Research on Kinematics and Biomechanics of the Bionic Mechanism

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Abstract. The kinematics model was constructed for musculoskeletal system of a kind of a small feline by using the coordinate transformation method based on the anatomical data, and the typical motions are marked with a series of mechanism figure during the feline running with a high speed, and the marked data could provide a support for the biomechanics model calculating of this small feline animal; Finally, the simulation experiment for the whole model of the constructed musculoskeletal system has been done, and the variable torque and the muscle force are solved by using the muscular force calculating method. All the work done in this paper is useful for the kinematics study of the bionic mechanism.

1. Preface

The mobile mechanism of bionic robots are usually constructed based on the bionics principle imitating animals’ motion parts of the body or motion model during walking or running, etc.

While, for achieving a high-speed movement ability of the bionic robot, developing the robot with a good bionic ability by using the biomechanical properties of animals has become the study focus for many researchers.

For example, Literature [1] presented a lizard bionic mechanism based on the quadruped robot walking patterns, which was a kind of morphological bionics, Literature [2] studied the turning motion characteristics of a hexapod bionic mechanism walking in the static stable movement, which was a kind of behavior bionics; Literature [3] studied force distribution of a eight-legged bionic mechanism moving in the dynamic steady state, which was also a kind of behavior bionics design; the robotics laboratory at the Massachusetts institute of technology developed a leopard robot, the running speed of which can reach 22 km/h, and the energy utilization efficiency (COT) was as high as 52% [4], this included both the morphological bionics and the behavior bionics design, which was the study focus in recent years.

The study of legged bionic mechanism is essential for the motion ability of bionic mobile robot. While, with the increase of the motion ability of bionic mechanism, the mechanical properties of its legs also gradually becomes the focus of the attention of the related scholars. For example, literature [5] depicted the motion performance of quadraped bionic mechanism from structure and motion characteristics, which was the study trends in the future work of the bionic mechanism design.

Therefore, based on the consideration of bionics, mechanisms, we constructed the musculoskeletal system of a small feline, using the calibrated joint motion law to calculate the muscle force of major muscle groups of fore and hind limbs, and finally obtaining the muscle force and the joint torque. Finally, we gave the conclusion at the end of the paper.
2. Musculo-skeletal system model

In this study, a small feline was obtained according to laboratory animal welfare laws. The small feline had died of natural causes, and its body was kept at 0°C for less than two weeks.

In order to obtain accurate biomechanical data in the process of the animal’s movement, a mathematical model for the skeletal muscle system of the feline was constructed, according to the original anatomic data acquired from the anatomy experiment doing by us. The measurement showed as follows, the torso length was 280mm, shoulder breadth was 60/70mm, body weight was 1.4KG. And other body features of the limbs are shown in Table 1:

| Table 1. The body features of the small feline |
|-----------------------------------------------|
| length/mm | mass/g | Section diameter/mm |
|----------|--------|---------------------|
| Scapula  | 44     | 2                   | --               |
| Humerus  | 69     | 4                   | 6.8              |
| Radius   | 58     | 3                   | 4                |
| Ulna     | 70     | 4                   | 4.5              |
| Metacarpus | 22   | 3                   | 3.1              |
| Femur    | 80     | 5                   | 6.9              |
| Tibia    | 82     | 6                   | 6                |
| Fibula   | 77     | 0.5                 | 2.5              |
| Metatarsal | 35  | 8                   | 3                |

The reference position of the length was joint center of the bone, the mass was got by the bone immersed in saline more than 3 hours, and the bone marrow is removed. The diameter of the cross section is measured as the mean value of the measured diameter along the length of the bone.

After the measurement of biologic parameters on the bone, the muscle distribution of the small feline were also analyzed and calibrated. By means of dissection, it was found that there were more muscle group distributing along the feline’s limbs and other moving parts of the body. And different muscle group had different action to the bone and joint movement, so the muscle groups were distributed between various joints and bones, even correlate the motions of different bones and joints.

For the distribution of the muscle group as mentioned above, the bones and joints of the feline could be driven to move flexibly, and transfer the concertina movement of the muscle to the rotational movement around the joint of the bones. By using muscle distribution data that the position for tendon attaching to the bone of the small feline, the skeletal muscle system could be built as shown in the following Fig. 1.

![Fig 1. Musculo-skeletal system model](image-url)
In Fig.1, the connection between the bone and the joint of the feline was simplified. Considering the different functional classifications of the limbs and the convenient method for analyzing and researching of the motion, the skeletal system was simplified, metacarpus and phalange of forelimbs were simplified to metacarpus, radius and ulna of forelimb was simplified to radius, tarsus, metatarsal and phalanx bones of posterior limbs were simplified to metatarsal bones, tibia and fibula were simplified to tibia as shown in Fig. 1.

The musculoskeletal system shown in Fig.1 established by using the method of coordinate transformation in kinematics, i.e, DH rule is utilized to construct the Kinematic equation of musculoskeletal system for forelimb and posterior limb.

When the feline moving in a fast speed, the bone and joint of each limb took some certain rules with a cyclic variation. As the method shown in Fig. 1, skeletal mechanism of the feline had been simplified, and the simplified bionic mechanism of the feline were measured and confirmed based on the photographed motion rule for running, and motion variation rules of main joints were shown in Fig. 2.

Fig 2. Running sequence of the feline

In Fig. 2, the variation rule of each joint move along the movement surface was calibrated through 30 groups’ data, the data of each joint was fitted with NINE-order polynomial as shown in Fig. 2.

3. Solution for the muscle force

During the motion, each joint of the feline rotates with a periodic movement in its own rules, muscle force and muscle line length were also changed with a periodic motion. Therefore, according to the distance change of muscle line attachment points shown in Fig. 1, the length of the muscle line could be calculated, and combined with Eq. (1), muscle force could also be solved.

\[ F_m = F_a + F_p = F_0(f_1 f_2 a(t) + f_3) \]
\[ f_1 = e^{1.6-1.6e^{0.1(x-0.22)^10}} \]
\[ f_2 = 1.6 - 1.6e^{0.1/(x-v+1)^{10}+0.1/(x-v+1)^{10}} \]
\[ f_3 = 1.3 \cdot \arctan(0.1(x-0.22)^10) \]
\[ x = l / l_0 \quad v = V / 2.5 \]

\( F_m \) is the muscle force value of single muscle line, \( F_a \) and \( F_p \) are the force value of flexor and extensor. \( l_0 \) is the length of the muscle line under the nature state, \( l \) is the varying value of the muscle line, \( V \) is the contraction speed of the muscle line, The functions \( f_1 \) and \( f_3 \) depend on muscle length \( l \), while \( f_2 \) depends on muscular contraction speed \( V \). The muscle force curve of the forelimbs and posterior limbs that moving within 0.3 second are shown in fig.3.
In Fig. 3, most of the calculated value of the muscle force was greater than the value of the forelimb, and it shows that the hind limbs are the major power source when the feline running in a fast speed, it plays a major role for the feline keeping the high speed.

In Fig. 3, some muscles of the hind limbs span over 2 or 3 joints, and have an important traction effect on movement of the joints, e.g. the muscle Fb1 shown in Fig.7 span over 3 joints of tibia and femur to connect with tarsal bone, so the joints also play an important role during the feline having a motion.

Multiply muscle force calculated in Eq.(5) by moment arm of joints, we can get the moment acting on each joints, and the moment arm of joints is the shortest distance from the muscle line to the joint rotation center, in the end add all the calculated muscle moment together, the final result of the joint torque can be obtained.

4. Conclusion
To further improve the performance of the bionic mechanism, in this paper we studied the mechanical properties of the motion system and bionic components of animals. To get accurate muscle force and torque, in this article we first built a mathematical model for the musculoskeletal system of a feline, calibrated the high-speed movement sequence of the animals, got the change rule of the joints and muscle force lines of the feline, and further got the stress condition variation of major joints during the high speed movement, providing a reasonable stress range to solve the mechanical properties of a single bone. Based on these results and simulated experiment, it could be provided more reasonable
implementation scheme to improve the function of bionic mechanism, and will conduct more in-depth research in follow-up work.

Acknowledgements
This study was supported by Tianjin Application Foundation and Advanced Technology Research Project (Grant number 14JCYBJC22000); TUTE Research Project No: KJ11-16.

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