Effects of structural gradient characteristics of yak horn on its mechanical properties

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Abstract. The yak horn analysis model is created based on the measurement and analysis of the macroscopic structural characteristics of yak horn. Then, the influences of the conical structure on the stress and strain distribution of the yak horn are analyzed using finite element method. The measurement results show that the macroscopic structure along the axial direction of the yak horn has a gradient distribution, and the steepness of the conical structure is about 42. The analysis results show that the steepness of the conical structure of the yak horn affects the distribution of stress and strain. When the yak horn model with the steepness of 42 is subjected to external load, its stress distribution is more uniform, which can effectively improve the strength and toughness of the horn. The above analysis results show that the excellent mechanical properties of yak horn are closely related to its structural gradient, and the steepness of 42 is a long-term natural optimization result, which is beneficial to structural bionic design.

1. Introduction
The geometric configuration of bovid horn is irregular curved cones, and its cross section decreases from bottom to top. Bovid horn has high strength, stiffness and toughness to prevent breakage [1,2]. The comprehension in the macro-structural characteristics and mechanical properties of bovid horns are helpful for gaining a deeper understanding of their natural design and adaptation of their structures and functions [3].

The horn is well known as the most powerful weapon of attack and defense during intraspecific combat [1,4]. These weapons have diverse forms and shapes arising over millions of years of evolution [5]. During fighting, the horns may bear large, impact and repeated loads. For example, the maximum force acting on the horns of a bighorn sheep during fighting is estimated to be as high as 3400 N [2], while the force needed to push a bull away in fighting can reach up to 2500 N [6]. The excellent mechanical properties of horn are related with its hierarchical structure [7]. At the macro scale, the horn of bovid animals mainly consists of two parts, a bony core and a keratinous horn sheath [8]. The bony core with marrow is vascularized, porous and highly mineralized, and it is similar to the endoskeleton of vertebrates [9]. The horn sheath from a cattle horn is mainly composed of hard keratin and it has a layered structure in which the laminae take a rippled tabular shape [10]. At the micro scale,
the fundamental material component of horns is \( \alpha \)-keratin, a structural protein synthesized by keratinocytes \([11,12]\). Keratin is one of the most common biopolymers found in nature \([13]\), showing remarkable mechanical efficiency because of its relatively high fracture toughness and Young’s modulus, and the keratin is much lighter than other highly mineralized biological materials, such as bone and teeth \([14,15]\).

To date, the researches about horns are mainly focus on the mechanical experiments and microstructure analysis of the horns, but there is a lack of research on the effects of the structural gradient of the horn on its mechanical properties. In the present paper, therefore, we mainly investigate the effects of macroscopic structural characteristics of yak horn on its mechanical properties. Firstly, the finite element method is used to analyze the stress and strain distribution of the yak horn model when subjected to the frontal load, and the analysis results are compared with the real structure of the yak horn to investigate the mechanism of the horns with excellent mechanical properties, which can provides useful guidance for structural bionic design.

2. Materials and methods

2.1. Structure characteristics of yak horn

The horn is mainly used to protect itself from external loads during attack and defense \([8]\). When two cattle collide with each other, a complete horn can withstand an external impact load of approximately 7.6kN \([16]\). Therefore, horn is a kind of tubular biomaterial with good mechanical properties in nature. However, due to the difference of species, growth environment and age etc, the mechanical properties of different kinds of horns may obvious different. In this paper, for investigating the influence structural gradient of the horn on its mechanical properties, the adult yak horn is selected as the research object, and its macroscopic structure is shown in Figure 1. First, the horn is sawn into two symmetrical parts along its longitudinal direction using a low-speed water-cooled diamond saw. After that, the structural characteristics and wall thickness distribution of the yak horn are observed and measured. According to the measured data, a finite element model is established to investigate the effect of the structural parameters of the yak horn on its biological and mechanical properties. Finally, the calculation results are compared with the real structure of the yak horn to investigate the mechanism of the horns with excellent mechanical properties.

![Figure 1 Macroscopic structure of yak horn](image)

2.2. Conical structure model of yak horn

The yak horn is cut symmetrically and one of the symmetrical yak horns as shown in Figure 2. The analytical model of 1:1 is established based on the measured data, as shown in Figure 3. The arc curve in the Figure 2 is the axis of the horn and its radius is \( R = 210 \text{mm} \). The curvature of the center curve of the model is \( 1/R \) and the continuous angle is \( 0^\circ \sim 75^\circ \). Although the thickness of the yak horn is not
uniform, the variation of yak horn's wall thickness is much smaller than the overall size of horn, so in the analysis model, the thickness of the yak is considered as \( h = 5 \text{mm} \). The internal radius of the horn model is \( r(\theta) \) (\( r \) varies linearly with the angle change). Therefore, the yak horn can be regarded as a curved conical structure extending the circular arc of 75°. Because the structural characteristics of yak horn is similar to that of spider fang [17], the horn-like model can be described as: \( r(\theta)=a(\theta/75)+a_0 \), where, \( a_0 \) represents the geometry at the tip (\( \theta = 0^\circ \)) and \( a \) represents the steepness of the conical structure, that is, the structural gradient of the horn. In the fighting and defense of bovine, the load on the horn is mainly frontal collision. Therefore, this paper only studies the effect of two components in the \( x-y \) plane on the horn (Figure 2).

When the steepness of conical structure is different (Figure 3), the stress and strain distribution of the horn model under the same frontal loads are compared and analyzed, and the analysis results are compared with the actual structural parameters of the yak horn, to investigate the effects of the structural characteristics of the yak horn on its stress distribution, strength and toughness.

3. Results

The measurement results show that the macroscopic structure along the longitudinal direction of the yak horn has a gradient distribution, and the steepness of the conical structure is about 42. Four horn models with different steepness are established (\( a = 0, 24, 42 \) and 72) for investigating the effects of the steepness of horn conical structure on the stress distribution. The tip radius of models \( r_0 = 6 \text{mm} \), with uniform wall thickness \( h = 5 \text{mm} \) (the radius of the small hole at the tip is 1mm), and other model parameters are the same as in Figure 2. It is assumed that the yak horn is isotropic material, elastic modulus is 1000MPa and Poisson's ratio is 0.3. Then the established models are qualitatively compared and analyzed in Abaqus 6.13. The analysis results of the stress and strain distribution of the four different models are shown in Figure 4.

Figure 4 (a), (c), (e), (g) are von-Mises stress distribution maps of four different horn models. The results show that as the steepness of the structure increases, the maximum stress is decreased correspondingly, and the maximum stress value of the thin tube model without steepness is much larger than that of the other three models. In addition, the maximum stress point will change regularly from the bottom to the tip of the model as the slope increases.

Figures 4 (b), (d), (f) and (h) are strain distribution maps of four different steepness horn models and the morphological comparison before and after deformation. The results show that as the steepness increases, the strain area gradually shrinks to the tip end. At the same time, as the steepness of the model increases, the maximum strain decreases accordingly. In the model with a steepness of 72, the strain is almost concentrated on the tip and the remaining regions is 0 (Fig. 4 (h)).
Based on the above calculation results, it can be seen that when the steepness of the model is too small, it is easy to generate a large stress concentration, resulting in poor structural strength and toughness. However, in the model with a large steepness, the stress and strain are all concentrated at the tip end (Figure 4(g)). As a result, material waste and structural bulk are too large, which is not conducive to lightweight design of the structure. From Figure 4(c)-(f) can be seen, the stress and strain distributions in the models with steepness of 24 and 42 are relatively uniform and reasonable. And the maximum stress is reduced by 39.4% compared to the thin tubular model. When subjected to external loads, the stress distribution is more uniform, thereby the strength and toughness of the horn can be

Figure 4 Von-Mises stress and strain distribution maps of four different steepness horn models under the same load. (a), (c), (e), (g) are von-Mises stress distribution maps; (b), (d), (f) and (h) are strain distribution maps.
improved effectively. The curved conical structure of the yak horn with a steepness of 42 is the result of natural evolution, and its structural shape and reasonable steepness make it has excellent mechanical properties.

4. Conclusions
Based on the measurement and analysis of the yak horn, a curved conical model of the yak horn is built, and the effects of the macroscopic structural gradient of the yak horn on its stress and strain distribution are investigated. The following main conclusions are obtained:

1) Along the axial direction of the horn, there is a gradient from the tip to the bottom, and the steepness of the conical structure is about 42;

2) The steepness of the conical structure of the yak horn affects the distribution of stress and strain. The curved cone structure with a steepness of 42 has more uniform stress and strain distribution when subjected to external loads, which can effectively improve the strength and toughness of the horn.

3) The excellent mechanical properties of yak horn are closely related to its structural gradient, and the steepness of 42 is a long-term natural selection and optimization result, which is benefit to structural bionic design.

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