

Paper:

Effects of the Lower Leg Bi-Articular Muscle in Jumping

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We studied the effects of the lower leg bi-articular muscle in vertebrates in jumping. We used the proposed Jumping Jack model in computer simulation to analyze the impact of bi-articular muscle on postural jumping stability, energy transition caused by postural change, and the relationship between the ground reaction force and the center of gravity. We made a trial model and measured the jumping posture, ground reaction force, and jumping height to verify simulation results. The bi-articular muscle adjusted the ground reaction force so that the line of action invariably passed near the center of gravity and the conversion of elastic energy to rotational kinetic energy was suppressed, leading to a stable posture after takeoff.

Keywords: lower leg, jumping, bi-articular muscle, jumping posture, ground reaction force

1. Introduction

Many humanoid robots that walk bipedally, cannot overcome underfoot irregularities or obstacles, preventing them from moving quickly. On the other hand, human, an original of these robots, can move across various irregularities or obstacles at high speeds by running, which can be considered continuous jumping. Jumping is indispensable when a humanoid robot implements high-speed locomotion.

Most of conventional jumping robots has the slide joint mechanism [2–5] based on a legged robot [1]. However, the joints of vertebrates extremity use a rotary joint without the slide joint. The vertebrate actuator (muscle) of articulated motion by multiple rotary joints is the bi-articular muscle, which acts simultaneously on two joints. The gastrocnemius in the human lower leg (Fig.1) is a bi-articular muscle that acts on the knee and ankle simultaneously.

One jumping robot [6] with springs acting on two joints simulating elasticity by the bi-articular muscle tendon, but is considered only in energy transfer. Control function

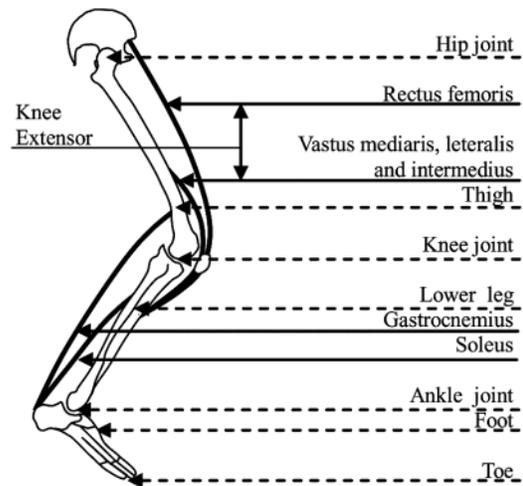


Fig. 1. Lower leg muscles necessary for jump.

[7, 8] in cooperation mono-articular muscle is involved in the bi-articular muscle function. For the impact of the bi-articular muscle on jumping, a musculoskeletal model was made and the electromyography input for computer simulation clarifying the relationship between muscular activities and jumping [9, 10]. Experiments on jumping by used the Jumping Jack model [11] with springs on the knee as a drive source. The gastrocnemius, a bi-articular muscle, was replaced with a wire and the function of energy transfer proved to use the bi-articular muscle to transfer energy generated by the knee extensor from a difference between models with and without the wire. Since Jumping Jack was manufactured focused on energy transfer by the bi-articular muscle and jumping height, it was given a guide rail restricting the jumping direction. The Jumping Jack thus prevented us from considering other than energy transfer of the bi-articular muscle due to the guide rail.

We used the Jumping Jack without the guide rail to clarify the impact of the bi-articular muscle on the jumping.

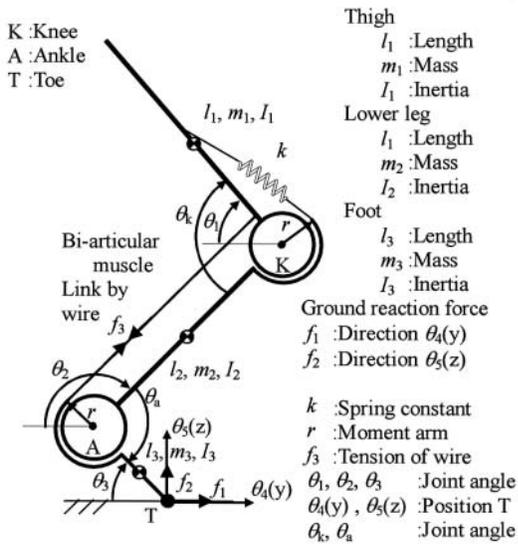


Fig. 2. Computer simulation model.

2. Analysis by Computer Simulation

We conducted computer simulation to analyze the impact of the bi-articular muscle on the jumping in stability of the jumping posture, energy transition caused by postural change, and the relationship between the ground reaction force and the center of gravity.

2.1. Computer Simulation Model

Figure 2 shows the Jumping Jack for computer simulation. This 3-link model consists of the link 1, i.e. the thigh (uniform rod of length $l_1 = 125\text{mm}$, mass $m_1 = 65\text{g}$), link 2, i.e. the lower leg (uniform rod of length $l_2 = 125\text{mm}$, mass $m_2 = 65\text{g}$), and link 3, i.e. the foot (uniform rod of length $l_3 = 25\text{mm}$, mass $m_3 = 20\text{g}$). A spring (spring constant $k = 5.3\text{N/mm}$, moment arm length $r = 14\text{mm}$, mass ignored) acts as an actuator equivalent to the knee extensor. Two models are used for comparison: one with a wire (moment arm length $r = 14\text{mm}$, mass ignored) that acts on the thigh and foot as the bi-articular muscle and the other without the wire. Since the wire function as the bi-articular muscle does not have a drive source, this muscle does not influence the generation of energy for jumping.

The posture ($\theta_k = \pi/2, \theta_a = \pi/2$) at the start of motion is assumed to be the initial posture (Fig.3) and three physical relationships between center of gravity G of the initial posture and toe T acting as the working point of the ground reaction force. These positions of the center of gravity are as follows:

Placed on the perpendicular passing through the working point of the ground reaction force (vertical position),

Placed $-\pi/6$ behind the perpendicular (posterior position),

Placed $\pi/6$ before the perpendicular (anterior position).

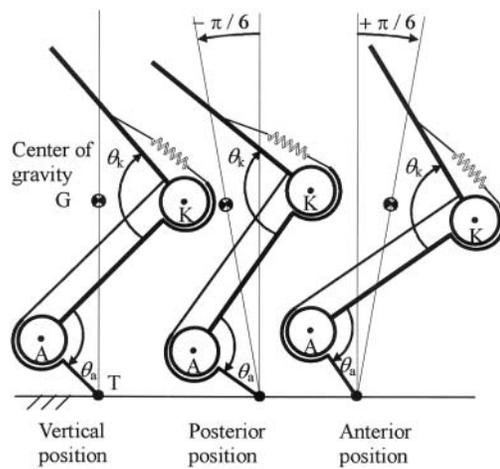


Fig. 3. Initial posture conditions.

The model without the bi-articular muscle has its leg joint fixed to retain these initial postures.

2.2. Computer Simulation

Simulation uses Mathematica, a mathematical expression software package developed by Wolfram Research, to solve the Lagrangian equation of motion. Assume a sum of U_g , a summation of gravitational potential energies at mass points of m_1 to m_3 , and U_s , a spring elastic potential energy, to be total potential energy $U (= U_g + U_s)$, and a sum of T_v , a summation of translational kinetic energies, and T_w , a summation of rotational kinetic energies, to be the total kinetic energy $T (= T_v + T_w)$. From this assumption, build up the equation of motion with the Lagrangian as $L (= T - U)$ using the following expression:

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}_i} - \frac{\partial L}{\partial \theta_i} = \sum_{j=1}^3 A_{ij} f_j \quad (i = 1, 2, \dots, 5) \quad (1)$$

where θ_i is generalized coordinate, $\theta_1, \theta_2,$ and θ_3 joint angles, θ_4, θ_5 positions of toe T, f_j Lagrange multiplier, f_1 and f_2 ground reaction force of toe T, f_3 wire tension, and A_{ij} is function of θ_i and found from initial conditions and constraints.

2.3. Stability of Jumping

Figure 4 shows model jumping with and without the bi-articular muscle. That without the bi-articular muscle jumps with a hard rotary motion with minimal height. The model with the bi-articular muscle jumps upwards with minimal rotary motion and considerable height. Without the bi-articular muscle, the center of gravity of the model jumps 0.20m heights in vertical as initial posture, 0.20 and 0.25m heights in posterior position and anterior position as the initial posture, respectively. With the bi-articular muscle, it has a jumping height of 0.55, 0.55 and 0.60m heights in the sequence of vertical, posterior position and anterior position as the initial posture.