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Comprehensive Robot Model Based on Horse Anatomy: Towards Understanding the Passive Dynamics of Limbs

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Horses, which exhibits high locomotor efficiency among mammals [1], have historically played a vital role in supporting pre-industrial society due to their superior power, speed, and stamina. Understanding the locomotion mechanism of horses will not only contributes to the development of biology but will also to the performance improvement of conventional quadruped robots. In this presentation, we will introduce our group's cross-disciplinary research on a robot model that replicates the tendon configuration and morphology in the limbs at the tissue level based on equine anatomy, investigating the contribution of each tissue to locomotion. Our focus is to reveal the complex mechanisms of tissue interaction within the body during locomotion.

Traditional biology has involved dissecting cadavers and measuring the motion of living organisms to understand the walking mechanisms of animals. However, dissection alone cannot provide observation of the internal structure of a living and moving animal. Furthermore, the sensors for measuring the internal structures of living animals still has technical limitations. Thus, we need new biological tools that can investigate the mechanisms inside the animal body where numerous tissues interact.

Robotics-inspired biology [2], which employs robotic models for biology, is a promising approach of investigating mechanisms within the animal body. Robotic models with real bodies enable a range of experiments that are challenging to perform in vivo or through simulation. The conditions inside a robot body during locomotion are more straightforward to measure than in a living body, and the experiments are more controllable. Invasive experiments that are difficult to perform on animals, such as cutting neural pathways or performing electrical stimulation on a walking robot, can also be performed [3]. The use of computer simulation provides the advantage of increasing the number of trials conducted, however, issues regarding numerical stability and approximation accuracy arise due to factors such as friction, contact, and complex link structures. Moreover, simulating the diverse and ambiguous real-world environments poses a challenge. In the future, the advancement of robot models as a tool for biology may offer novel advantages that were previously unattainable.

When utilizing robots for the investigation of animal locomotion mechanisms, one of the primary concerns is the validity of the robot as a biological model. Most current robot models possess a simple structure comprising a motor and rigid links to facilitate design and maintenance. While such simple models are useful for investigating the coarse dynamics surrounding animals, such as the impact of shape changes on the animal's body surface and the conduct of its center of gravity, an elaborated model that reproduces the configuration and morphology of the tissues under investigation on a biological basis is necessary to examine the interactions between tissues in an animal and the contribution of each tissue to the motion. A comparable argument is presented in the ”Templates and Anchors” paper [4].

Furthermore, we wish to stress the importance of ”comprehensive biomimetics” in animal modeling [5]. Despite having finite physical and computational resources, animals exhibit the versatility to survive in a diverse and complex environment, where they encounter an almost infinite number of situations. In other words, animals display situation-dependent multi-functionality, wherein one part of the body can demonstrate various capabilities depending on the circumstances. The author think that the such versatility of the animal body is generated by the embodiment at the tissue level within the animal body and by chance encounters between the tissues and the environment. Conversely, a simple robot model that replicates only certain functions will overlook many potential functions other than the one focused on. To explore the versatility of situation-dependent animal bodies in the future, it is necessary to create a complex model that reproduces the structure of the animal body at the tissue level and has potential multi-functionality.

We have designed an elaborated anchor model of the muscle-tendon network inside a horse limb to understand the locomotion mechanism of the horse at the tissue level. Re-

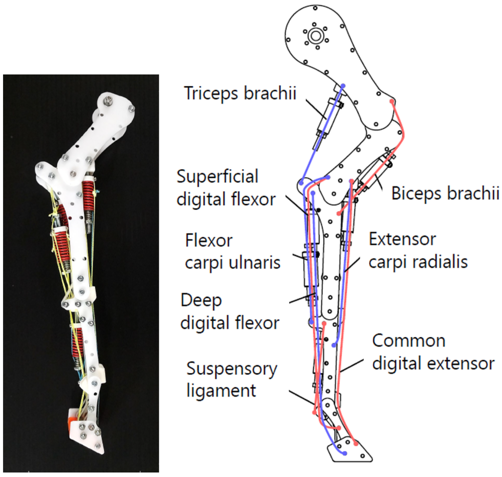

Figure 1: A comprehensive robotic model of a horse forelimb. We reproduced mass of each part, elasticity, and the interlocking mechanisms between the joints.

cently, we have realized the forelimb model shown in Fig. 1 in addition to the conventional hindlimb model [6]. We have approximated the horse skeleton with a linkage structure based on dissection of a horse cadaver and have been conducted walking experiments by reproducing the six major muscle-tendon complexes in the hind and forelimbs.

We ensured the validity of the robot model from two perspectives: the tissue level and the behavioral level. To ensure the validity at the tissue level, the mass of each part of the horse limb and the nonlinear elasticity of the muscle-tendon complex were modeled at a 1/4 size based on the scaling rule [6, 7]. Additionally, to ensure the validity of the behavioral level, the interlocking mechanisms of the horse limb was reproduced. The equine limb is equipped with a network of muscle-tendon networks called the stay apparatus, which passively interlocks multiple joint angles. Thus, we measured the interlocking patterns between joints by dissecting a horse and designed the natural length of tendons in the robot model to match these patterns.

Since this model reproduces the passive dynamic characteristics of the limbs of a deceased horse, each muscle-tendon complex module is not equipped with an actuator and does not move actively. Despite this, the walking robot equipped with this model generated a smooth walking motion like a horse simply by swinging its hip joints. The results suggest that a significant portion of the coordinated patterns of the horse's joint motion is a result of the passive dynamics.

The advantage of utilizing an comprehensive biomimetic robot as a biological tool is that it can emulate the muscle-tendon network of animals, with each element corresponding to a specific musculе-tendon unit. In future, by measuring the elastic energy of each spring module, we aim to elucidate the complex mechanisms involved in the leg motion of the horse at a tissue-level resolution. As these robot models become more sophisticated as a tool for biology, they may offer various advantages to biology that were not available in the past. Researches have also been conducted in recent years to construct anchor models of animals [6, 8–13], and the research field will become increasingly crucial in the future. The attempt to simultaneously contribute to both biology and robotics by bringing robot models closer to animals has the potential to establish a novel interdisciplinary domain that seamlessly integrates the processes of comprehending biological mechanisms and designing and controlling robots.

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