Exceeding the Maximum Speed Limit of the Joint Angle for the Redundant Tendon-driven Structures of Musculoskeletal Humanoids

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**Abstract**—The musculoskeletal humanoid has various biomimetic benefits, and the redundant muscle arrangement is one of its most important characteristics. This redundancy can achieve fail-safe redundant actuation and variable stiffness control. However, there is a problem that the maximum joint angle velocity is limited by the slowest muscle among the redundant muscles. In this study, we propose two methods that can exceed the limited maximum joint angle velocity, and verify the effectiveness with actual robot experiments.

I. INTRODUCTION

The musculoskeletal humanoid \([1]–[3]\) has many biomimetic benefits such as the radioulnar structure of the forearm \([4]\), the flexible spine \([5]\), and the scapula structure with a wide range of motion \([6]\). One of the most important characteristics among these benefits is redundant muscle arrangement. This enables fail-safe redundant actuation that can continuously move even if a few muscles are ruptured \([7], [8]\), and variable stiffness control using the redundancy and nonlinear elastic elements \([7], [9]\). On the other hand, there is a problem that high internal muscle tension or slack of antagonistic muscles can occur due to the model error. To solve the problem, antagonist inhibition control \([10]\), dynamic modification of antagonistic relationships \([11]\), and muscle relaxation control \([12]\) have been developed so far.

In this study, we handle a newly found problem of the redundant muscle arrangement. The maximum joint angle velocity is limited by the slowest muscle among the redundant muscles. We propose methods to exceed the limited maximum joint angle velocity and solve the problem. In other words, this becomes not a problem but a benefit, in which the robot can move faster than the limited joint angle velocity that we have thought was the maximum so far.

To increase the joint angle velocity, optimization methods by software \([13]\) have been developed so far. However, these optimizations cannot make use of the hardware characteristics of musculoskeletal humanoids. Also, regarding the axis-driven robots with variable stiffness mechanism, velocity maximization methods using the hardware have been developed \([14], [15]\). In this study, we propose simple methods to exceed the limited maximum joint angle velocity by making use of the redundant tendon-driven characteristics.

This paper is organized as follows. In Section II, we will explain the basic musculoskeletal structure and its problem. In Section III, we will propose two simple methods to exceed the limited joint angle velocity. In Section IV, we will conduct experiments of two proposed methods using the musculoskeletal humanoid Musashi \([3]\). In Section V, we will compare the experimental results and discuss the advantages and disadvantages of these two methods.

II. MUSCULOSKELETAL HUMANOID

In this study, we generalize our explanation so that the complex musculoskeletal humanoids \([1]–[3]\), in which the moment arms of muscles to joints are not constant, can be handled. The simple tendon-driven robots such as \([16], [17]\) can also be handled. Although we assume that the muscle actuator is an electric motor, we can also apply the principle of this study to pneumatically actuated robots.

A. Basic Structure of the Musculoskeletal Humanoid

We show the basic musculoskeletal structure in Fig. 1. Muscles are antagonistically arranged around joints. The robot usually has not only monoarticular but also polyarticular muscles for the benefits of balancing and joint coordination \([18]\). We call the muscles contributing to the direction of the intended movement “agonist muscles,” and the muscles restraining the movement “antagonist muscles.” The relationship between joint angle and muscle length is represented as below,

\[
\begin{align*}
\mathbf{l} &= h(\theta) \\
\Delta \mathbf{l} &= G(\theta) \Delta \theta
\end{align*}
\]

where \(\mathbf{l}\) is muscle length, \(\theta\) is joint angle, \(\Delta \{\mathbf{l}, \theta\}\) is a small displacement of \(\{\mathbf{l}, \theta\}\), \(h\) is a mapping from \(\theta\) to \(\mathbf{l}\), and \(G\) is muscle Jacobian which is a differential matrix of \(h\). Here, \(\mathbf{l}\) is a \(m\)-dimensional vector and \(\theta\) is a \(n\)-dimensional vector (\(m\) and \(n\) are the numbers of muscles and joints, respectively).

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B. Problem of the Redundant Tendon-driven Structure Addressed in This Study

As a movement with fast joint angle velocity, we consider the movement of swinging down the arm, such as striking the desk, hitting with a hammer, and swinging a golf club. We determine the joint angle $\theta^{\text{start}}$ when the arm is swung up, and the joint angle $\theta^{\text{end}}$ when swung down. If we represent the current joint angle as $\dot{\theta}$ and the current joint angle velocity as $r$ during the motion of swinging down the arm, the moment arms of muscles to joints $r$ are represented as below,

$$r(\theta, \dot{\theta}) = G(\theta)\dot{\theta}/||\dot{\theta}||_2$$

where $|| \cdot ||_2$ represents L2 norm. If $r$ of the muscle is positive, it is an antagonist muscle, and if $r$ of the muscle is negative, it is an agonist muscle. The absolute value of $r$ is the moment arm.

To solve the problem of Section II-B, we will propose two simple methods. The first one is a method inhibiting antagonist muscles with large $q$, thus making their current 0, and using backdrivability of muscles. The second one is a method elongating antagonist muscles with large $q$ in advance.

III. A Method Exceeding the Limited Speed of the Joint Angle

To solve the problem of Section II-B, we will propose two simple methods. The first one is a method inhibiting antagonist muscles with large $q$, thus making their current 0, and using backdrivability of muscles. The second one is a method elongating antagonist muscles with large $q$ in advance.

A. Method Inhibiting Antagonist Muscles

This is a method not to manage the antagonist muscles but to inhibit them. This control is very simple, and the muscle motor current with large $q$ is inhibited to 0 as below, soon after starting the movement,

$$o[i] = 0 \text{ if } q[i] > C$$

where $i$ is the muscle index, $o$ is the current of the motor, and $C$ is a constant value. If $C = 0$, the currents of all the antagonist muscles become 0, and if $C > 0$, the currents of antagonist muscles with large moment arms and small $\dot{\theta}$ become 0. If the muscle actuators have backdrivability, the muscles spontaneously elongate when pulled, and we do not have to consider their maximum muscle length velocities. Because $q$ gradually changes during the movement, this control runs at a high frequency. This method assumes that the muscle actuators have backdrivability, and we verify it later using the actual robot.

B. Method Elongating Antagonist Muscles

This is a method managing the maximum muscle velocity by elongating the antagonist muscles with large moment arms in advance. When choosing which muscle we should elongate, we must consider two points stated below.

First, when swinging up the arm or leg, the posture of $\theta^{\text{start}}$ must be achievable. Because antagonist muscles when swinging down are agonist muscles when swinging up, if we simply elongate them when swung up, the robot cannot achieve the posture of $\theta^{\text{start}}$. Thus, when considering a mask $m$ whose values of muscles to elongate are 1 and those not to elongate are 0, the quadratic programming below must have a solution.

$$\text{minimize } f \left( m \otimes f \right)^TW_1 \left( m \otimes f \right)$$

subject to

$$r_{\text{act}} = -G(\theta^{\text{start}}) \left( m \otimes f \right)$$

$$m \otimes f \leq m \otimes f \leq m \otimes f_{\text{max}}$$

In this study, we focus on the management of antagonist muscles with large $q$ so that they do not achieve $\dot{\theta}$.
where \( \odot \) is element-wise multiplication, \( f \) is the calculated muscle tension, \( W_1 \) is a weight matrix (identity matrix in this study), \( \tau_{\text{acc}} \) is a joint torque which is necessary to achieve \( \theta_{\text{start}} \), and \( f_{\text{min},\text{max}} \) is a minimum or maximum muscle tension. If \( f \) satisfying this condition can be calculated, \( \theta_{\text{start}} \) is achievable, and the robot can elongate the muscles whose \( m \) is 0 while keeping \( \theta_{\text{start}} \). This is a principle enabled by the muscle redundancy. Although elongating the muscles increases the muscle tension of the others, it is not a problem for a short time.

Second, by elongating the chosen antagonist muscles, the joint angle velocity must become faster. By determining \( m \) and conducting a simulation as below, we can calculate the time cost to achieve \( \theta_{\text{start}} \) to \( \theta_{\text{end}} \).

\[
\begin{align*}
\text{minimize} & \quad (\theta_{\text{end}} - \theta - \Delta \theta)^T W_2 (\theta_{\text{end}} - \theta - \Delta \theta) \\
\text{subject to} & \quad -m \odot l_{\text{limit}} \Delta t \leq m \odot (G(\theta) \Delta \theta) \leq m \odot l_{\text{limit}} \Delta t
\end{align*}
\]

where \( \Delta \theta \) is the simulated displacement of the joint angle from \( \theta \), \( W_2 \) is a weight matrix (identity matrix in this study), \( t \) is the current time step, and \( \Delta t \) is the time interval of simulation. We can calculate \( \Delta \theta \) representing how much \( \theta \) can get closer to \( \theta_{\text{end}} \) in \( \Delta t \) seconds. We update this simulation like \( \theta \leftarrow \theta + \Delta \theta \) and \( t \leftarrow t + \Delta t \), by starting from \( \theta = \theta_{\text{start}} \). We stop the simulation when \( ||\theta - \theta_{\text{end}}||_2 < \epsilon \), and the last \( t \) is the time cost of the movement \( t_{\text{cost}} \). We need to calculate \( m \) that makes \( t_{\text{cost}} \) smaller. Although this calculation is a rough estimate because this simulation does not consider the motor inertia, model error, hysteresis, etc., we can obtain the rough characteristics of the movement. Because the musculoskeletal humanoid is difficult to model due to its complex structure compared with the ordinary axis-driven humanoid, we use such a simple method.

We search \( m \) which can achieve \( \theta_{\text{start}} \) by the calculated muscle tension and which makes \( t_{\text{cost}} \) smaller. Although we can conduct a full search of all the candidates of \( m \), \( t_{\text{cost}} \) clearly decreases when not using muscles with large \( q \). Therefore, we make \( m \) of antagonist muscles equal 0 in decreasing order of \( q \), and stop the search when \( f \) achieving \( \theta_{\text{start}} \) no longer exists.

Finally, we calculate how long the muscles, whose \( m \) are 0, should be elongated. We can obtain the transition of \( \Delta \theta \) using a simulation conducted with the calculated \( m \). From the transition of joint angle, we can calculate the transition of muscle length using \( G(\theta) \Delta \theta \). The maximum difference between the calculated muscle length transition and the fastest muscle length transition to elongate the muscles by \( l_{\text{limit}} \) is \( \Delta \theta_{\text{longate}} \), which is the minimum amount of muscle length that should be elongated. By elongating the chosen muscles by \( \Delta \theta_{\text{longate}} \) at \( \theta = \theta_{\text{start}} \) in advance, the antagonist muscles do not restrain the movement of agonist muscles, and the robot can move faster.

IV. EXPERIMENTS

A. Experimental Setup

In this study, we use the left arm of the musculoskeletal humanoid Musashi [3] for experiments. We show its muscle arrangement in Fig. 3. We mainly use its five DOFs of the shoulder and elbow. We represent these joint angles as S-p, S-r, S-y, E-p, E-y (S is the shoulder, E is the elbow, and rpy is roll, pitch, and yaw). These joints involve ten muscles including one polyarticular muscle. The motors of all the muscle actuators [19] are 90W Maxon BLDC Motor with 29:1 gear ratio, and \( l_{\text{limit}} \) of them are the same. However, the current control in [19] cannot achieve \( l_{\text{limit}} \) quickly. This is because the motor driver uses single-shunt approach to reduce the substrate size and we cannot increase the gain of current control to avoid the vibration of output. Therefore, we replace \(-l_{\text{limit}}\) and \( l_{\text{limit}} \) in Eq. 7 by \( l_{\text{min}} \) and \( l_{\text{max}} \), and we update them as below when the current muscle length velocity \( l > 0 \).

\[
\begin{align*}
\dot{l}_{\text{max}} &= \min(\dot{l}, \alpha \Delta t, \dot{l}_{\text{limit}}) \\
\dot{l}_{\text{min}} &= \min(\dot{l}, \alpha \Delta t, 0)
\end{align*}
\]

where \( \alpha \) is a constant value. In this study, from Fig. 4, we identified that \( \alpha = 0.46 \text{ [m/s]} \) and \( \dot{l}_{\text{limit}} = 0.30 \text{ [m/s]} \). This is a constraint that while \( l \) can gradually increase in proportion to time, \( l \) can decrease to 0 at once. When \( l < 0 \), the constraint is the same that \( l \) can gradually decrease in proportion to time, and \( l \) can increase to 0 at once. This expressed the behavior of actual muscle modules well.

In this study, we handle the movement of swinging down the left arm of Musashi. We show the experimental movements in simulation and in the actual robot, in Fig. 5. Although we cannot measure the joint angle of the ordinary musculoskeletal humanoid due to the complex joint structures, we can measure the joint angle of Musashi using the equipped joint modules. Also, we can measure muscle

![Fig. 3: Muscle arrangement of the left arm of the musculoskeletal humanoid Musashi [3].](image)

![Fig. 4: Characteristics of muscle length velocity transition.](image)
length from the encoder attached to the muscle actuator and muscle tension from the tension measurement unit. In this study, we set $C = 0$, $\Delta t = 0.03$, $f_{\min} = 10$ [N], and $f_{\max} = 200$ [N].

B. Basic Experiment

Before verifying the proposed methods, we conducted the target movement in simulation and in the actual robot without any proposed controls. Regarding all experiments, starting from $q_{\text{start}}$, we sent the muscle length achieving $q_{\text{end}}$ for 0 seconds. First, we conducted the simulation method explained in the latter half of Section III-B. We set the mask $m$ as a vector whose elements are all 1. We show the transition of the joint angle velocity in Fig. 6. The maximum joint angle velocity was 2.4 rad/s of E-P, and $t_{\text{cost}}$ was 0.99 seconds.

Second, we show the transition of joint angle velocity, muscle length velocity, and muscle tension when conducting the actual robot experiment, in Fig. 7. The maximum joint angle velocity was 2.6 rad/s of E-P, and the result was similar to the simulation. The muscle length velocities of the biceps brachii #9 and brachialis #10 achieved $\dot{l}_{\text{limit}}$. Also, the maximum muscle tension was about 290 N, and a heavy load was constantly applied to the pollyarticular muscle of the biceps brachii #9.

C. Experiment with Method Inhibiting Antagonist Muscles

We conducted the target movement in simulation and in the actual robot with the method of Section III-A. First, we conducted a simulation by assuming that the robot has backdrivability and setting the mask $m$ as a vector whose elements of muscles with $q[i] > C$ (#2, #3, #9, #10) are 0 as explained in Eq. 5. We show the transition of the joint angle velocity in Fig. 8. The maximum joint angle velocity was 4.4 rad/s of E-P, and $t_{\text{cost}}$ was 0.6 seconds.

Second, we show the transition of joint angle velocity, muscle length velocity, and muscle tension when conducting the actual robot experiment, in Fig. 9. The maximum joint angle velocity was 3.7 rad/s of E-P, and the observed velocity was lower than the simulation result. The muscle length velocities of the biceps brachii #9 and brachialis #10 were faster than $\dot{l}_{\text{limit}}$. Also, the maximum muscle tension was about 180 N, and a heavy load was mainly applied to the agonist muscle of shoulder #1 and elbow #6. Regarding antagonist muscles, about 50 N was constantly applied to the polyarticular muscle of the biceps brachii #9.

D. Experiment with Method Elongating Antagonist Muscles

We conducted the target movement in simulation and in the actual robot with the method of Section III-B. First, we calculated the mask $m$ satisfying the conditions explained in Section III-B. Although the $q$ of #9, #10, and #3 are large in decreasing order, if both #9 and #10 are elongated, the torque of the elbow cannot be kept. Therefore, we set $m$ as a vector whose element of only #9 is 0. We show the transition of joint angle velocity in Fig. 10. The maximum joint angle velocity was 3.3 rad/s of E-P, and $t_{\text{cost}}$ was 0.78 seconds.

Second, we show the transition of the joint angle velocity, muscle length velocity, and muscle tension when conducting the actual robot experiment, in Fig. 11. The maximum joint angle velocity was 3.4 rad/s of E-P, and the result was
similar to the simulation. The muscle length velocities of the deltoid (front) #3 and brachialis #10 achieved $\dot{l}_{\text{lim}}$. Also, the maximum muscle tension was about 140 N, and a heavy load was mainly applied to the agonist muscles of elbow #6 and #8. Regarding antagonist muscles, about 60 N was constantly applied to the brachialis #10.

V. DISCUSSION

We show the comparison among the ordinary movement (Basic) and movements using the method of Section III-A (Method-1) or Section III-B (Method-2), in Table I. First, from the simulation results, the theoretical maximum joint angle velocity has the relationship of Basic<Method-2<Method-1. Also, the relationship of the actual robot experiments is the same with that of the simulation. Thus, the methods of this study are effective in maximizing joint angle velocity. However, regarding Method-1, there is a large error between the simulation and actual robot experiments. This is because Method-1 is a method that assumes the muscle actuators have backdrivability. Although the gear ratio of the muscle actuator is relatively low, 29:1, the joint angle velocity can decrease if we increase the gear ratio, due to the lack of backdrivability. Second, we consider the difference of muscle length velocities. Because Method-1 makes the antagonist muscles elongate spontaneously, the muscle length velocity is higher than $\dot{l}_{\text{lim}}$. On the other hand, because Method-2 elongates the antagonist muscles in advance, we cannot see the high muscle length velocity. Third, we consider the difference of muscle tensions. While large muscle tension emerges by large internal force regarding Basic, only about half of the muscle tension emerges regarding Method-1 and Method-2. Thus, by inhibiting antagonist muscles or elongating them in advance, not only is joint angle velocity maximized but also muscle tension is reduced.

Summarizing the above, although Method-1 is effective if the backdrivability is high, the performance can be worse.
TABLE I: Comparison among the basic motion (Basic), the motion when using the method of Section III-A (Method-1), and the motion when using the method of Section III-B (Method-2).

<table>
<thead>
<tr>
<th></th>
<th>Basic</th>
<th>Method-1</th>
<th>Method-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum θ (simulation) [rad/s]</td>
<td>2.4</td>
<td>4.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Maximum θ (actual robot) [rad/s]</td>
<td>2.6</td>
<td>3.7</td>
<td>3.4</td>
</tr>
<tr>
<td>Maximum ( l ) [m/s]</td>
<td>( \leq \text{limit} )</td>
<td>( &gt; \text{limit} )</td>
<td>( \leq \text{limit} )</td>
</tr>
<tr>
<td>Maximum ( T ) [N]</td>
<td>290</td>
<td>180</td>
<td>140</td>
</tr>
</tbody>
</table>

than Method-2 if the backdrivability is low. On the other hand, while the performance of Method-2 is usually worse than that of Method-1, Method-2 does not depend on the backdrivability. However, because Method-2 elongates antagonist muscles in advance, high muscle tension is necessary when the joint angle is \( \theta_{\text{start}} \).

In this study, we developed simple methods exceeding the limited maximum joint angle velocity. By modeling the friction, hysteresis, and dynamics better, we can analyze the performance in more detail. In the future, we need to develop a method of realizing the accurate joint angle trajectory with fast velocity.

VI. CONCLUSION

In this study, we proposed two methods to exceed the maximum joint angle velocity limited by the actuator specifications for musculoskeletal humanoids with redundant tendon-driven structures. One of them is a method inhibiting antagonist muscles, thus making their current 0 and using backdrivability of muscles. Another one is a method elongating a few of the antagonist muscles in advance. From the simulation and actual robot experiments, we verified that the two methods can work well. Also, the performance of the former depends on the backdrivability, and that of the latter does not.

In future works, we would like to apply this method to more realistic situations.

REFERENCES


