Acta Biomaterialia 44 (2016) 41–50

Contents lists available at ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat

Full length article

Horn and horn core trabecular bone of bighorn sheep rams absorbs impact energy and reduces brain cavity accelerations during high impact ramming of the skull

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ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form 20 June 2016
Accepted 16 August 2016
Available online 17 August 2016

Keywords:
Horn
Trabecular bone
Impact
Concussion
Bioinspired materials

ABSTRACT

Bighorn sheep (*Ovis canadensis*) routinely experience violent impacts to the head as part of intraspecific fighting. Dynamic 3D finite element models of the skull and horns of a male bighorn sheep were developed to gain an understanding of the roles that the horn and bone materials and structure play in absorbing the impact that occurs during ramming. The geometry and volume mesh of the model were derived from CT scan images. The models included the horn, bony horn core, and bone of the skull. The horn core fills a portion of the hollow horn and consists of a thin cortical bone shell filled with foam-like trabecular bone. Two modified models were also created: one with the distal half of the horn length removed to assess the effects of the tapered spiral geometry of the horn, and one with the internal trabecular bone material of the horn core removed. The trabecular bone material stored three times more strain energy during impact than the horn material in the intact model. Removing half of the horn length had the effect of increasing translational accelerations in the brain cavity by 49%. Removing the trabecular bone in the horn core resulted in a 442% increase in rotational accelerations within the brain cavity. These findings support the investigation of novel bioinspired materials and designs that could be used in mitigating brain injuries and in other applications involving high-impact collisions.

Statement of Significance

Bighorn sheep routinely experience violent impacts to the head and horns without apparent negative consequences to the brain or horns. A portion of the horn is filled with a thin cortical bone shell containing foam-like trabecular bone. We developed novel dynamic finite element models of the skull and horns of bighorn sheep to gain an understanding of the roles that the horn and bone materials play in absorbing the impact that occurs during ramming. The study revealed that both horn and bone materials and the structures made from these materials (i.e., tapered spiral horns and foam-like trabecular bone struts) are important for absorbing impact energy and reducing brain cavity accelerations.

1. Introduction

The skulls and horns of male bighorn sheep (*Ovis canadensis*) undergo massive impact loads during ramming, suggesting their structure and material constituents have been evolutionarily adapted to sustain very large dynamic forces while preventing catastrophic failure and brain injury. In contrast, human head impacts often result in traumatic brain injury in the form of concussions, which are caused by translational or rotational accelerations of the skull [1–3]. The horn of a bighorn sheep consists of a large, hollow curled structure (Fig. 1a) composed primarily of the protein keratin; its shape can be generalized as a tapered spiral [4–6]. Within the hollow horn is a short bony horn core, consisting of a thin solid layer of cortical (compact) bone filled with trabecular bone in the form of large bony plates (Fig. 1b).

Bighorn sheep horns are not shed and regrown annually and thus cannot rapidly heal damage. Therefore, they must sustain

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http://dx.doi.org/10.1016/j.actbio.2016.08.019
1742-7061/

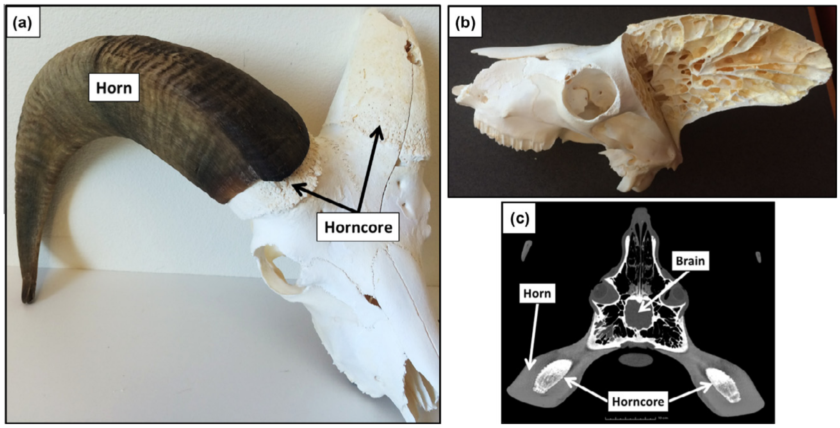

Fig. 1. a) Horn and horn core spatial arrangement b) Horn core longitudinal-section showing the architecture of the bony plates that comprise the foam-like trabecular bone inside the thin cortical shell c) Example CT scan transverse cranial slice which is roughly the region identified by the arrows in a) (white regions are bone, lighter grey regions are less dense materials i.e. horn, brain, etc).

the repetitive high impact loads and harsh environments experienced throughout the animal's lifetime without mechanical failure. Keratin-based hard materials, such as horn, are much tougher [4,5,7–9] than mineralized hard biological materials like bone [10]. Bovid horns are highly resistant to fracture, displaying a large work to failure and are also very insensitive to notches [11]. Bone is stiffer and stronger than keratin materials in non-impact loading situations; however, bone is less fracture resistant [12] and has properties that are highly dependent on strain-rate and load state [13–15]. However, unlike horn, bone material is capable of repairing mechanical damage from fatigue and traumatic events [15].

Head-to-head ramming during intraspecific fighting is an important social event for male bighorn sheep and is a means of determining hierarchy and gaining mating privileges. Rams may ritualistically butt heads for up to several hours until the subdominant male concedes [16]. These findings have lead researchers to study the horn and skull material and structure in regards to energy dissipation, storage, and redirection with implications for understanding brain trauma prevention. The tapered spiral horn geometry reduces impulsive loads more effectively than other simple geometries, such as a cylindrical or tapered bar [6]. Furthermore, the frontal sinus and foam-like bone architecture present in the horn core of bighorn sheep stores substantial strain energy under simulated quasi-static loading [17]. Woodpecker beaks and skulls are another keratin/bone complex that undergoes impact loading during pecking, and key structural constituents, such as the hyoid bone have been shown to contribute to energy dissipation during impact [18]. The dynamic response of the bighorn sheep bone and horn has not been investigated either computationally or experimentally when subjected to impact loading. Therefore, we hypothesized that both the material combination and the geometric configuration of the bighorn sheep horn/bone complex minimizes mechanical failure due to the impact loading that occurs during ramming. We also hypothesized that factors that may cause brain trauma (e.g., brain cavity translational acceleration) in bighorn sheep are reduced by key geometric features, i.e. the tapered spiral horn and the horn core trabecular bone. To explore these hypotheses, dynamic finite element models were developed that simulate ramming in bighorn sheep.

2. Methods

2.1. Model development

A mature male bighorn sheep's skull and horns, provided by The Colorado Division of Parks and Wildlife, were used to develop the geometry for finite element modeling. X-ray computed tomography (CT) transverse cranial slices of the skull and horn were obtained with an interslice spacing of 1 mm and produced a stack of 737 images with an in-plane resolution of 0.9 mm (Fig. 1c) using a Gemini Time-of-Flight Big Bore PET/16 slice CT (Philips Healthcare, Andover, MA). Scanning voltage and current were 140 kV and 321 mA, respectively. When factoring in pitch and rotation time the exposure delivered was 350 mAs and the built in "Sharp" filter was utilized. Upon visual inspection, it was apparent that this resolution was adequate to capture the intricate geometry of the horns and skull, including the bone struts and plates making up the horn core's internal trabecular architecture.

The stack of images was imported into 3D Slicer, an open source medical image analysis and visualization software platform, which was used to define the horn and bone regions and to produce 3D surface models for volume mesh generation (Fig. 2). A threshold segmentation tool was used to define horn and bone materials within the model given their differing densities. As bone density is much greater than keratin, the trabecular structure was easily identified in comparison to the horns, as all bone within the scans was of similar brightness. Three-dimensional surface models composed of connected triangles (facets) were generated that enclosed the horn and bone material regions. Two separate surface models were created for the horn and bone material regions. The surfaces were smoothed to remove any unnecessarily sharp features and to simplify volume meshing. This method of scanning biological tissues using CT is a common approach and has been widely used to develop finite element models of bone and keratin [19–25].

ICEM CFD mesh generation software (a product of ANSYS, Inc.) was used to compute volume meshes because of its ability to efficiently mesh large, complex models from dirty CAD or faceted geometries. Volume meshing of the horn and skull was done independently, and the meshes were later reassembled in the finite element analysis software. Only the right half of the skull and the right horn were meshed, taking advantage of the symmetry of the ram's head geometry in order to reduce computational cost and model complexity. A sagittal plane was created that bisected the skull geometry, which served as the plane of symmetry. A build domestic topology feature, which defines sharp features with curves and points, was implemented in conjunction with a curvature/proximity based refinement algorithm to adequately mesh the intricate foam-like bone architecture. A tetrahedral mesh was produced for both the half skull and horn geometries. The half skull mesh consisted of 1,027,874 elements and 253,807 nodes and the horn mesh consisted of 261,788 elements and 62,586 nodes.