THE CHALLENEGE OF NEW APPROACHES IN BIOMECHANICS

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Introduction: The target of our biomechanical research is to analyze the mechanics of motion, focusing especially on the behavior of the muscle-tendon complex during dynamic human movements. In our quest to better understand human motion, we have developed the several research methodologies. In the keynote lecture, I will discuss some of the techniques we have used and what we have learned from them. Specifically I will focus on the following:

1. Ultrasonography
2. Computer Simulation
3. Optical vs Inertial Sensor Analysis

1-1. Ultrasonography: Instantaneous measurement of the muscle-tendon complex

For evaluating the behavior of the muscle-tendon complex during human movements, it is important to observe the force as well as length changes in the muscle-tendon complex itself. One of our challenges has been to quantitatively determine the viscoelasticity of the muscle-tendon complex. We have succeeded in determining the muscle architecture (length and angle of fascicle) and elongation of tendinous structures of human muscle *in vivo* during movements using B-mode real time ultrasonography (Fukashiro et al., 1995).

This method was adapted to the triceps surae muscle during natural and complex human movements (Fukashiro et al., 2005). In squat and countermovement jumps, the muscle-tendon complex of m. gastrocnemius (MG) shortened rapidly just before take-off, although the fascicle shortened while the tendinous structure (Achilles tendon) was elongated in the previous phase. In other words, the fascicle contracted isometrically in the last phase of take-off. The rapid shortening of the muscle-tendon complex in the last phase of take-off depends on the shortening of the tendinous structure in these two jumps (Kurokawa, et al., 2001 & 2003). This mechanism has been called a 'catapult action' (Hof et al., 1983). On the other hand, in the drop jump, which is much more dynamic at the ankle joint, the muscle-tendon complex of MG stretched during the first phase of take-off and shortened during the last phase. Since the fascicles shortened only slightly during the whole take-off phase, the lengthening and shortening of the muscle-tendon complex was largely dependent upon the properties of the tendinous structures.

In the force-length relation, when comparing the above three types of jumps, the working range of fascicles (sarcomeres) in the drop jump was very narrow and slightly shifted to the left in comparison with the squat or countermovement jumps. This condition in the drop jump is advantageous for muscle fibers to generate relatively high force, which is required in order to accelerate the body center of gravity during the latter half of the push-off phase, despite the slightly lower maximum force generation at the optimal length. In the force-velocity relation, on the other hand, the fascicles generated force quasi-isometrically during the late push-off phase in the two jumps. It is well documented that the force generated by muscle fibers decreases with increasing shortening velocity in artificially activated animal muscle fibers as well as voluntarily activated human muscle (Fenn and Marsh, 1935). Therefore, working quasi-isometrically would enable the fascicles to generate relatively high force according to the force-velocity relationship. On the other hand, the tendinous structures behave in the region from high-stretching velocity to high-shortening velocity. The quasi-isometric contraction of the fascicles can occur because the considerably rapid shortening of tendinous structures ensures that the net shortening velocity of the muscle-tendon complex is high. These conditions imply that the fascicles play a role in generating high force (*i.e.,* force generator), and the tendinous structures create a high shortening velocity due to elastic recoil (*i.e.*, velocity generator) to allow the muscle-tendon complex to generate high mechanical power during the late push-off phase.

2-1. Simulation: Effects of the length ratio between the contractile and the series elastic elements on the stretch-shortening cycle in the muscle-tendon complex

We performed computer simulations that investigated the effects of the length ratio between the series elastic element and the contractile element on the biomechanical behavior of the muscle-tendon complex during a stretch-shortening cycle (Nagano et al., 2004). The proximal end of the contractile element was affixed to a point in the gravitational field, and a supporting object was affixed to the distal end of the series elastic element. A body was held on the supporting object. Initially the muscle-tendon complex was fixed at a certain length, and the contractile element was activated at full activation. Through this process, the contractile element shortened as much as the series elastic element was stretched (the total length stayed constant). Thereafter, the supporting object was released. This caused the muscle-tendon complex to thrust the body upwards, simulating a stretch-shortening cycle. The length ratio between the series elastic element and the contractile element, mass of the body, and the initial length of the muscle-tendon complex were systematically modified. As a result, the following were found: When the load imposed on the muscle-tendon complex was small, higher performance was obtained with a longer series elastic element; and when the load imposed on the muscle-tendon complex was large, higher performance was obtained with a shorter series elastic element.

2-2. Simulation: Effects of neuromuscular strength training on vertical jumping

We have also used computer simulations to systematically investigate the effects of altering specific neuromuscular parameters and strengthening specific muscle groups on maximum vertical jump height (Nagano et al., 2001). A two-dimensional musculoskeletal model, which consisted of four rigid segments, three joints, and six muscle-tendon complex models representing the six major muscles and muscle groups in the lower extremity that contribute to jumping performance, was trained systematically. Maximum isometric force, maximum shortening velocity, and maximum activation on muscle, which were manipulated to simulate the effects of strength training, all had substantial effects on jumping performance. Part of the increase in jumping performance could be explained solely by the interaction between the three neuromuscular parameters. It appeared that knee extensor training, more than any other lower extremity muscle group, was the most effective way to improve jumping performance. For the model to fully benefit from any training effects of the neuromuscular system, it was necessary to continue to reoptimize the muscle coordination, in particular, after the strength training sessions that focused on increasing maximum isometric force.

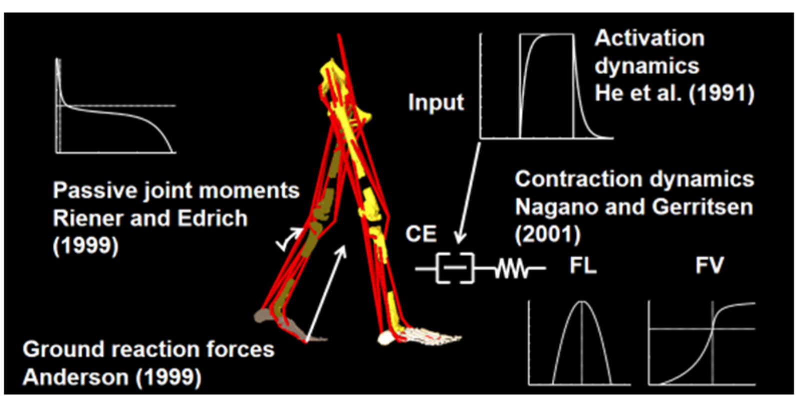
2-3. Simulation: Effect of bilateral asymmetry of muscle strength on the height of a squat jump

Furthermore, we have used computer simulations to understand the effect of bilateral asymmetry of muscle strength on maximal height of the squat jump (Yoshioka et al., 2010).

Two kinds of 3D human lower limb musculoskeletal models (symmetric and asymmetric) were developed. The total muscle strength of the two models was set to be identical. Bilateral muscle strength was equal in the symmetric simulation, while the asymmetric simulation was performed with a 10% bilateral strength asymmetry. A forward dynamics approach was used to simulate squat jumps. The squat jumps were successfully generated, producing jump heights of 0.389 m for the symmetric and 0.387 m for asymmetric models. The small difference in height (0.5%) indicated that the effect of the 10% bilateral asymmetry of muscle strength on jump height is negligible. In the asymmetric model, the strong leg compensated for the muscle strength deficit of the weak leg. The most important contributors were the mono-articular and large extensor muscles of the hip and knee joint of the strong leg, including the gluteus maximus, adductor magnus, and vasti group.

2-4. Simulation: Locomotion of *Australopithecus afarensis* (A.L. 288-1)

The skeleton of *Australopithecus afarensis* (A.L. 288-1, "Lucy") is by far the most complete record of locomotor morphology of early hominids currently available. Even though researchers agree that the postcranial skeleton of Lucy shows morphological features indicative of bipedality, only a few studies have investigated Lucy's bipedal locomotion itself. Lucy's energy expenditure during locomotion has been the topic of much speculation, but had not been investigated prior to our study, except for several estimates derived from experimental data collected on other animals. To gain further insights into how Lucy may have walked, we generated a full 3D reconstruction and forward-dynamic simulation of upright bipedal locomotion of this ancient human ancestor (see Figure, Nagano et al., 2005). Laser-scanned 3D bone geometries were combined with state-of-the-art neuromusculoskeletal modeling and simulation techniques from computational biomechanics. A detailed full 3D neuromusculoskeletal model was developed that encompassed all major bones, 10 joints, and 52 muscles of the lower extremity. A model of muscle force and heat production was used to actuate the musculoskeletal system, and to estimate total energy expenditure during locomotion. Neural activation profiles for each of the 52 muscles that produced a single step of locomotion, while at the same time minimizing the energy consumed per meter traveled, were searched through numerical optimization. The numerical optimization resulted in smooth locomotor kinematics, and the predicted energy expenditure was appropriate for upright bipedal walking in an individual of Lucy's body size.



3-1. Optical motion analysis: V2 skating in cross country skiing

There are two types of profiles of ski reaction forces during V2 skating. One of the differences between these two profiles is in the existence of the “flight phase,” i.e., the phase in between gliding and kicking off, in which the skis float above the snow while skiing. It has been suggested that the difference is caused by the skating velocity. The purpose of this section was to clarify whether or not there is a relationship between the occurrence of the flight phase and the increase in velocity during V2 skating (Fujita et al., 2010). Elite male cross-country skiers performed two trials that correspond to the competitive pace for a sprint race (high speed) and a 10-km race (medium speed). The kinematics for each trial were measured using two video cameras and a panning DLT (i.e. Optical) technique. The flight phase was determined by the ski load data obtained from a sensor attached to the ski. No flight phase was confirmed during medium-speed skating, but a flight phase was confirmed during high-speed skating, indicating the existence of the flight phase is related to an increase in skating velocity. However, the hip- and knee-joint angles and the vertical displacement of the center of mass were not changed by an increase in skating velocity. These results suggested that the flight phase was a small change kinematically, but it may cause changes in muscle activity since the leg muscle groups hold the ski off the snow during this brief period.

3-2. Motion analysis by inertial sensor

In the above optical research on cross country skiing, we had to digitize the points in each frame manually, which is time-consuming and tedious work. In order to improve efficiency and maximize automation of the data collection process, we have utilized a new methodology that use inertial sensor equipment. This new process enables us to analyze a wide range of movements within a large space. Typically difficult-to-capture sports motions like downhill skiing can be effectively measured with our technique. Utilizing this methodology, we plan on expanding our ability to simultaneously collect data that will shed light on the biomechanical and physiological processes of athletic performance.

Concluding remarks

Using ultrasonography, it is possible to directly observe the actions of the muscle tendon complex *in vivo*. Detailed quantitative analysis can be performed off-line. Using computer simulation, it is possible to access numerous biomechanical variables that cannot be obtained through experimental procedures. Furthermore, we have developed a new analytical approach using inertial sensors. As biomechanists, we have developed, and will continue to develop, both applied and theoretical approaches to investigate the mechanics of human motion.

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