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A Study on Jumping of Two Degrees of Freedom one-leg Robot

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Abstract This study aims to improve human jumping capability from an engineering perspective by proposing a supportive device, as in a robot suit. The robot expresses the time-oriented optimal torque pattern, which is the most efficient jump motion and timing, of each joint that can jump the highest by a motor. Then humans learn the most efficient jump motion. To actualize the most efficient jump motion, we observe human jumping motions and analytically calculate the most efficient torque patterns based on them.

Keywords: human jumping motion, jump robot, torque pattern

I. INTRODUCTION

The purpose of this study is to improve human jumping capability from an engineering perspective. Other studies have improved human jumping capability with additional torques on leg-joint-assisted motors. In this study, we analytically calculate the most efficient torque patterns only using human power without additional motor torques with the following processes:

Step 1: Observation of human jumping motion
Step 2: Construction of a two degrees of freedom jumping model
Step 3: Analysis by Lagrange motion equations
Step 4: Calculation of the most effective torque patterns of leg joints
Step 5: Verification experiments
Step 6: Showing the points for moving each leg joint when jumping
Step 7: Design of a supportive device to improve human jumping capability

II. OBSERVATIONS OF HUMAN JUMPING MOTION

First, we observed the human jumping motion to investigate which joint most influences the height of the jump. A tracer was installed in the node of each human leg joint (Fig. 3). We recorded the testee's jump motion with high-speed video camera, measured each joint angle and the jump height using motion capture (Fig. 1), and observed the following four kinds of jumping motion:

1. When nothing is fixed
2. When the waist joint is fixed
3. When the knee joint is fixed
4. When the ankle joint is fixed

Fig.1 Joint angle

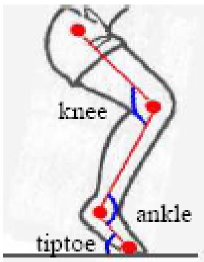


Fig.2 Each joint angle pattern from squatting to takeoff

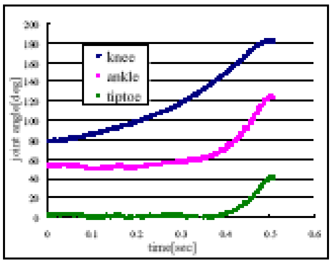


Fig.3 Human jump motion captured

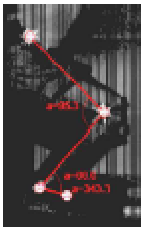


Table.1 Four human jumping motions

	waist	knee	ankle	Height
1	○	○	○	29cm
2	×	○	○	25cm
3	○	×	○	18cm
4	○	○	×	**13cm**

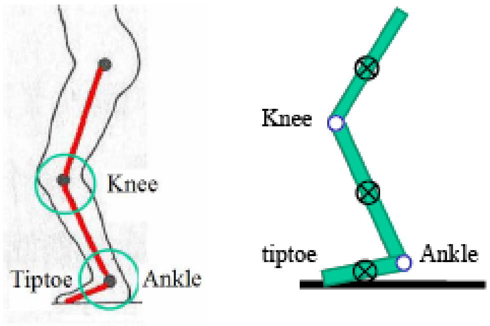
×: fixed ○: free

When the ankle joints are fixed, the height of the jump is the lowest (Table 1). The ankle joints influence the height of the jump most. Figure 2 shows each joint angle transition from the squatting position to take off when nothing is fixed. The knee joints changed gradually (Fig. 2). On the other hand, the ankle and tiptoe angles changed rapidly before take off. The ankle angle should be within 90°to work effectively in a vertical direction when not standing on tiptoe. By standing on tiptoe, even if the ankle is above 90°, it is possible to work effectively in a vertical direction.

III. CONSTRUCTION OF TWO DEGREES OF FREEDOM JUMP MODEL

A human jumping model in the sagittal plane was constructed as the easiest two degrees of freedom jump model based on the results of Section II. Fig. 4 shows a two degrees of freedom jumping model. The two degrees of freedom with ankle and knee joints and mass are defined in each center of gravity of the three links. The initial position is squatting. We calculated the most efficient torque pattern of each joint until taking off so that the height of the jump of this model is maximum. Using the Newton method is difficult, because the motion of the two degrees of freedom model is complex [2]. Then we analyzed it by motion equation of the Lagrange method.

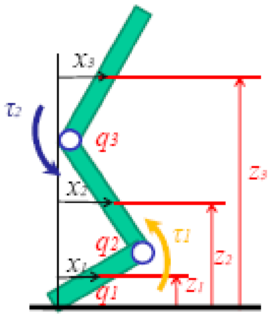
Fig.4 Two degree of freedom modeling



IV. ANALYSYS BY LAGRANGE MOTION EQUATIONS

Each parameter of the two degrees of freedom model is defined (Fig.5).

Fig.5 Parameters of Two degrees of freedom model



The parameters are defined about the i-th link of the three links as follows. Time is defined as "t".

Joint angle: $q_i(t)$
Center of gravity displacement in vertical direction: $z_i(t)$
Center of gravity displacement in horizontal direction: $x_i(t)$
Link mass: m_i
Link length: $2r_i$
Inertia moment around center of gravity of link: J_i
Torque of ankle: $\tau_1(t)$
Torque of knee joint: $\tau_2(t)$
Kinetic energy of link: $T_i(t)$
Potential energy of link: $V_i(t)$

Here, the displacement of each link is shown geometrically.

$$\begin{cases} z_1(t) = r_1 \sin q_1(t) \\ x_1(t) = r_1 \cos q_1(t) \end{cases}$$

$$\begin{cases} z_2(t) = 2r_1 \sin q_1(t) + r_2 \sin\{q_2(t) - q_1(t)\} \\ x_2(t) = 2r_1 \cos q_1(t) - r_2 \cos\{q_2(t) - q_1(t)\} \end{cases}$$

$$\begin{cases} z_3(t) = 2r_1 \sin q_1(t) + 2r_2 \sin\{q_2(t) - q_1(t)\} + \\ \qquad r_3 \sin\{q_3(t) - q_2(t) + q_1(t)\} \\ x_3(t) = 2r_2 \cos q_1(t) - 2r_2 \cos\{q_2(t) - q_1(t)\} + \\ \qquad r_3 \cos\{q_3(t) - q_2(t) + q_1(t)\} \end{cases} \tag{1}$$

Moreover, since the kinetic and the potential energies in each link are

$$\begin{aligned} T_i(t) &= \frac{1}{2} m_i \left\{\dot{z}_i^2(t) + \dot{x}_i^2(t)\right\} + \frac{1}{2} J_i \dot{q}_i^2(t) \\ V_i(t) &= m_i g z_i(t) \end{aligned} \tag{2}$$

Lagrangian L is

$$L(t) = \sum_{i=1}^{3} \{T_i(t) - V_i(t)\} \tag{3}$$

Here, if generalized coordinates are defined as *q1*, *q2*, and *q3*, Lagrange's motion equations are the following nonlinear simultaneous differential equations.

$$\begin{aligned} \frac{d}{dt}\left(\frac{\partial L(t)}{\partial \dot{q}_1(t)}\right) - \frac{\partial L(t)}{\partial q_1(t)} &= 0 \\ \frac{d}{dt}\left(\frac{\partial L(t)}{\partial \dot{q}_2(t)}\right) - \frac{\partial L(t)}{\partial q_2(t)} &= \tau_1(t) \\ \frac{d}{dt}\left(\frac{\partial L(t)}{\partial \dot{q}_3(t)}\right) - \frac{\partial L(t)}{\partial q_3(t)} &= \tau_2(t) \end{aligned} \tag{4}$$

Moreover, the center of gravity displacement of the entire faction in the vertical direction is defined as:

$$z_G(t) = z_2(t) + \frac{m_3\{z_3(t) - z_2(t)\} - m_1\{z_2(t) - z_1(t)\}}{m_1 + m_2 + m_3} \tag{5}$$

Next, we consider when to take off. The ground reaction force in the vertical direction is defined as N.

When this model is attached to the ground, the motion equation is as follows:

$$(m_1 + m_2 + m_3)\ddot{z}_G = N - (m_1 + m_2 + m_3)g \tag{6}$$

The ground reaction force is calculable from Expression(6) as follows:

$$N = (m_1 + m_2 + m_3)(\ddot{z}_G + g) \tag{7}$$

It is thought that this model takes off at N=0[3]. Height h of the jump is as follows from the law of the conservation of mechanical energy, when friction and air resistance are disregarded. Here, the speed of the center of gravity of the time is defined as $\dot{z}_G$

$$h = \frac{\dot{z}_G^{\,2}}{2g} \tag{8}$$

V. CALCULATION OF THE MOST EFFECTIVE TORQUE PATTERNS OF LEG JOINTS

We generate two or more torque patterns and assume that the total energy of each is constant and equal and apply each to the motion equations analyzed in Section III. The most efficient torque patterns define the highest jump among the generated torque patterns. Fig. 6 shows one example of torque patterns. We generated two kinds of torque patterns for the torque curve smooth and rapid slopes.

Fig.6 One leg joint torque pattern

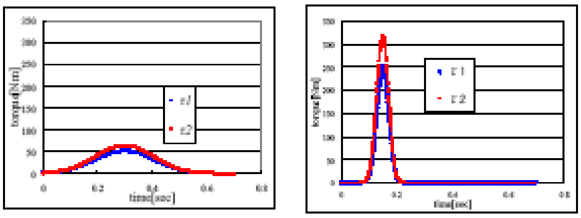


Fig.7 Each joint angle pattern from squatting to takeoff

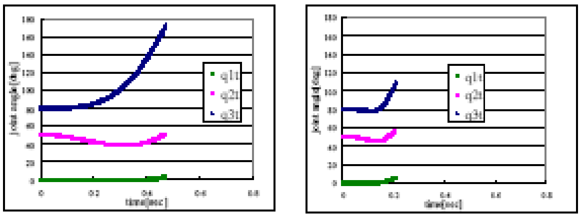


Fig.8 Ground reaction force from squatting to takeoff

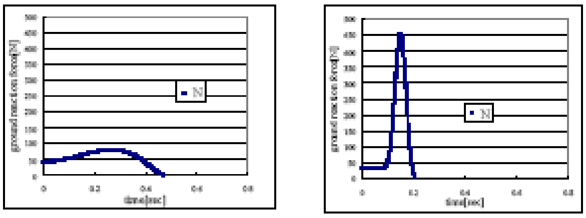
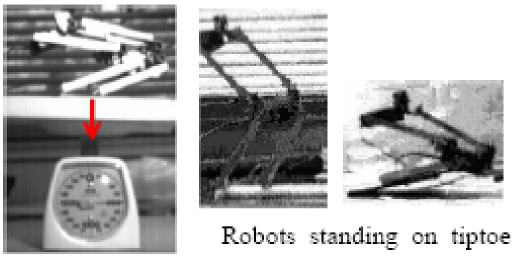


Figure 7 shows each joint angle displacement and the ground reaction force from squatting position to takeoff when the torque patterns are added.For torque patterns of the smooth slope, each joint accelerates gradually and takes off at t=0.47[sec] from Fig.9. But the height of the jump was about 0.1cm. On the other hand, for the rapid slope, each joint accelerates rapidly and takes off at t=0.2[sec]. The height of the jump was about 45 cm. Adding a rapid torque results in higher jumps, although both have identical power. The above torque patterns show some examples, and none is very efficient. We must consider the timing and the dynamic characteristics of human joints and optimize them. If the most efficient torque patterns can be given to a human leg joint, a maximum jump becomes possible. Human jumping capability improvement can be attempted with a supportive device that sets up each joint motor to teach humans the most efficient leg joint motion.

VI. PRE-CHECK EXPERIMENT

As a simple pre-check experiment, a two degrees of freedom, one-leg robot described in Section III was produced that jumped in experiments. Additionally, we produced a one-leg robot that doesn't stand on its tiptoes. The robot jumped under the same condition, and we compared these models. Fig. 9 shows the experimental apparatus. Moreover, the assumption of each robot is shown in Table 2.

Fig.9 Experiment and one-leg robots



Experiment

Robots standing on tiptoe and not

Table.2 Asumption of each robot

	Tiptoe model	Non-tiptoe model
Tiptoe	0°<q_1<90°	q_1=0°
Ankle	0°<q_2<180°	0°<q_2<90°
knee	0°<q_3<180°	0°<q_3<180°

We used a KONDO KRS-2350HV motor for each joint. The experiment procedure is shown as follows:

1. We added a constant torque to each joint motor of the one-leg robot.
2. We measured the ground reaction force from the squatting position to takeoff because in a simple pre-check experiment, the spring response of the measuring instrument was not considered.
3. We calculated the height of the jump from the measured ground reaction force.

Fig. 9 shows the measured ground reaction force. Both robots are compared in Table 3.

Fig.10 Ground reaction force of each one-leg robot from squatting position to takeoff

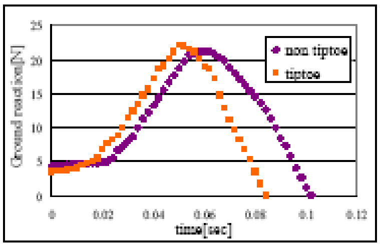


Table.3 Comparison of both robots

	Tiptoe model	Non-tiptoe model
Extension time[ms]	84	100
Maximum ground reaction force[N]	23	21
Jump height[cm]	2.2	2.6

Table 3 shows that the robot that doesn't stand on tiptoe jumps higher. But for the robot standing on tiptoe, the maximum value of the ground reaction force is larger. If the parameter of timing is considered, the robot can jump higher.

VII. CONCLUSION AND PROSOSAL

In this study, human jumping motion was observed. We found that the joint of the ankle is the overarching point in the jumping motion and showed the calculation method of each leg joint torque pattern by Lagrange's motion equation. In addition, we did a simple exploratory experiment and found the difference of jumping motion between robots that stand on tiptoe and those that don't. We also found the possibility of a supportive device for jump capability improvement.

We propose as follows:

1. The points for moving each leg joint when jumping

We propose the timing of the ankle joint and the knee joint to jump higher from the calculated the most efficient torque patterns.

2. A supportive device to improve human jumping capability

We target the sports player's jump capability improvement and rehabilitation support by wearing the robot suit that sets up the motor in each joint, and teaching the most efficient way to move the joint.

3. Application to other motions

We will study the application to complex motions such as a running motion, up and down motions of the stairs, and a baseball pitching form, etc. in the future.

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