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Morphometric structural diversity of a natural armor assembly investigated by 2D continuum strain analysis

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ABSTRACT

Many armored fish scale assemblies use geometric heterogeneity of subunits as a design parameter to provide tailored biomechanical flexibility while maintaining protection from external penetrative threats. This study analyzes the spatially varying shape of individual ganoid scales as a structural element in a biological system, the exoskeleton of the armored fish *Polypterus senegalus* (bichir). X-ray microcomputed tomography is used to generate digital 3D reconstructions of the mineralized scales. Landmark-based geometric morphometrics is used to measure the geometric variation among scales and to define a set of geometric parameters to describe shape variation. A formalism using continuum mechanical strain analysis is developed to quantify the spatial geometry change of the scales and illustrate the mechanisms of shape morphing between scales. Five scale geometry variants are defined (average, anterior, tail, ventral, and pectoral fin) and their functional implications are discussed in terms of the interscale mobility mechanisms that enable flexibility within the exoskeleton. The results suggest that shape variation in materials design, inspired by structural biological materials, can allow for tunable behavior in flexible composites made of segmented scale assemblies to achieve enhanced user mobility, custom fit, and flexibility around joints for a variety of protective applications.

1. Introduction

Structural biological materials integrate heterogeneity in classical material structure (e.g. materials selection, crystallography, local surface chemistry) with morphometry (geometry or shape-based design parameters) to tune their functionality to physiological need and organism survival (Arciszewski and Cornell, 2006; Ortiz and Boyce, 2008; Oyen et al., 2006; Wainwright et al., 1976; Chen et al., 2012; Meyers et al., 2008; Weiner and Addadi, 1997; Dunlop et al., 2011). Armored fish have evolved protective exoskeletons that provide penetration resistance while maintaining flexibility through scale geometry, arrangement, and interlocking mechanisms (Song et al., 2010; Browning et al., 2013; Yang et al., 2013). One model species, *Polypterus senegalus* (bichir), possesses a mineralized, full-coverage exoskeleton with flexibility (Sire, 1990; Daget et al., 2001) for axial bending and torsion (Gemballa and Bartsch, 2002), escape maneuvers (Tytell and Lauder, 2002), and recoil aspiration (Brainerd, 1994). Heterogeneity in material structure and properties provides protection: each mineralized scale has a quad-layered nanocomposite microstructure with a porous architecture for penetration resistance, toughness, and non-catastrophic pathways for energy dissipation while exhibiting load-dependent material properties, circumferential surface cracking, minimized weight, and tailored layer thickness for threat matching to predatory biting attacks (Bruet et al., 2008; Song et al., 2011; Wang et al., 2009; Han et al., 2011; Meunier, 1987; Meinke et al., 1979; Sire, 1994). Scales are assembled into overlapping columns with organic connective tissue reinforcing the articulating joints and attaching the scales to the dermis (Gemballa and Bartsch, 2002; Pearson, 1981). Scale shape and size vary spatially, yet the integument achieves high bending curvatures in every location due to scale geometry and joint articulation (Gemballa and Bartsch, 2002). Little is known regarding geometric heterogeneity's contribution to the local, inter-scale mobility mechanisms that enable global flexibility.

This study examines shape and shape variation as a structural design element in a biological system, the armored exoskeleton

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of *P. senegalus*. Scale geometry is analyzed along the anteroposterior and dorsoventral axes of the *P. senegalus* exoskeleton and into its pectoral fin. Digital 3D reconstructions of the mineralized scales are generated using X-ray microcomputed tomography (μCT). Geometric variation among scales is investigated using landmark-based geometric morphometrics (GM), and a set of geometric parameters describing shape variation is defined. A continuum mechanical strain formalism is developed to quantify the morphometric variation. GM transformation grids and strain plots illustrate the mechanisms of shape morphing by modeling shape variation through the complex loading conditions of heterogeneous strain fields. Five scale geometry variants are defined, and their functional implications are discussed in terms of the inter-scale mobility mechanisms that allow flexibility within the exoskeleton. The method is further discussed to show that the application of strain fields to a given geometry can achieve a target morphology. While GM is often used to visualize inter-organismal geometric variation as a metric for species differentiation (Elewa, 2010), this intraspecies analysis probes morphometric heterogeneity of subunits within one specimen. The results suggest that the use of shape and shape variation as a materials design parameter can be used to tune the behavior of bioinspired, flexible composite materials for a protective applications.

2. Materials and methods

2.1. X-ray microcomputed tomography (μCT)

Scales from a deceased *P. senegalus* specimen (22 cm body length) were scanned by μCT (VivaCT40, Scanco Medical AG, Switzerland) operated at 45 kV and 177 μA with no filter on the incident X-rays following our previously published procedure (Song et al., 2010). Microtomographic slices were recorded every 8–18 μm with 360° rotation and were reconstructed with 8 × 8 μm to 18 × 18 μm volume elements (voxels) in plane. A constrained 3D Gaussian filter ($\sigma = 0.8$ and support = 1) was used to partially suppress noise in the volumes. Medical imaging software (MIMICS 15.1, Materialise, Belgium) was used to threshold the reconstructed transverse slices by white value with lower (7500) and upper (30,000) values chosen manually through trial and error to isolate the mineralized scales from the organic connective tissue elements attached to the scales, and to build 3D polygonal meshes, using a bilinear and interplane interpolation algorithm, which were exported as stereo-lithography objects (STL). The specimen used in this study, shown in the μCT reconstruction in Fig. 1a, has 56 columns and 18 rows of scales identified subsequently by their column and row number (C#R#).

2.2. Geometric morphometric analysis

A custom-written visual basic script extracted the 3D spatial coordinates of mouse-clicked landmarks (LM) on the STL objects in CAD software (RHINOCEROUS, Robert McNeel and Associates, USA). Twenty LMs, eighteen to define the 2D outline plus two interior points, were chosen to represent the 2D scale geometry, shown on a single scale (C9R5) in Fig. 2 and described in Table 1, based on their consistency of relative position, adequate coverage of form, and repeatability across scales (Zelditch et al., 2004; Bookstein, 1991). LM coordinates were then: (i) translated to set the centroid (calculated as the 3D mean of all LM coordinates) as the origin of the local coordinate system, (ii) scaled by normalizing the vectors from the centroid to each LM by least squares fit to leave size-independent scale geometry, and (iii) rotated about the centroid to define a consistent coordinate system with LM18–LM6 defining

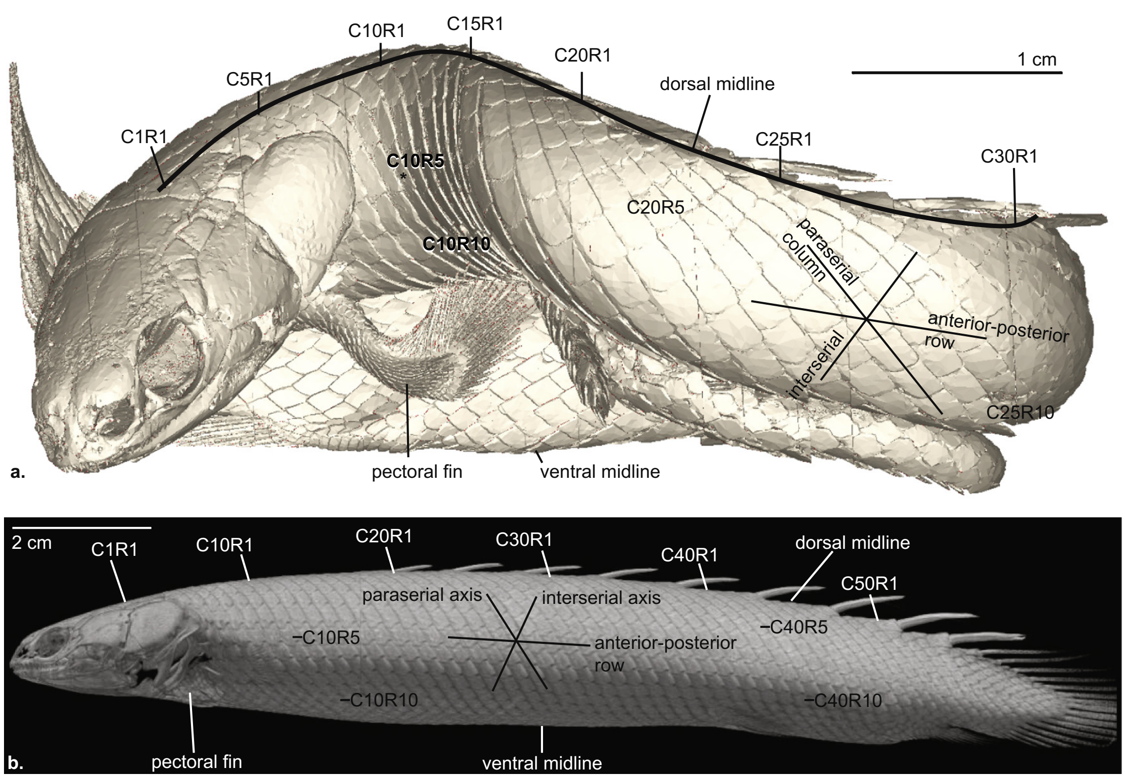

Fig. 1. The *P. senegalus* exoskeleton. (a) μCT reconstruction (18 μm scan resolution) of the *P. senegalus* exoskeleton used in the morphometric analysis, and (b) μCT reconstruction of a *P. senegalus* specimen in a fully extended configuration (95 μm scan resolution), image used with permission from (Humphries, 2003). Images show the paraserial axis of scale articulation (column), the interserial axis of scale overlap, the anterior–posterior row, dorsal and ventral midlines of mirror symmetry, and pectoral fin. Select scales are numbered by column and row number (C#R#). The asterisked scale (C9R5) in (a) is used in Fig. 2.