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Smart body armor inspired by flow in bone

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Abstract. An understanding of biomaterials' smart properties and how biocomposite materials are manufactured by cells provides not only bio-inspiration for new classes of smart actuators and sensors but also foundational technology for smart materials and their manufacture. In this case study, I examine the unique smart properties of bone, which are evident at multiple length scales and how they provide inspiration for novel classes of mechanoactive materials. I then review potential approaches to engineer and manufacture bioinspired smart materials that can be applied to solve currently intractable problems such as the need for "smart" body armor or decor *cum* personal safety devices.

Keywords: smart material; bio-inspired design; mechanoactive materials; bone; body armor; flow directing material; multiscale structure and function; load-induced fluid flow.

1. Introduction

From a "top-down" perspective, a defining characteristic of biomaterials, including tissues, is that they interact with cells. From a "bottom-up" perspective, cells build the biomaterial (tissue) they inhabit (Knothe Tate 2011). Cells are also the living component of their biomaterial habitat, enabling self-annealing and dynamic structural alterations in response to changes in mechanical function. Hence, in addition to their role as micromanufacturing plants, cells serve as actuators or "micromachines" for biomaterial integration or tissue repair and adaptation in a dynamic mechanical and biochemical environments. Furthermore, cells serve as sensors or "living beacons", providing spatiotemporally resolved signals that can be "decoded" to elucidate the state of a biomaterial or tissue at any given location and time, and in "real time", over the lifetime of the biomaterial/tissue. (Knothe Tate *et al.* 2010a,b, Knothe Tate *et al.* 2009, Knothe Tate *et al.* 2008, Knothe Tate and Anderson 2008, Anderson *et al.* 2006, Knothe Tate *et al.* 2004, Knothe Tate *et al.* 1998).

In short, bone, comprising mineralized extracellular matrix, vascular canals, and cellular inhabitants, is a smart structure, defined by Cao *et al.* as "...a system containing multifunctional parts that can perform sensing, control, and actuation..." made up of "[s]mart materials...used to construct these smart structures...[whose] 'I.Q.'...is measured in terms of ... 'responsiveness' to environmental stimuli and 'agility' (as in capacity for dynamic response)" (Cao *et al.* 1999). An understanding of biomaterials' smart properties and how the biocomposites are manufactured by cells provides not only bio-inspiration for new classes of smart actuators and sensors but also foundational technology for smart

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materials and their manufacture (Knothe Tate and Anderson 2008, Mukherjee and Ganguli 2010).

In this case study, I examine the unique smart properties of bone, which are evident at multiple length scales, and how they provide inspiration for novel classes of mechanoactive materials. I then review potential approaches to engineer and manufacture bioinspired smart materials that can be applied to solve currently intractable problems such as the need for "smart" body armor.

2. Multi-scale load-induced fluid flow in bones

Bone of the mature skeleton exhibits flow-directing behavior at multiple length scales (Knothe Tate *et al.* 2009, Knothe Tate and Anderson 2008). As suggested first by Basset in the 1960s (Bassett 1965) and Piekarski and Munro more than a decade later (Piekarski and Munro 1977), bone exhibits poroelastic behavior (Biot 1941). Like a stiff, fluid filled sponge, loading of, e.g., the femur, during normal physiological activity induces flow of the interstitial (extravascular) fluid in bone, from regions of high to regions of low pressure Fig. 1(a)-(d). Piekarski and Munro suggested that this pressure gradient driven flow provides a means to insure efficient transport of nutrients and wasteproducts, to, and from, bone cells called osteocytes that are embedded within mineralized spaces in bone tissue (Piekarski and Munro 1977). The concept of load-induced fluid flow as a means to feed osteocytes and remove toxins from their local environment bridged length scales from macroscopic physiologic activity to metabolic activity of microscopic cells (*as reviewed in* (Knothe Tate 2003)).

Piekarski and Munro's postulate that loading of bone induces displacement of fluid within bone (Piekarski and Munro 1977) was demonstrated experimentally two decades later (Knothe Tate *et al.* 1997). Using intravital tracer transport methods and microscopy, it could be shown that bone exhibits not only poroelastic properties including load-induced fluid displacements (Knothe Tate *et al.* 1997, Knothe Tate *et al.* 1998, Knothe Tate *et al.* 2000), but also that bone acts as a molecular sieve (Tami *et al.* 2003, Steck *et al.* 2005) where, above a certain molecular size threshold, convective transport is necessary to enable efficient delivery of factors key to bone health. Finally, computational models show that drag induced shear flow predominates within the lacunocanalicular spaces around osteocyte processes and that hydrodynamic pressures prevail in lacunar spaces around osteocyte bodies (Anderson *et al.* 2005).

More recently, we discovered that bone exhibits remarkable intrinsic properties including fortuitous combinations of anisotropic stiffness and permeablity coefficients that enable directed flow to and from osteocytes in areas far from the vascular supply (Fig. 1(e)-(h)) (Knothe Tate *et al.* 2009). Similar to the load-induced flow concept described above, physiologic loading (walking, running, lifting) causes gradients in pore pressures within the bone, providing impetus for fluid flow in the direction of least resistance (Knothe Tate *et al.* 2009). For a particular pressure gradient, flow velocities decrease with decreasing porosity and higher pressures are required to move the fluid a given distance; in contrast, flow velocities increase with increasing porosity, requiring lower pressures to move the fluid the same distance.

Counterintuitive to typical sponge behavior, for certain combinations of material stiffness and porosity distribution, compression of the material results in the formation of negative pore pressures, causing imbibement of fluid in areas that are being compressed (Fig. 2(a)-(b) left, Fig. 2(c)). Similarly, application of tensile loads results in formation of positive pore pressures that push fluid out of areas under tension (Fig. 2(a)-(b) right, Fig. 2(d)). Previous computational models as well as *in silico* and *in vitro* validation studies showed that the counterintuitive flow phenomenon is attributable to the effective expansion of the flow volume in the radial direction during axial compression (e.g., of a cylinder) and effective compression of the volume in the radial direction during application of

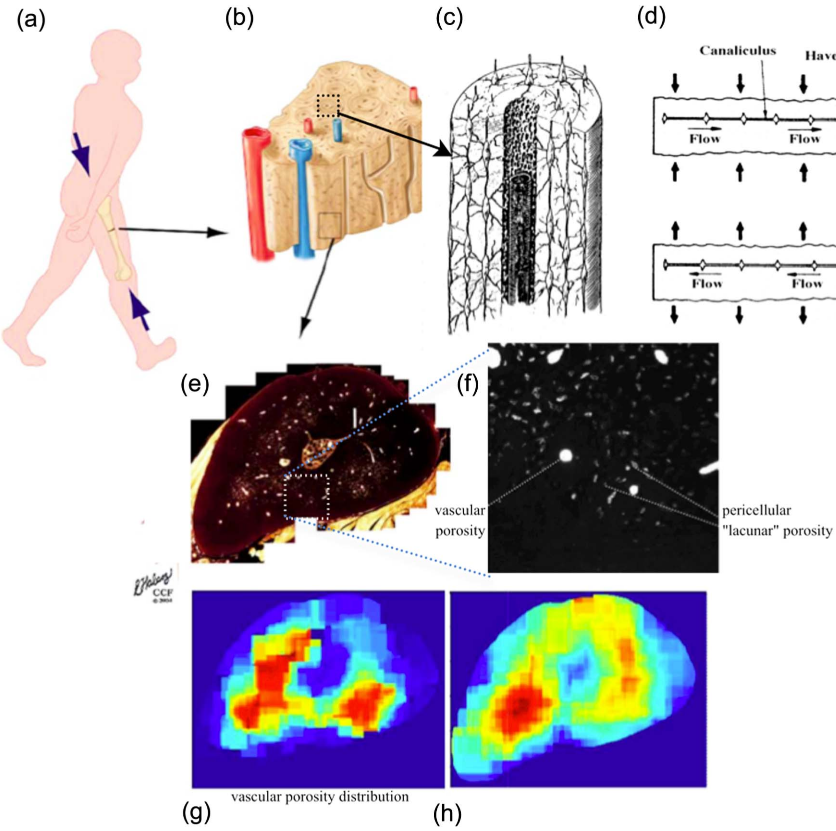

Fig. 1 Fluid in bone is transported via vascular (blood) and extravascular (interstitial fluid) channels. The heart pump provides the pressure gradient to pump blood through the circulatory system, aided by muscular contractions to increase pressure along venous routes back to the heart. In contrast, pressure gradients induced through physical activity are key to pumping interstitial fluid through less permeable tissues such as bone, which are like stiff, fluid filled, "smart" sponges with intrinsic porosity and stiffness to direct flow to and from cells (osteocytes) immobilized within. **(a)** For example, the femur is exposed to cycles of compression and relaxation during walking that **(b)** result in pressure gradients at multiple length scales (**c**), providing impetus for fluid flow (along the canaliculi) to and from osteocytes (within lacunae) far from the vascular supply (within the Haversian Canal) **(d)**. Human cortical bone **(a-d)** is organized as a composite structure comprised of osteons **(b)** or units, organized radially around a central blood vessel. At a length scale of approximately 3 cm (diameter), the composite structure of cortical bone in the human femur maximizes efficient mass transport from the circulatory system to cells (all within approximately 250 microns of any given blood vessel). In contrast, bone of the rat femur is at an order of magnitude smaller length scale (approximately 3 mm diameter) and is organized with less complexity. Osteonal, composite structure is not found in rat bone **(e-h)**; rather, blood vessels are distributed throughout the cortex so that each cell is located less than 250 microns away. (Mishra and Knothe Tate 2003). Through fortuitous distribution of vascular **(e,g)** and pericellular "lacunar-canalicular" porosities **(f,h)**, resistance to flow is decreased in areas further from the blood supply. *Color plots can be interpreted as "heat maps"* **(g,*h*)**, *where relative density of a given porosity in space increases from areas indicated by coolest to warmest colors. After* (Knothe Tate *et al.* 2009, Knothe Tate *et al.* 2010a), *used with permission*

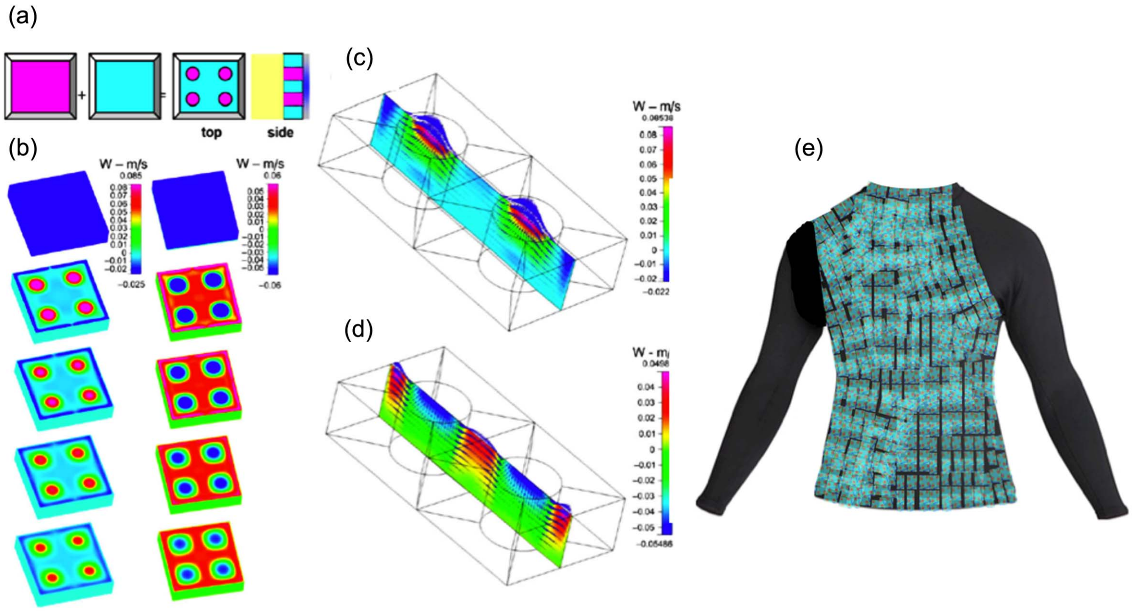

Fig. 2 Schematic diagram and *in silico* study of counterintuitive flow in bone, demonstrating the feasibility of the flow directing material as a modular design concept for development of smart, flow directing armor. **(a)** One composite module incorporates material regions that imbibe fluid (pink) and other regions that exude fluid (turquoise) under compressive load (and exude, respectively imbibe, fluid under tensile load). The composite module can be configured with varying densities of imbibing and exuding regions (top view). The outer material (side view) is a limiting barrier that prevents loss of fluid from the system and the inner, yellow area, represents the skin (side view). **(b)** Computational fluid dynamics models show flow properties within the module over time, where the "top" of the module (outwards from the plane of this page) would be covered by the barrier membrane to prevent fluid loss. Flow properties of "dots" and surrounding areas are controlled through definition of regional material properties including stiffness and permeability **(c**,**d)**. Under compression **(b**, **left panel)**, "dots" deliver fluid out of the module (and plane of the page) and surrounding areas imbibe fluid into the module (and plane of page). The opposite flow behavior is observed under tension **(b**, **right panel)**. *After* (Knothe Tate *et al*. 2009, Knothe Tate and Anderson 2008), *used with permission.* **(e)** The smart, flow directing armor concept incorporates modules, described above **(a-d)**, to protect the skin and inner organs from blast injuries

tensile loads to the cylinder. Hence, areas under tension expand radially, resulting in efflux of fluid orthogonal to the plane and areas of compression shorten radially, resulting in influx of fluid orthogonal to the plane (Fig. 2) (Knothe Tate *et al*. 2009, Knothe Tate and Anderson 2008).

2.1 Approaches to engineer and manufacture bio-inspired smart, flow directing materials

Here I introduce and discuss the concept of applying bone flow's bio-inspiration to the development of smart, flow directing armor that absorbs and redirects the energy of the blast away from the body by directing energy dissipative fluid flow outward (Fig. 2(e)). In one conceptualization (Fig. 2(e)), the armor incorporates flow-directing modules to protect the skin and inner organs from blast injuries. In this conceptualization, the areas surrounding the “dot zones” absorbs the energy of the blast by directing fluid within radially, producing a pressure gradient that is dissipated via exudation of the fluid in the dot regions. The stiffness and permeability of the modules is designed such that pressure gradient of the initial impact is absorbed in the areas surrounding dots. Flow is immediately redirected outwards, away from the body, to the “delivery dots”, which fill up and act as local “air bags”.

To reduce to practice the concept described above, it will be necessary to develop inexpensive and scale-able methods for manufacture of anisotropic, poroelastic textiles that incorporate both the necessary distribution of stiffness and permeability and flow channels in three dimensions. Although perhaps difficult to envision in textile form, one might envision an open cell version of neoprene like materials used for water sports and diving. Neoprene is a closed cell foam material in which the closed cells are filled with nitrogen gas to increase bouyancy and decrease thermal conductivity; a critical aspect of the neoprene wetsuit design is that it fits snugly to the body in order to trap water as an additional layer of insulation between the surface of the skin and the suit. Neoprene wetsuits are typically available in 2 mm to 8 mm thickness (Rainey 1998).

In my first conceptualization of bio-inspired body armor, the armor is manufactured like a wetsuit, *e.g.* with oriented titanium fibers in areas requiring additional anisotropic stiffness and lycra or spandex fibers in areas requiring additional compliance. The textiles can either be imbibed with a single phase fluid or potentially with two fluids separated by elastic barrier membranes which allow displacement without mixing. For implementation in body armor, the fluid(s) of interest would need to be nonflammable and low density. Unlike wetsuits that are sewn or taped or glued together from flat fabric, the presence of seams in flow directing body armor would create sites of stress concentration and likely failure. Hence, the armor would likely have to be produced using a multiple step injection process where stiffness and compliance fibers are first formed as a fabric around which a mold is placed and into which open cell foam is injected. The fluid phase could either be injected into the open cells in a last phase or could be included in a preformed conduit structure incorporated in the fabric in the first stage of manufacture. If a two fluid model is used, conduits between fluids could be connected via high drag valves, further dissipating energy as the radial directed fluid displacements induced by the initial blast open the unidirectional conduit valves, and redirect flow outwards, away from the body. In a further refinement, fluid viscosity could also be tuned to harness energy dissipation via viscous flow. Interesting, from the materials, “top-down” perspective, this concept is inspired by the counterintuitive flow resulting from fortuitous, anisotropic stiffness and porosity distributions observed in bone tissue (Knothe Tate *et al.* 2009). From the cellular, “bottom-up” perspective, this approach reiterates observations of fluid induced drag dominated flow regimes around osteocyte processes and hydrodynamic compression prevailing around the main body of the osteocyte. (Anderson *et al.* 2005).

3. Conclusions

By studying nature’s “top-down” materials paradigms as well as nature’s “bottom-up” manufacturing mechanisms in a case study of cortical bone tissue, I reviewed our recently developed platform technology for mechanoactive, flow directing materials and then reviewed potential approaches to engineer and manufacture bio-inspired "smart" body armor. Further applications are only limited by our ability to imagine the implementation of mechanoactive materials, e.g., in the interior design of transport vehicles for the next generation of upholstery cum protective devices (airbags, seatbelts, head restraints) or fatigue or trauma-preventative flooring materials.

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