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A novel stress distribution organ in the arthropod exoskeleton

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ABSTRACT

The vertebrate endoskeleton possesses a massive internal network of load-distributing trabeculae that in most locations accounts for the vast majority of bone cross sectional area. In contrast, arthropods rely on the external cuticle and its intermittent outpocketings to distribute the daily stresses of physiological loading. One of the constraints of the arthropod exoskeleton is the necessity to house the musculature involved in locomotion, feeding and etc. Because of this lack of an extensive internal load-distributing trabecular network, any load-distributing mechanism in arthropods would necessarily have to incorporate the exoskeleton. Several authors have identified structural apophysi whose functions presumably have mechanical significance, but few have been identified using quantitative analyses. This study investigates a novel stress-reducing structure arising from the articulation sites in the exoskeleton of the blue crab, *Callinectes sapidus*. During dissection of the merus-carpus joint and leg cuticle of the blue crab, an unique system of internal strut-like members was found radiating, both longitudinally and laterally, from the articular surface of the proximal merus segment, tapering into the diaphyseal region. This strut system, an internal outpocketing of the exoskeleton and semi-circular in cross section, mirrors the trabecular pattern seen radiating from vertebrate joint surfaces. Earlier reports of this structural system described it as a muscle attachment site and made little or no reference to potential load distribution properties. Finite element analysis (FEA) models confirm the efficacy of stress distributing properties of this articular strut system in the blue crab leg. In the models, the struts significantly reduce stress concentrations, reduce localized strains and minimize the risk of failure via buckling. Models lacking this strut system generate 94.7% larger peak von Mises stress at the articulation site, 37% higher peak displacement and 4% greater equivalent strain. The model with the struts is capable of withstanding an applied physiological load of up to 16.6 N prior to buckling, more than twice that of the model without struts (7.8 N). We suggest that this novel arthropod strut system is likely utilized at many joint surfaces at locations of high skeletal stress concentrations, is an adaptation for minimizing skeletal failure via localized buckling, and may be present in other arthropod taxa.

1. Introduction

Relatively high loads are placed on the arthropod skeletal system during movement. Large propulsive forces must be generated in order to locomote in the dense medium of water or when weight bearing on land. These forces are transmitted from one skeletal member to an adjacent member by the joint articulations. Whereas the cuticle at joint articulations is robustly built, the supporting arthropod skeletal segment is a thin-walled structure, highly susceptible to high stresses and strains due to localized loads, and to buckling failure for the case of compressive loads. These relatively high forces are due to a combination of body mass, muscle activity, hydrostatic pressure, and the resulting ground reaction forces. The hard skeletons of organisms are adapted in order to reduce stress concentrations due to high loads and thus avoiding skeletal failure. In vertebrates, trabecular bone a matrix bone with architecture adaptable over the life and loading history of an organism distributes loads throughout the bone cortex, enabling it to withstand the relatively high peak loads resulting from daily physiological loading at joint surfaces (Cullinane and Einhorn, 2002). Arthropods, having an external skeleton, cannot take advantage of such a massive internal mesh of supporting skeletal elements by which they can distribute loads and thereby reduce stresses. Instead, they rely exclusively on the relatively thin cortex of the exoskeleton, albeit with mechanical innovations in layering and alternating orientations of fibers (Gorb, 1997). Thus, is

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there a trabecular bone-like, stress distributing mechanism in the cortex of the blue crab exoskeleton, and can its function be quantified?

1.1. Arthropod anatomy

The exoskeleton of arthropods is structurally different from the vertebrate endoskeleton. The arthropod exoskeleton, or cuticle, covers the outside of the body, functioning as structural reinforcement (Vincent and Wegst, 2004). In addition, musculature in arthropods is internal to the skeleton, creating a space constraint that precludes massive, internal, structural skeletal elements, although some mechanical modifications to the cuticle do exist (Cheng et al., 2008; Vincent and Wegst, 2004). Specifically, the insect exoskeleton is composed of serial layers of chitin-protein microfibrils in alternating orientations, within and between layers (Gorb, 1997). The crustacean model also contains mineral salts that endow the cuticle with added stiffness and density (Chen et al., 2008), as well as architectural features that dissipate impact forces such as those from aquatic predators (Tarsitano et al., 2006). There are obvious differences, based on location, in the physical properties of the exoskeleton of any particular species, but the differences in mechanical properties between anatomical locations are not universally significant (Cribb, 2008). Another practical factor to consider is the hydrostatic pressure within the exoskeleton of the crab. It has been suggested that arthropod body fluid has proteins that are charged and create a hyper-osmotic environment within the shell due to the ions in the surrounding water (Mangum and Johansen, 1975). This hyper-osmotic condition could create added pressure within the exoskeleton of the arthropod, increasing the skeletal rigidity and creating an additional stiffening effect.

The purpose of this study was to explore the possibility that an unique and effective stress-reducing organ exists in the exoskeleton of the blue crab, and to quantify the efficacy of that organ. A system of strut-like exoskeletal outcroppings or inner surface trabeculae has been found to radiate from the articular surfaces of joints in the leg of the blue crab. In an effort to explore the load-bearing properties of the arthropod joint and this proposed stress-reducing system of struts, the legs of the blue crab, *Callinectes sapidus*, were investigated through dissection and the construction of finite element analysis (FEA) models. The specific aim of this research was to determine whether the strut system in the merus-carpus joint could potentially minimize stress concentrations, reduce localized strains, and reduce the possibility of local failure via bucking of the exoskeleton when acted upon by compressive loads.

1.2. Finite element analysis

FEA is a numerical method used to solve the equilibrium equations that govern the physical behavior of a system based on its geometry, material properties, kinematic constraints, and loading environment. For structural analysis problems FEA is used to quantify the deformation and distribution of stresses and strains of load-bearing objects. The development of a finite element model involves the discretization of the geometry of the system into a contiguous mesh of small, but finite sized elements connected together at common vertices called nodes. The results of the analysis are an approximate deformation of the structure and an approximate but complete state of strain and stress throughout the structure. Properly constructed finite element models will converge to the theoretically exact solutions admitted by the theory of elasticity as the finite element mesh is refined. Another powerful feature of FEA is the fact that every finite element may have different material properties, loading conditions, and geometry. Thus, using FEA, one can model and simulate the behavior of geometrically complex anatomical structures with complex loading conditions and non-homogenous material properties. Geometrically complex anatomical structures are often digitally reconstructed models from computer tomography (CT) scans or idealized using simpler geometries. With FEA, one can create a virtual object, alter the architecture of the object to create comparative models, apply various loads, and map out the resulting stresses and strains. The specific aim of this study was to determine if the internal strut system with the blue crab merus segment could theoretically reduce stress concentration and strain, and thus reduce the likelihood of structural failure via buckling.

2. Materials and methods

Walking legs of the blue crab were carefully dissected from the carapace (Fig. 1). Each leg was cut to isolate the merus-carpus joint, and the joint was disarticulated by gently teasing apart the segments. Longitudinal, sagittal cuts were made on the merus segment and the internal tissues and muscles were carefully extracted. The segments were photographed under a dissecting microscope at 40X. The thickness, width and length of the segments and struts used for creating the finite element models were measured manually using a micrometer and calipers.

2.1. Finite element analysis

A geometry model of the leg segment was created in ANSYS Workbench 11.0 *Design Modeler* (Fig. 2). To simplify the modeling process, the medial and lateral struts were considered to be identical, enabling two perpendicular planes of symmetry containing the *z*-axis (i.e. the longitudinal direction of the leg) to be established. A solid model of one fourth of the leg section, one half of an articulation, one half of the center strut and one of the anterior/posterior struts was then created. This solid was then mirrored about the two planes of symmetry to create the full model. To

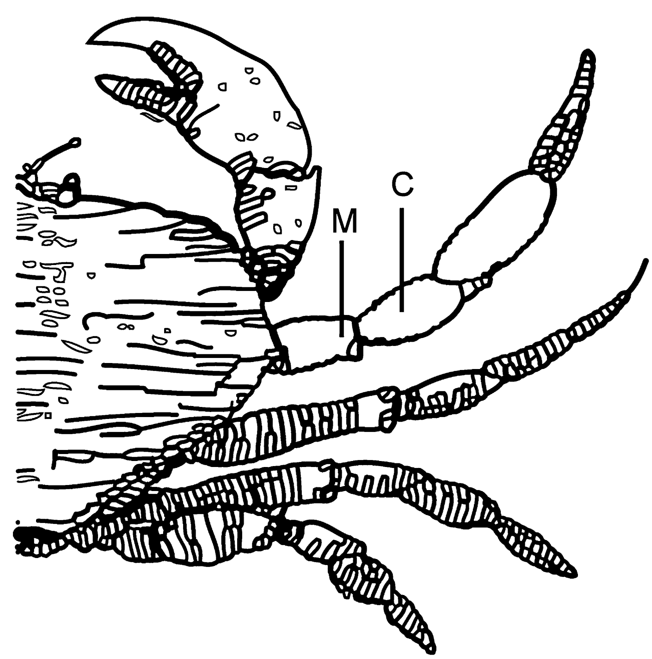

Fig. 1. The merus(M)-carpus(C) joint in the blue crab. The walking legs bear the load of body mass and force generation during terrestrial locomotion, as well as resistance to movement in the high density medium of water. Loads and stresses must be channeled through the articulation sites between joint segments, raising the likelihood of element failure due to structural buckling.