GEOMETRIC ORIGINS OF TUNABLE, BIOMECHANICAL FLEXIBILITY IN FISH SCALE ARMOUR

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Introduction. The armoured fish *Polypterus senegalus* has an exoskeleton of mineralized, ganoid scales with a unique geometry that balances bite protection, full-body coverage, and flexibility [Bruet et al, 2008; Song et al, 2011; Tytell et al, 2002]. This project investigates the morphometric (shape-based) principles underlying tunable biomechanical performance in the exoskeleton based on hosting surface requirements to develop bio-inspired flexible human body armour.

Methods. Scale units were excised from a deceased *P. senegalus* exoskeleton and scanned by micro-computed X-ray tomography (μCT) (VivaCT40, Scanco Medical AG, Switzerland). Medical imaging software (MIMICS 15.1, Materialise, Belgium) was used to convert the 3D geometric voxels into 3D polygonal meshes and export into stereo-lithography (STL) objects. Custom-written scripts digitally placed twenty landmarks on the STL objects and performed morphometric analysis by (i) translation, (ii) scaling, and (iii) re-orientation in 2D and 3D space [Bookstein, 1991; Dryden, 1999; Zelditch et al, 2004]. Local shape variation was quantified by the virtual deformation of landmark coordinates to reference scales.

Results & Discussion. The spatial variation of geometric features was observed from anterior to posterior, such as the relative peg to scale length ratio (0.27 to 0.13) and the scale length to height aspect ratio (1.2 to 0.7), resulting in an increase in virtual energy along the peg-and-socket axis (0 to 1) and correlated with increased flexibility of the tail for dynamic undulation. From dorsal to ventral, the angle θ between the peg and anterior process increased (23°-33°) alongside broadening of the anterior process and scale curvature, correlated with the inherently curved-yet-mobile hosting surface under the ventral midsection of the fish.

The full morphometric profile informed how heterogeneous armour assemblies utilize variable rigid unit geometries on multiple length scales, articulated arrangements of units, functional joints, and unit-to-unit overlap to provide uniform protection from predatory attacks while maintaining high-speed agility. Specialized units of the exoskeleton, such as the pectoral fin, utilize geometry to effectuate properties such as extreme flexibility.

The scale unit geometry was abstracted, parameterized, and 3D-printed as an assembly on a flexible substrate. The resulting hybrid prototype yielded full body coverage with anisostropic mechanical flexibility across multiple scales, giving insight into using geometry in the design of tailorable flexible body armour systems. Future work seeks to translate design principles from animal biomechanics onto the domain of human physiology using a predictive parametric model that integrates heterogeneous geometry into digitally fabricated prototypes.

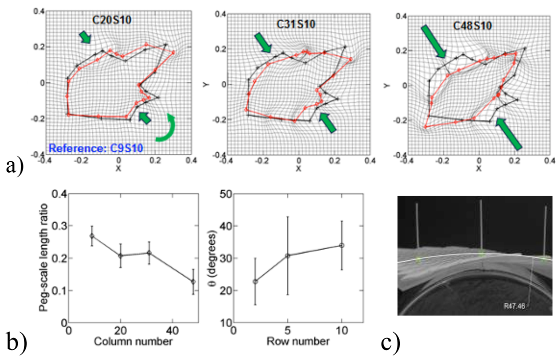

Figure 1: (a) Virtual deformation of three scale geometries (anterior to posterior), (b) reduction of peg-to-scale length ratio (anterior to posterior) and increase in θ (dorsal to ventral), and (c) oblique view of 3-D printed flexible armour prototype.

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