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Biomechanics of Musculoskeletal System and Its Biomimetic Implications: A Review

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Abstract

Biological musculoskeletal system (MSK), composed of numerous bones, cartilages, skeletal muscles, tendons, ligaments *etc*., provides form, support, movement and stability for human or animal body. As the result of million years of selection and evolution, the biological MSK evolves to be a nearly perfect mechanical mechanism to support and transport the human or animal body, and would provide enormously rich resources to inspire engineers to innovate new technology and methodology to develop robots and mechanisms as effective and economical as the biological systems. This paper provides a general review of the current status of musculoskeletal biomechanics studies using both experimental and computational methods. This includes the use of the latest three-dimensional motion analysis systems, various medical imaging modalities, and also the advanced rigid-body and continuum mechanics musculoskeletal modelling techniques. Afterwards, several representative biomimetic studies based on ideas and concepts inspired from the structures and biomechanical functions of the biological MSK are discussed. Finally, the major challenges and also the future research directions in musculoskeletal biomechanics and its biomimetic studies are proposed.

Keywords: musculoskeletal system, biomechanics, multi-scale, biomimetics, biologically inspired robots and mechanisms

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1 Introduction

A musculoskeletal system (MSK) is a biological system composed of bones, cartilages, skeletal muscles, tendons, ligaments and other connective tissues (see Fig. 1). The major function of the MSK is to provide form, support, movement and stability for the human or animal body. The MSK can be roughly considered to have two constituent sub-systems: the skeletal system and the muscular system.

The skeletal system consists of all the bones in the body and also the connecting tissues, *e.g*. cartilages and ligaments. The skeletal system provides the fundamental framework for body shape and load bearing, and also protects internal organs, *e.g*. brain, heart, lungs and liver *etc*., from external impacts. In the skeletal system, bones are connected to each other by joints, which provide articulations in MSK. The most common type of joint is synovial joint, which consists of fibrous connective tissue capsule (ligaments) and the periosteum of the connecting bones lubricated by synovial fluid inside of the joint.

The muscular system is the prime mover of human or animal body. For humans, there are approximately

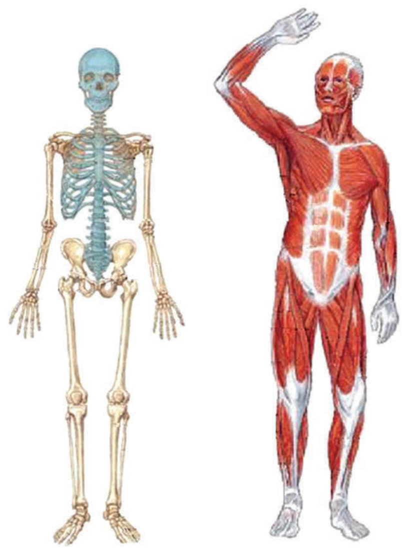

Fig. 1 The musculoskeletal system of human body[1].

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over 430 skeletal muscle groups accounting for up to 40% of body weight[2]. The skeletal muscles are made up of hundreds, or even thousands of muscle fibers, which range in thickness from approximately 10 µm to 100 µm and in length from about 1 cm to 30 cm[2]. Skeletal muscles are also arranged in layers over the bones, and they are normally attached to bones through tendons so that the forces generated by the contractile elements of the muscle fibers can drive body motions.

As the result of million years of selection and evolution, the biological MSK evolves to be a highly efficient and economic mechanical mechanism to support and transport the human or animal body with many extraordinary characteristics compared to their man-made counterparts. For example, cheetah is known as the fastest living land quadrupedal animal, which can reach to a speed of 29 $\text{m}\cdot\text{s}^{-1}$[3]. Some special features of cheetahs' MSK have been reported probably contributing to attaining such a high speed. For example, their divergent talar ridges may help to avoid limb interference in the aerial phase of galloping. Their long hindlimb bones may potentially assist them in making large stride length. Moreover, their particularly large psoas muscles may help them to rapidly protract the hindlimbs and also to resist pitching moments around the hip during accelerating[4]. Another example is horses, a representative athletic ungulate land animal with excellent locomotor capacity. Their third metacarpus bone has a small hole where blood vessels enter the bone[5]. As common knowledge from mechanical engineering, holes normally weaken structures by increasing dramatically the stresses near the holes as a result of stress concentration[5] (see Fig. 2). However, the holes at the third metacarpus bones of horses do not appear to cause bone fractures even for racing horses. This is probably due to an increased compliance near the foramen[5]. The sharp discontinuity in geometry due to the hole is softened by an embedded compliant region[5]. A reinforcing ring with increased stiffness, together with the ring of lamellar bone along the foramen's inner edges, might help to reduce the possibility of cracking[5]. The special configuration of the hole helps to move the highest stresses away from the foramen to regions with higher material strength[5] (see Fig. 2).

The human foot complex is another good example of highly efficient mechanical mechanism from the biological world. The human foot is a complicated structure comprising numerous bones, muscles, tendons, ligaments, synovial joints and other tissues. It has been found recently that such a small body component delivers multiple critical biomechanical functions in attenuating ground impact, supporting body against gravity, maintaining locomotor stability, generating and transmitting propulsive power during locomotion[6–8].

The fascinating structure and characteristics of the biological MSK, which has been optimally selected after million years' evolution, would provide enormously rich resources to inspire engineers to innovate new technology and methodology to develop mechanisms and machineries as effective and economical as the biological systems. For example, legged locomotion, as a biological transportation solution over rough terrain, has been attracting intensive researches from mechanical engineering and robotics field[9–13]. This may greatly facilitate the development of legged robots with high agility, stability and energy efficiency.

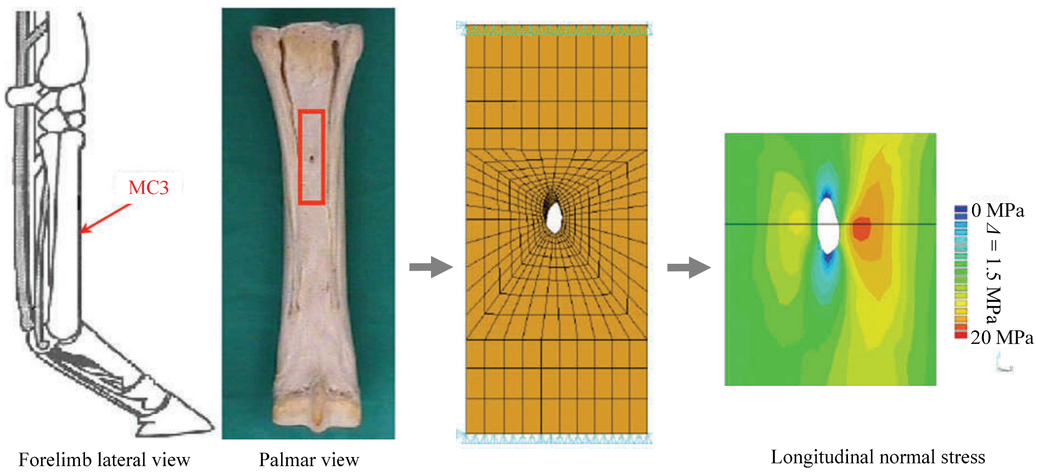

Fig. 2 The foramen in horse third metacarpus bone and its stress analysis[5].