodegradable osteogenic scaffold **330** within the biodegradable sleeve **310**, coupling the biodegradable sleeve **310** to the fixation member **340**, positioning the biodegradable sleeve **310** between the proximal bone structure PBS and the distal bone structure DBS, and attaching the fixation member **340** to each of the proximal bone structure PBS and the distal bone structure DBS.

[0049] In some embodiments, the region of bone may be resected using one or more cutting guides fabricated based on CT scans of the patient's limb. For an epiphyseal defect, approximately 40% of the distal radius may be removed, along with a slightly larger section of the ulna to enable insertion

of the device **300**. In some embodiments, the biodegradable osteogenic scaffold **330** may be treated with one or more bioactive agents to facilitate bone growth or angiogenesis before positioning the biodegradable osteogenic scaffold **330** within the biodegradable sleeve **310**. For example, the biodegradable osteogenic scaffold **330** may be treated with rhB M P-2 to facilitate bone growth and/or VEGF to facilitate angiogenesis. In some embodiments, one or more collagen sponges containing the one or more bioactive agents may be inserted within the central passage **338** of the biodegradable osteogenic scaffold **330**. In some embodiments, the biodegradable osteogenic scaffold **330** may be positioned within the biodegradable sleeve **310** such that the proximal end **332** of the biodegradable osteogenic scaffold **330** is offset from the proximal end **312** of the biodegradable sleeve **310**, and a distal portion of the proximal bone structure PBS may be inserted into the first passage **316** of the biodegradable sleeve **310** and in contact with the proximal end **332** of the biodegradable osteogenic scaffold **330**. For an epiphyseal defect, a distal portion of the remaining host radius may be inserted into the first passage **316** of the biodegradable sleeve **310** and in contact with the proximal end **332** of the biodegradable osteogenic scaffold **330**. In some embodiments, the biodegradable osteogenic scaffold **330** may be positioned within the biodegradable sleeve **310** such that the distal end **334** of the biodegradable osteogenic scaffold **330** is flush with the distal end **314** of the biodegradable sleeve **310**, and a proximal portion of the distal bone structure DBS may be positioned in close contact with the distal end **334** of the biodegradable osteogenic scaffold **330** and the distal end **314** of the biodegradable sleeve **310**. For an epiphyseal defect, the proximal end of the carpus may be positioned in close contact with the distal end **334** of the biodegradable osteogenic scaffold **330** and the distal end **314** of the biodegradable sleeve **310**. In some embodiments, the biodegradable osteogenic scaffold **330** may be positioned within the biodegradable sleeve **310** such that the distal end **334** of the biodegradable osteogenic scaffold **330** is offset from the distal end **314** of the biodegradable sleeve **310**, and a proximal portion of the distal bone structure DBS may be inserted into the first passage **316** of the biodegradable sleeve **310** and in contact with the distal end **334** of the biodegradable osteogenic scaffold **330**.

[0050] In some embodiments, the biodegradable sleeve **310** may be coupled to the fixation member **340** before the biodegradable sleeve **310** is positioned between the proximal bone structure PBS and the distal bone structure DBS. In some embodiments, the biodegradable sleeve **310** may be coupled to the fixation member **340** by sliding the biodegradable sleeve **310** over the fixation member **340** such that the intermediate portion **356** of the fixation member **340** is positioned within the second passage **318**, the proximal end portion **352** of the fixation member **340** extends beyond the proximal end **312** of the biodegradable sleeve **310**, and the distal end portion **354** of the fixation member **340** extends beyond the distal end **314** of the biodegradable sleeve **310**. In some embodiments, the proximal end portion **352** of the fixation member **340** may be attached to the proximal bone structure PBS using a first plurality of the screws **360**, and the distal end portion **354** of the fixation member **340** may be attached to the distal bone structure DBS using a second plurality of the screws **360**. For an epiphyseal defect, the proximal end portion **352** of the fixation member **340** may be attached to the remaining host radius, and the distal end portion **354** of the fixation member **340** may be attached to the third metacarpal. In some embodiments, the biodegradable sleeve **310** may be coupled to the fixation member **340** and positioned between the proximal bone structure PBS and the distal bone structure DBS after the fixation member **340** is attached to the proximal bone structure PBS but before the fixation member **340** is attached to the distal bone structure DBS. In other words, the proximal end portion **352** of the fixation member **340** may be attached to the proximal bone structure PBS, the biodegradable sleeve **310** then may be slid onto the fixation member **340** from the proximal end **342** toward the distal end **344** and positioned between the proximal bone structure PBS and the distal bone structure DBS, and the distal end portion **354** of the fixation member **340** then may be attached to the distal bone structure DBS.

[0051] Although specific embodiments of the disclosure have been described, one of ordinary skill



in the art will recognize that numerous other modifications and alternative embodiments are within the scope of the disclosure. Further, while various illustrative implementations have been described in accordance with embodiments of the disclosure, one of ordinary skill in the art will appreciate that numerous other modifications to the illustrative implementations described herein are also within the scope of this disclosure.

[0052] Although embodiments have been described in language specific to structural features and/or methodological acts, it is to be understood that the disclosure is not necessarily limited to the specific features or acts described. Rather, the specific features and acts are disclosed as illustrative forms of implementing the embodiments. Conditional language, such as, among others, “can,” “could,” “might,” or “may,” unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments could include, while other embodiments do not include, certain features, elements, and/or steps. Thus, such conditional language is not generally intended to imply that features, elements, and/or steps are in any way required for one or more embodiments.

## Claims

1. A method for treating a bone defect, the method comprising: positioning a biodegradable osteogenic scaffold within a passage defined by a biodegradable sleeve; positioning the biodegradable sleeve along a first bone portion and a second bone portion such that the biodegradable osteogenic scaffold is disposed within the bone defect; and coupling the biodegradable sleeve to each of the first bone portion and the second bone portion.
2. The method of claim 21, wherein coupling the biodegradable sleeve to the fixation member comprises sliding the biodegradable sleeve onto the fixation member.
3. The method of claim 1, wherein positioning the biodegradable sleeve along a first bone portion and a second bone portion comprises: inserting a distal end portion of the first bone portion into a proximal end of the biodegradable sleeve such that the distal end portion contacts the biodegradable osteogenic scaffold; and inserting a proximal end portion of the second bone portion into a distal end of the biodegradable sleeve such that the proximal end portion contacts the biodegradable osteogenic scaffold.
4. The method of claim 21, wherein coupling the biodegradable sleeve to each of the first bone portion and the second bone portion comprises: coupling the biodegradable sleeve to the first bone portion using a first plurality of screws; and coupling the biodegradable sleeve to the second bone portion using a second plurality of screws.
5. The method of claim 1, further comprising treating the biodegradable osteogenic scaffold with one or more bioactive agents to facilitate bone growth or angiogenesis.)
6. The method of claim 21, further comprising treating the biodegradable sleeve and the fixation member with an antibiotic to inhibit infection.
7. The method of claim 1, further comprising: obtaining computed tomography scans of the patient; and fabricating the biodegradable osteogenic scaffold and the biodegradable sleeve based at least in part on the computed tomography scans.
8. The method of claim 7, further comprising resecting a region of bone between the first bone portion and the second bone portion and encompassing the bone defect, the method further comprising fabricating a cutting guide based at least in part on the computed tomography scans, wherein resecting the region of bone between the first bone portion and the second bone portion and encompassing the bone defect comprises resecting the region of bone using the cutting guide.
9. The method of claim 1, wherein the biodegradable osteogenic scaffold is formed of a calcium phosphate-based material or a composite comprising a calcium phosphate and a polymer, and wherein the biodegradable sleeve is formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone.

**10.** The method of claim **21**, further comprising detaching the fixation member from the first bone portion and the second bone portion and removing the fixation member from the patient after the bone defect has healed and the biodegradable osteogenic scaffold and the biodegradable sleeve have degraded.

**11.** A device for treating a bone defect, the device comprising: a biodegradable sleeve configured for positioning along a first bone portion and a second bone portion; a biodegradable osteogenic scaffold configured for positioning within a passage defined by the biodegradable sleeve; and wherein the biodegradable sleeve is configured for coupling to each of the first bone portion and the second bone portion such that the biodegradable osteogenic scaffold is disposed within the bone defect.

**12.** The device of claim **22**, wherein the passage defined by the biodegradable sleeve is a first passage extending from a proximal end to a distal end of the biodegradable sleeve and configured for receiving the biodegradable osteogenic scaffold therein, wherein the biodegradable sleeve further comprises: a second passage extending from the proximal end to the distal end of the biodegradable sleeve and configured for receiving a portion of the fixation member therein.

**13.** The device of claim **12**, wherein the biodegradable sleeve further comprises support ribs disposed between the first passage and the second passage and extending from the proximal end to the distal end of the biodegradable sleeve, and wherein the first passage is in communication with the second passage through a gap defined between the support ribs.

**14.** The device of claim **13**, wherein a portion of the biodegradable osteogenic scaffold extends into the gap when the biodegradable osteogenic scaffold is positioned within the biodegradable sleeve.

**15.** The device of claim **12**, wherein the first passage is further configured for receiving a distal end portion of the first bone portion and a proximal portion of the second bone portion therein.

**16.** The device of claim **12**, wherein the biodegradable sleeve further comprises a plurality of apertures disposed along one or more sides of the biodegradable sleeve and extending from an outer surface of the biodegradable sleeve to the first passage, and wherein the apertures are configured for controlling transcortical perfusion.

**17.** The device of claim **12**, wherein the biodegradable sleeve further comprises a plurality of openings disposed along a side of the biodegradable sleeve and extending from an outer surface of the biodegradable sleeve to the second passage, and wherein the openings expose respective portions of the fixation member when the fixation member is coupled to the biodegradable sleeve and are configured for receiving respective collagen sponges carrying an antibiotic therein.

**18.** The device of claim **12**, wherein the biodegradable osteogenic scaffold comprises a central passage extending from a proximal end to a distal end of the biodegradable osteogenic scaffold and configured for receiving a collagen sponge carrying rhB M P-2 or VEGF therein.

**19.** The device of claim **12**, wherein the fixation member comprises: a proximal portion configured for extending beyond the proximal end of the biodegradable sleeve when the fixation member is coupled to the biodegradable sleeve; a distal portion configured for extending beyond the distal end of the biodegradable sleeve when the fixation member is coupled to the biodegradable sleeve; and an intermediate portion configured for positioning within the second passage when the fixation member is coupled to the biodegradable sleeve.

**20.** The device of claim **11**, wherein the biodegradable osteogenic scaffold is formed of a calcium phosphate-based material or a composite comprising a calcium phosphate and a polymer, and wherein the biodegradable sleeve is formed of polycaprolactone or a composite comprising a calcium phosphate and polycaprolactone.

**21.** The method of claim **1**, further comprising coupling the biodegradable sleeve to a fixation member, wherein coupling the biodegradable sleeve to each of the first bone portion and the second bone portion comprises coupling the fixation member to each of the first bone portion and the second bone portion.

**22.** The device of claim **11**, further comprising a fixation member configured for coupling to the

biodegradable sleeve, wherein the biodegradable sleeve is configured to be coupled to each of the first bone portion and the second bone portion by coupling the fixation member to each of the first bone portion and the second bone portion.

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