Bionic design and anti-slip characteristics study of quadruped robot foot

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Abstract. Quadruped robot has been widely used in the field of national defense because of its high adaptability. The stability and balance capacity is the important performances needed during the quadruped robot moving under uneven terrains, and the slip resistance of the foot affects the balance performance of robot. As the goat hoof with irregular surface morphology adapts to rugged terrain, its plantar geometric shape was reconstructed using reverse engineering technology based on the point clouds which were obtained by using a 3D hand laser scanner. The bionic foot was designed based on goat hoof plantar surface, and the anti-slip characteristics were analyzed by finite element method, and then compared with the spherical foot and cylindrical foot. The frictions between these feet and soils or rocks at different pressures were investigated, and the result shows that the maximum static frictions between bionic and soil and rock are greater than that of the two others, which means bionic foot has better anti-slip performance.

1. Introduction

The foot structure is one of the important factors affecting quadruped robot’s walking performance [1-5]. Feet mainly function as cushion and support and show unique functions and characteristics during the activities of robots that need to adapt to different types of ground. The most important thing is that the anti-slip performance is largely determined by the foot structure, which plays a decisive role in the stable walking of the robot [6-10].

There are many ways for the foot to contact the ground, which results in many different mechanical properties [11-15]. Animals walk on the ground with different rules, Zhen D et al. studied the contact mechanics of locusts and other animals and found that the friction generated by their feet has clear anisotropy and self-locking characteristics [16]. Wang Z et al. designed an experiment to measure the force on each foot of a gecko climbing a 0 ° to 180 ° slope and recorded the foot contact status. The results show that Gecko's superb climbing ability is achieved through cooperation between multiple contact mechanisms [17].
Some animals have excellent anti-slip properties after a long evolution, it is meaningful to study and apply them to engineering [18-22]. Zhang R et al. based on Reverse Engineering technology, applied the characteristic structure of reindeer feet to the design of tread element structure, which could effectively improve the passing performance of tires on ice [23]. Researchers at Stanford University were inspired by the soles of geckos. They adhered millions of extremely fine artificial hairs to the soles of gecko-like robots, which greatly enhanced the friction between the feet and the ground [24].

Goats inhabit high-altitude areas with bare rocks all year round and have good anti-slip ability on smooth rocks [25]. Goat's hooves are divided into two parts, the special structural form with an oblique and concave in the middle, which plays the role of soil fixation. It can also hold the rock firmly during the climbing process to provide support and balance for the body. The adaptability of goats to various rugged terrain, especially smooth rocks, is closely related to the characteristics of foot structure. Therefore, a 3D model of goat's hoof was constructed based on reverse engineering technology, and the anti-slip ability of goat's hoof on rugged terrain was investigated by finite element analysis of the 3D model.

2. Materials and methods
In total, 1 adult and healthy white male goat without lameness was bought from a farmer in the suburb area of Changchun. The goat's forepaw contributes more bodyweight than the hind hoof and plays a major braking role (friction with the ground). Therefore, the goats’ left forepaw was selected for research. Use pure water to remove the dirt on the surface of the goat's hoof, and then use acetone and absolute ethanol to remove oil and other pollutants, finally wash it in an ultrasonic shaker for 20 minutes to remove the surface impurities. The treated goat hoof is shown in figure 1.

![Goat hoof](image1)

Figure 1. Goat left forefoot.

The scanning accuracy of the 3D scanner was set to 0.02mm, via launch and receive laser beam towards the surface of a goat's hoof, which on a table with mark points. Then calculates the 3D coordinates of the points on the surface of the hoof and records information such as reflectance and texture, which is converted into point cloud data to construct a point cloud model (figure 2).
Because the shape of the goat's hoof surface is not smooth, the laser beam cannot be reached in some areas, resulting in many irregular pits distributed on the surface of the point cloud model. Therefore, fix point cloud model in Geomagic Studio software to build the ideal goat foot model, hereinafter referred to as bionic foot. (figure 3).

3. FEM result and analysis

3.1. Calculation model of foot-ground interaction

Use FEM software ABAQUS to perform a finite element analysis to find the maximum static friction between bionic foot (foot A) and normal foot and soil and rocky ground under 50N, 100N, and 150N pressure. Spherical foot (foot B) and cylindrical foot (foot C) were selected as the normal foot. Through applying vertical pressure and horizontal tension to the three feet, the walking or running of goats was simulated as well as the process of feet contacting the ground. At the beginning, the foot and the ground remain stationary due to friction, and the foot starts to slide during the increase in tension. At this time, the value of the tension is the maximum friction between the foot and the ground. Abaqus / Explicit display analysis module was used to perform finite element simulation analysis of different foot and ground sliding processes.

The goat's hoof 3D model was saved in IGESG format and imported into ABAQUS (figure 4 (a)).
The foot B (figure 4 (b)), foot C (figure 4 (c)) and ground model (figure 4 (d)) were built and ground on ABAQUS. The ground model was a cuboid, and the length, width, and height were 700mm, 300mm, and 30mm.

Figure 4. Feet and ground model (a) bionic foot (foot A), (b) spherical foot (foot B), (c) cylindrical foot (foot C), (d) ground model.

Assembling foot and ground models with ABAQUS (Figure 5).

Figure 5. Model assembly (a) model A, (b) model B, (c) model C.
The interaction between the foot and the ground is similar to that of the tire and the ground, so the material used for the foot in the finite element simulation analysis is the hard rubber commonly used in tires. The properties of hard rubber materials are shown in table 1.

| materials   | $C_{10}$ (MPa) | $C_{01}$ (MPa) | Poisson's ratio | density $(1\text{e-9} \text{t/mm}^3)$ |
|-------------|----------------|----------------|-----------------|---------------------------------|
| Hard rubber | 0.5792         | 0.1448         | 0.5             | 1.112                           |

The ground uses the Mohr-Coulomb model. The specific material properties of soil and rock are shown in tables 2 and 3.

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Volume density $(\text{mg} \cdot \text{m}^{-3})$ | 1.79  |
| Young's modulus/MPa                           | 1.14  |
| Poisson's ratio                               | 0.3   |
| Friction angle $(^\circ)$                     | 12.21 |
| Stress ratio                                  | 1     |
| Dilation angle $(^\circ)$                     | 0     |
| Moisture content/%                            | 20.03 |

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Volume density $(\text{kg} \cdot \text{m}^{-3})$ | 2720  |
| Young's modulus/MPa                           | 75000 |
| Poisson's ratio                               | 0.3   |
| Friction angle $(^\circ)$                     | 51.8  |
| $c$/Mpa                                       | 29.5  |
| Dilation angle $(^\circ)$                     | 0     |

Contact properties set to Tangential Behavior with Mechanical options. Soil and rocky ground friction coefficients set to 0.25 and 0.4, respectively. Set the interaction order of the model, select the upper surface of the ground as the first surface, and select the lower surface of the foot that is in contact with the ground as the secondary surface. The load parameters are set in three steps. The first step is to set the vertical pressure to 1N to establish a stable contact between the foot and the ground.
The second step is to modify the vertical pressure to 50N, 100N, and 150N. The third step is to apply a linearly increasing tensile force to the foot to simulate the sliding of the foot on the ground under different pressures. After setting the parameters, it needs to mesh the model before performing the finite element analysis. Because foot B (Figure 6 (b)) and C (Figure 6 (c)) are regular geometric models, the mesh can be directly divided after determining the appropriate mesh density. Foot A (Figure 6 (a)) shape is irregular, needs to be manually meshed.

![Figure 6. Divide grid (a) foot A, (b) foot B, (c) foot C.](image)

### 3.2. FEM Result and Analysis

#### 3.2.1. Foot-to-ground contact stress. The process of the foot contacting the ground and slide was simulated on ABAQUS. First, get the stress cloud diagram of the three feet and the ground. Select the stress cloud diagram of the interaction between the feet and the soil ground under the pressure of 150N. This is because the rocky ground is relatively hard, and the deformation is minimal during the simulation. Selecting the soil ground can observe clear foot contact marks. As shown in Figure 7, all three kinds of feet have obvious stress concentration positions. The stress concentration positions of foot B and C are in the middle part, while the stress concentration position of foot A is at the rear end of the foot. This is because the goat's forepaw is mainly supported by the heel when it is supporting. The front part of the hoof helps the goat to walk stably on rugged terrain. Almost all hoofed animals have this characteristic, which is the result of a long evolution. It can be seen that the goat's heel load capacity is stronger, so the stress concentration part of the bionic foot in the simulation is on the heel, which also verifies that the bionic foot is more suitable for robot walking than the normal foot.

![Figure 7. Soil ground stress cloud (a) foot A, (b) foot B, (c) foot C.](image)
3.2.2 Foot friction on the ground. During the motion of a goat, the friction when the hooves contact the ground is one of the important indices to measure the anti-slip ability of foot. As shown on the start of sliding time (Figure 8), the normal foot started to slide about the same time, while the bionic foot significantly later. The maximum static friction of the bionic foot is significantly larger than that of the normal foot. When the pressure is 50N, the maximum static friction force of foot C is significantly larger than the maximum static friction force of foot B. This is because the rubber cannot be fully compressed under low pressure, so the highest point of foot B is similar to the ground in point-to-surface contact. As the vertical pressure on the feet rose from 50 to 150 N, the ratio of maximum static friction from the bionic foot to the normal foot declined from 1.36 to 1.27, and the changing rate decreased (Figure 8). This is because the soil ground is relatively soft, as the pressure increases, the deeper the feet sinks into the ground, it largely prevents the feet from sliding, resulting in a significant increase in the maximum static friction of the three feet, and the maximum static friction force does not comply with the formula for $F_f = \mu F_p$. Generally, the start time of the bionic foot sliding under three pressures is later than the other two feet, and the maximum static friction force is also larger, which indicates that the bionic foot has better anti-slip ability than the normal foot when it comes into contact with the soil ground.

![Figure 8. Friction between foot end and soil ground](image)

(a) pressure of 50N, (b) pressure of 100N, (c) pressure of 150N.
When the vertical pressure is 50N, the displacements of the foot A and B were nearly the same, but as the pressure increases, the difference of the maximum static friction between the two feet gradually increases (Figure 9). The bionic foot's sliding start time is still later than the normal foot. In general, bionic foot still have a better anti-slip performance on the rocky ground than normal feet.

![Friction between the foot and rock ground](image)

Figure 9. Friction between the foot and rock ground (a) pressure of 50N, (b) pressure of 100N, (c) pressure of 150N.

4. Conclusion
Goats rely on the anti-slip ability of their feet for stable walking on rugged terrain. Based on the point clouds which were obtained by using a 3D hand laser scanner to build a 3D model, comparative analysis of the anti-slip performance of bionic and normal feet using ABAQUS. The result is as follows,

1. The stress concentration of spherical and cylindrical feet in the experiment was in the middle of the foot, while the stress concentration of the bionic foot was at the rear of the foot. This is because the hoofed animals are mainly supported by the heel, indicating that the bionic foot has biologically excellent characteristics.

2. When the foot is in contact with the soil ground, the maximum static friction of the bionic foot under different pressures is 15N, 26N and 40N, the spherical foot is 10N, 24N and 35N, and the cylindrical foot is 12N, 24N and 32N. The maximum static friction of the bionic foot under different
pressures is the largest, indicating that the bionic foot has the best anti-slip ability on the soil ground.

3. When the foot is in contact with the rocky ground, the maximum static friction of the bionic foot under different pressures is 18N, 40N and 60N, the spherical foot is 17N, 35N and 55N, and the cylindrical foot is 12N, 24N and 40N. The maximum static friction of the bionic foot under different pressures is the largest, indicating that the bionic foot has the best anti-slip ability on the rocky ground.

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