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# Applications of Stretch Reflex for the Upper Limb of Musculoskeletal Humanoids: Protective Behavior, Postural Stability, and Active Induction

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***Abstract*— The musculoskeletal humanoid has various biomimetic benefits, and it is important that we can embed and evaluate human reflexes in the actual robot. Although stretch reflex has been implemented in lower limbs of musculoskeletal humanoids, we apply it to the upper limb to discover its useful applications. We consider the implementation of stretch reflex in the actual robot, its active/passive applications, and the change in behavior according to the difference of parameters.**

## I. INTRODUCTION

The musculoskeletal humanoid [1]–[4] has various biomimetic benefits such as redundant muscle arrangement [5], ball joints without singular points, and the flexible spine [6] and fingers [7]. Also, the fact that we can directly apply human control schemes to such human-like structures is important. Especially, human reflexes are important for human beings to survive, and it is considered to be also useful for musculoskeletal humanoids.

There are various kinds of human reflexes, and the most basic reflexes are stretch reflex, goldi tendon reflex, and reciprocal innervation. We introduce examples of applying these reflexes to the musculoskeletal structure of a simulation or the actual robot. Stretch reflex is used to increase the stability of jumping [8], [9] and walking [10]. Reciprocal innervation is effective to permit model error and conduct a wide range of limb motions [11]. [12] has embedded all the three reflexes into the fingers and showed the possibility of moving safely, especially by goldi tendon reflex. [13] has verified that these reflexes can stabilize the whole control system. Also, [14] has discovered the self-organization of reflexive behaviors from spontaneous motor activities using a Hebb learning rule and dynamics simulation.

From these studies, we can see that stretch reflex is useful for postural stability of lower limbs, goldi tendon reflex is useful for safe motions, and reciprocal innervation is useful for the reduction of internal muscle tensions and efficient movements. However, stretch reflex has been effectively used for only lower limbs, and we have not found effective applications for the upper limbs of the actual musculoskeletal humanoids. Therefore, we handle stretch reflex of the upper limbs in this study. We apply it to the musculoskeletal humanoid Musashi [4], and construct hypotheses about its effective applications. We verify the hypotheses using the actual robot.

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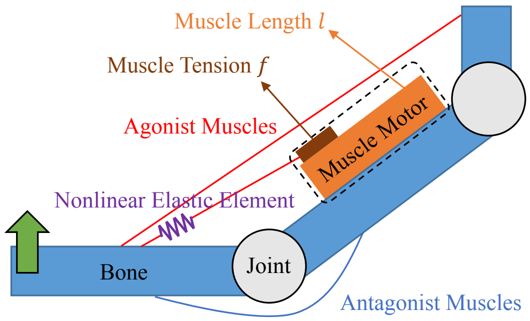


Fig. 1: The basic musculoskeletal structure.

This paper is organized as follows. In Section II, we will explain the basic musculoskeletal structure and the human stretch reflex. In Section III, we will consider the implementation of stretch reflex and the classification of its applications. In Section IV, we will conduct four experiments from the classification. Finally, we will discuss our experimental results and state the conclusion.

## II. MUSCULOSKELETAL HUMANOIDS AND HUMAN STRETCH REFLEX

### *A. The Basic Structure of the Musculoskeletal Humanoid*

In this study, although we handle tendon-driven structures whose muscle wires are wound by electric motors, the same principle as this study can be applied to pneumatic-driven musculoskeletal structures. We show the basic musculoskeletal structure in Fig. 1. Monoarticular and biarticular muscles are redundantly arranged around joints. The muscles contributing in the direction of the movement are agonist muscles, and the muscles contributing in the direction to inhibit the movement are antagonist muscles. The abrasion resistant synthetic fiber (e.g. Dyneema) is used as the muscle wires, and it is wound by electric motors. Muscle length $l$ can be measured from the encoder attached at the motor, and muscle tension $f$ can be measured using a loadcell or strain gauge. A nonlinear elastic element is usually attached to the endpoint of the muscle, in order to enable variable stiffness control. Although the joint angle cannot be usually measured, some musculoskeletal humanoids have joint angle sensors for experimental verification or learning [4].

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### B. Stretch Reflex in Human Beings

The Human muscle has two sensory receptors of the muscle spindle and goldi tendon organ. The muscle spindle is the spindle-shaped organ attached in parallel with the muscle fiber, and can detect muscle length $l$ and muscle velocity $\dot{l}$. The goldi tendon organ is arranged at the edge of the muscle in series with the muscle fiber, and can detect muscle tension $f$. Group Ia fiber from the muscle spindle is directly connected to the $\alpha$ motor neurons through excitatory connections. When the muscle is suddenly stretched, the frequency of impulse from the muscle spindle increases, it excites $\alpha$ motor neurons, and the stretched muscle finally contracts. This creates the reflex loop called stretch reflex, and it is a negative feedback system of muscle length.

## III. Stretch Reflex for Musculoskeletal Humanoids

### A. Implementation of Stretch Reflex

As explained in Section II-B, stretch reflex contracts the muscle when the muscle length $l$ is stretched quickly. Here, we consider a condition of inducing stretch reflex. From the definition above, when the difference of muscle lengths (muscle velocity) $\Delta l = l_{t+1} - l_t$ ($l_t$ is the muscle length at the time step $t$) exceeds a threshold $C^{stretch}$, stretch reflex occurs. However, as explained in Section II-A, the musculoskeletal humanoids usually have nonlinear elastic elements in the muscles. In this case, even when the arms are suddenly pushed, the deformation of the nonlinear elastic elements, which can flexibly react to the impact, is dominant compared to the movement of motors. By setting the muscle tension applied to the nonlinear elastic element as $f$ and the relationship between $f$ and its elongation $\Delta n$ as $f = e^{k\Delta n}$ ($k$ is a constant), we can judge whether the muscle is stretched or not, as below,

$$\begin{aligned} \Delta n_{t+1} - \Delta n_t &> C^{stretch} \\ \frac{1}{k}\log(f_{t+1}) - \frac{1}{k}\log(f_t) &> C^{stretch} \\ f_{t+1} - f_t &> C^{stretch'} \end{aligned} \tag{1}$$

where $C^{stretch'} = e^{kC^{stretch}}$. When the difference of muscle tension $\Delta f = f_{t+1} - f_t$ exceeds $C^{stretch'}$, stretch reflex occurs.

Next, we consider the behavior of stretch reflex. As its definition, stretch reflex contracts the reference muscle length $l^{ref}$ by a constant value $\Delta l^{stretch}$ when the conditions are satisfied. After that, $l^{ref}$ gradually loosens by $\Delta l^{stretch}$ over $\Delta t^{loose}$ seconds. Here, to avoid the situation in which the stretch reflex of a certain muscle induces that of other muscles around the muscle, making the antagonistic muscles vibrate coordinately, stretch reflex of other muscles around the contracted muscle should be inhibited. Therefore, the flow chart of stretch reflex is as shown in Fig. 2. Because the process of Fig. 2 occurs in parallel with all the muscles, stretch reflex of multiple muscles can occur when the conditions of stretch reflex are satisfied in the multiple muscles at the same time. Also, by applying this process independently to limbs that do not induce stretch reflex to each other, even if the timing is off, stretch reflex can occur in each limb (e.g. the left and right arms).

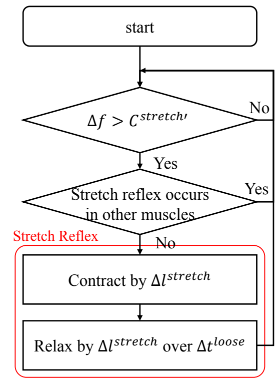



Fig. 2: The flow chart of the implemented stretch reflex.

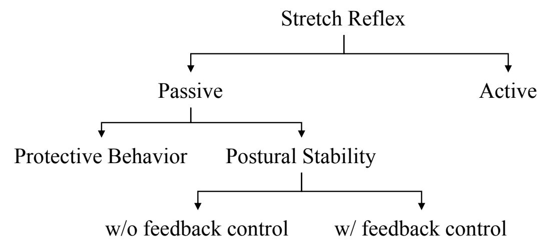



Fig. 3: The classification of applications of stretch reflex.

There are three parameters, $C^{stretch'}$, $\Delta l^{stretch}$, and $\Delta t^{loose}$, which determine the behavior of stretch reflex. We will discuss the difference of behaviors by the change in parameters in the subsequent experimental sections.

### B. Applications of Stretch Reflex

We consider useful applications of stretch reflex when it is applied to the upper limbs. We show the classification of applications in Fig. 3. In this study, first, we divide it into passive and active applications.

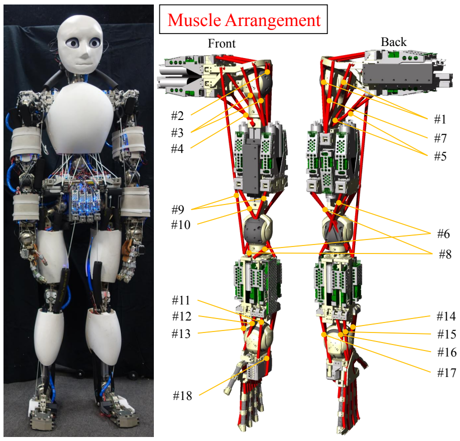
The passive applications are the cases in which stretch reflex is passively induced by sudden impact to the upper limbs. This is divided into protective behavior and postural stability. In protective behavior, it is hypothesized that stretch reflex can keep the posture in the safe range of joint angles when sudden impact occurs around the joint angle limit. In postural stability, it is hypothesized that stretch reflex can keep the same posture of the upper limbs before and after the sudden impact. Also, we can divide postural stability into the case without any feedback controls (the constant muscle length is kept) and with a feedback control (the joint angle is constantly kept by joint angle feedback control).

In the active application, it is hypothesized that stretch reflex can exert a faster and larger force than ordinary motions by applying excessive force to the environment and inducing stretch reflex on purpose. Weight lifting and jumping are considered to be good examples.

## IV. Experiments

### A. Experimental Setup

We show the musculoskeletal humanoid Musashi [4] used in this study and the muscle arrangement of its left arm




| Number | Muscle name |
|---|---|
| #1 | Deltoid (rear) |
| #2 | Deltoid (middle) |
| #3 | Deltoid (front) |
| #4 | Subscapularis |
| #5 | Infraspinatus |
| #6 | Triceps brachii |
| #7 | Teres major |
| #8 | Pronator teres |
| #9 | Biceps brachii |
| #10 | Brachialis |
| #11 | Extensor carpi radialis |
| #12 | Flexor carpi radialis |
| #13 | Flexor digitorum (index, middle) |
| #14 | Adductor pollicis |
| #15 | Flexor pollicis |
| #16 | Flexor digitorum (ring, little) |
| #17 | Extensor carpi ulnaris |
| #18 | Extensor digitorum |

Fig. 4: Muscle arrangement of the musculoskeletal humanoid Musashi used in our experiments.

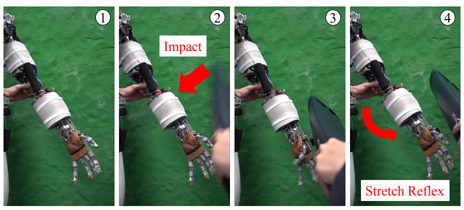



Fig. 5: The experiment of the protective behavior of stretch reflex when adding sudden impact to the elbow joint.

in Fig. 4. As in Section II-A, muscle tension and length of Musashi can be measured, and it has nonlinear elastic elements. Also, the joints are constructed by joint modules [4] which can measure joint angles for experimental evaluation. The joint angle values are a little noisy because of using analog potentiometers. Musashi has a biomimetic muscle arrangement, and each upper limb has 18 muscles (#1–#18). In this study, we mainly use five DOFs of the shoulder and elbow, and ten muscles (#1–#10), including one biarticular muscle (#9), are involved with the DOFs. We represent these DOFs as S-p, S-r, S-y, E-p, and E-y (S means the shoulder, E means the elbow, and rpy means roll, pitch, and yaw). We basically control Musashi using length-based muscle stiffness control [5].

We will conduct four experiments using Musashi, shown in the classification of Fig. 3. As stretch reflex does not easily occur, we set $C^{stretch'} = 15$ N which is larger than the maximum value of $\Delta f$ measured during ordinary motions, for all the subsequent experiments. Unless otherwise noted, we set $\Delta l^{stretch} = 10.0$ and $\Delta t^{loose} = 0.5$.

### B. Protective Application of Stretch Reflex

We conducted experiments regarding the protective behavior of stretch reflex. As shown in Fig. 5, E-p was bent to a small degree (about -0.04 rad), and impact forces were consecutively added to the forearm with the upper arm fixed. We verified the difference of behaviors with or without stretch reflex.

We show the joint angle of E-p $\theta$, the comparison of reference $l^{ref}$ and measured muscle length $l$ of biceps brachii #9 and brachialis #10, which were mainly stretched by the impact, the changes in muscle tensions $\Delta \boldsymbol{f}$, and muscle tensions $\boldsymbol{f}$, in Fig. 6. Without stretch reflex, when adding the impact force, the joint angle of E-p exceeded the joint angle limit of 0.0 rad. The part that physically limits the joint angle is made by a 3D printer, and a large force to deform it was exerted. On the other hand, with stretch reflex, the joint angle did not reach the joint angle limit. Stretch reflex occurred quickly when $\Delta f$ exceeded $C^{stretch'}$, the reference muscle length quickly contracted by $\Delta l^{stretch}$, and it loosened to the original length over $\Delta t^{loose}$. Stretch reflex occurred in each or both the biceps brachii #9 and brachialis #10. Although there was no large difference of muscle tension between with and without stretch reflex, large muscle tension continued a little longer with stretch reflex than without it.

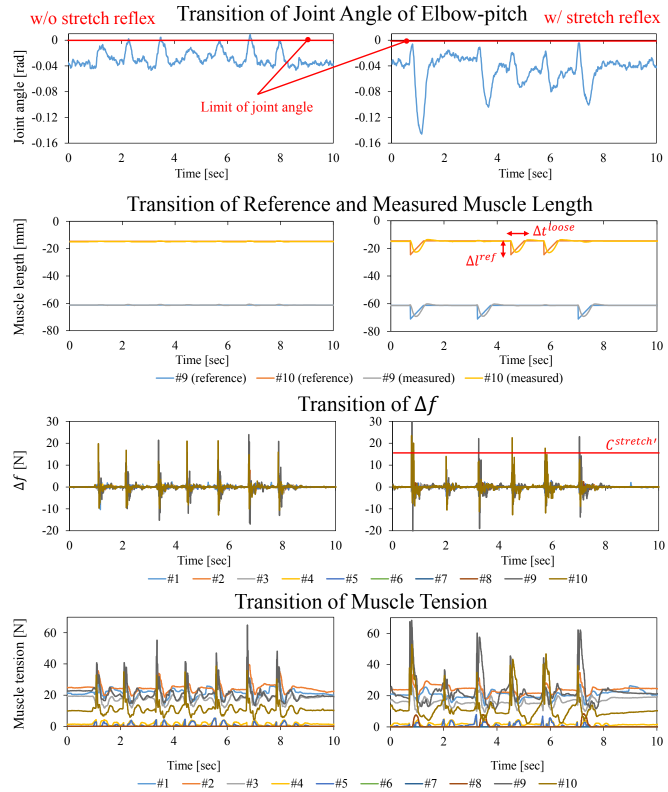



Fig. 6: The experimental results of the protective behaviors with or without stretch reflex. The graphs show the joint angle of E-p, the comparison between the reference and measured muscle lengths regarding #9 and #10, the change in muscle tension $\Delta \boldsymbol{f}$, and muscle tension $\boldsymbol{f}$.

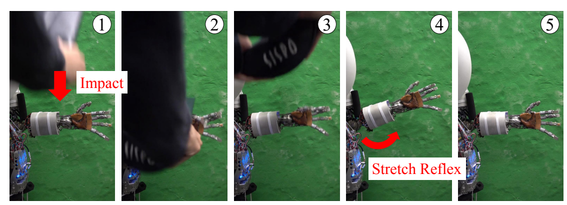



Fig. 7: The experiment of stretch reflex for postural stability.

### C. Application of Stretch Reflex for Postural Stability

We verified the effectiveness of stretch reflex for postural stability. As shown in Fig. 7, E-p was bent by about 90 deg,

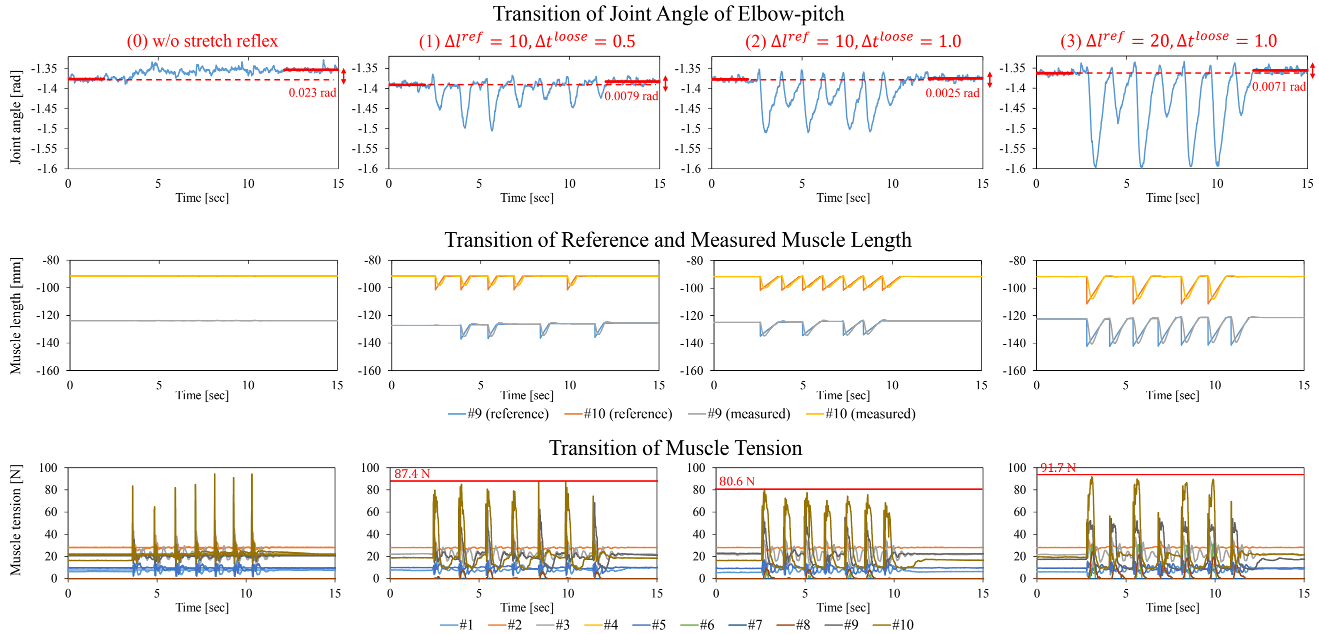



Fig. 8: The experimental results of stretch reflex for postural stability. The graphs show the joint angle of E-p, the comparison between the reference and measured muscle lengths regarding #9 and #10, and muscle tension $\boldsymbol{f}$, without stretch reflex (0) and with stretch reflex: (1) $\Delta l^{stretch} = 10, \Delta t^{loose} = 0.5$, (2) $\Delta l^{stretch} = 10, \Delta t^{loose} = 1.0$, and (3) $\Delta l^{stretch} = 20, \Delta t^{loose} = 1.0$.

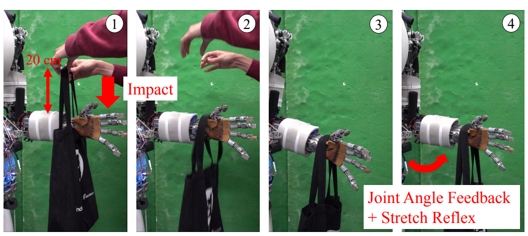



Fig. 9: The experiment of using stretch reflex with joint angle feedback control for postural stability.

and impact force was consecutively added to the forearm. While Section IV-B verified the protective behavior around the joint angle limit, we consider the change in posture before and after the impact force in this experiment. Also, we verify the difference in the behaviors by the change in parameters of stretch reflex.

We show the joint angle of E-p $\theta$, the comparison of reference and measured muscle lengths of #9 and #10, and muscle tension $\boldsymbol{f}$, in Fig. 6. We compared the cases without stretch reflex (0) and with stretch reflex of modified parameters: (1) $\Delta l^{stretch} = 10, \Delta t^{loose} = 0.5$, (2) $\Delta l^{stretch} = 10, \Delta t^{loose} = 1.0$, (3) $\Delta l^{stretch} = 20, \Delta t^{loose} = 1.0$. From the graphs of muscle lengths, according to the respective parameters, reasonable behaviors of reference muscle lengths were generated. Here, we verify the difference of joint angles of E-p between before and after the seven impacts. While the difference was 0.023 rad without stretch reflex, the differences with stretch reflex were (1) 0.0079 rad, (2) 0.0025 rad, and (3) 0.0071 rad. We can see that the change in joint angles by the sudden impact was inhibited by embedding stretch reflex. Also, although the maximum muscle tension was the largest regarding (3) with the largest $\Delta l^{stretch}$, a large difference could not be seen overall.

### *D. Application of Stretch Reflex with Joint Angle Feedback Control for Postural Stability*

We verified the effectiveness of stretch reflex for postural stability when adding joint angle feedback control. As shown in Fig. 9, we conducted a feedback control to keep the joint angle of E-p at -90 deg, and dropped a bag with 3.6 kg dumbbell from about a 20 cm height to the forearm. We compared the behaviors by changing parameters as in Section IV-C. The joint angle feedback control is a control that measures the current joint angle $\boldsymbol{\theta}$ and updates the virtual reference joint angle $\boldsymbol{\theta}^{virtual}$ by $\boldsymbol{\theta}^{virtual} \leftarrow \boldsymbol{\theta}^{virtual} + \alpha(\boldsymbol{\theta}^{ref} - \boldsymbol{\theta})$. Here, $\boldsymbol{\theta}^{ref}$ is the reference joint angle (constantly -90 deg in this experiment). This feedback control is necessary because the muscles have hysteresis. After that, by using a mapping from joint angles to muscle lengths $\boldsymbol{h}$ [15], we send reference muscle length $\boldsymbol{l}^{ref}$ as $\boldsymbol{l} = \boldsymbol{h}(\boldsymbol{\theta}^{virtual})$. In this study, we set $\alpha = 0.3$, and this feedback control is executed at 5 Hz.

We show the joint angle transition of E-p without stretch reflex (0) and with stretch reflex of modified parameters: (1) $\Delta t^{loose} = 1.0$, (2) $\Delta t^{loose} = 3.0$, and (3) $\Delta t^{loose} = 5.0$, in Fig. 9. The maximum joint angles when the impact force was added were (0) -1.49 rad, (1) -1.52 rad, (2) -1.50 rad, and (3) -1.51 rad, and the change in joint angle from the reference $\theta^{ref} = -1.57$ was the largest without stretch reflex. Thus, stretch reflex inhibited the maximum change in joint angle when the sudden impact was added. Also, we set a threshold $f^{thre} = -1.55$ [rad], and defined $\Delta t^{conv}$ as the time interval from the time of the impact to the earliest time at which $f$ does not exceed $f^{thre}$ from then. We can see that (0) $\Delta t^{conv} = 1.81$ [sec], (1) $\Delta t^{conv} = 2.51$ [sec], (2) $\Delta t^{conv} = 4.03$ [sec], and (3) $\Delta t^{conv} = 0.42$ [sec]. While the convergence time when using stretch reflex with small $\Delta t^{loose}$ became longer

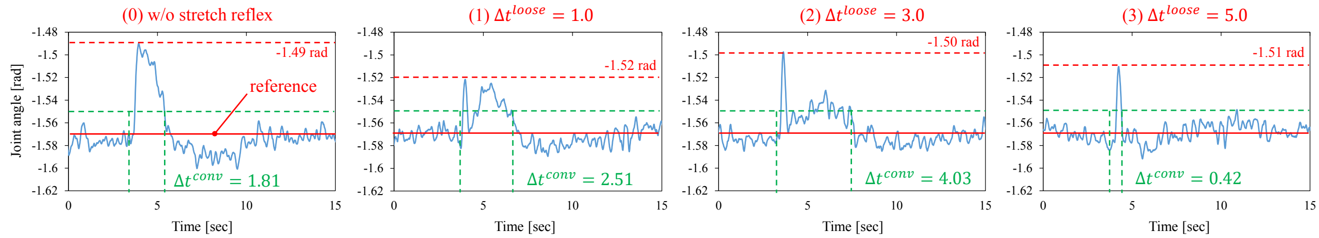



Fig. 10: The experimental results of using stretch reflex with joint angle feedback control for postural stability. The graphs show the joint angle of E-p without stretch reflex (0) and with stretch reflex of modified parameters: (1) $\Delta t^{loose} = 1.0$, (2) $\Delta t^{loose} = 3.0$, and (3) $\Delta t^{loose} = 5.0$.

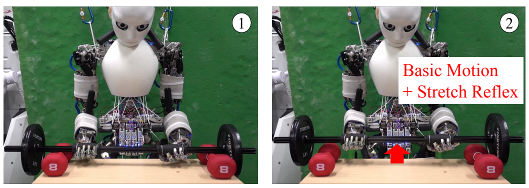



Fig. 11: The experiment of actively using stretch reflex when lifting a heavy dumbbell.

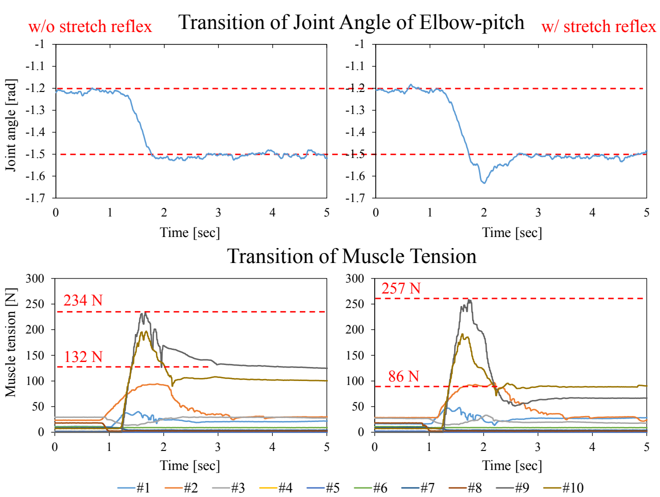



Fig. 12: The experimental results of actively using stretch reflex when lifting a heavy dumbbell. The graphs show the joint angle of E-p and muscle tension, without stretch reflex (0) and with stretch reflex of modified parameters: (1) $\Delta t^{loose} = 1.0$, (2) $\Delta t^{loose} = 3.0$, and (3) $\Delta t^{loose} = 5.0$.

than without stretch reflex, when $\Delta t^{loose}$ exceeds a certain threshold, the convergence time became much shorter than without stretch reflex.

### *E. Active Application of Stretch Reflex When Lifting a Heavy Dumbbell*

We verified the active applications of stretch reflex by taking an example of lifting a heavy dumbbell. As shown in Fig. 11, we sent the motion of lifting a 10 kg dumbbell with both arms over one second. We verify the effectiveness of stretch reflex for the motion.

We show the joint angle of E-p and muscle tension of the right arm with or without stretch reflex, in Fig. 12. The joint angles before and after lifting the dumbbell had no difference with or without stretch reflex. However, with stretch reflex, the joint angle largely changed in a moment and was reverted after that. The maximum muscle tensions were 234 N without stretch reflex and 257 N with stretch reflex. Also, the maximum muscle tensions after lifting the dumbbell were 132 N without stretch reflex and 86 N with stretch reflex. By embedding stretch reflex, the maximum muscle tension increased, but the muscle tension after lifting a heavy dumbbell decreased.

## V. Discussion

We summarize and discuss the four experimental results.

In Section IV-B, we verified the behaviors of stretch reflex around the joint angle limit when sudden impact is added. While the joint angle reaches the limit and large force is applied to the part that physically limits the joint angle without stretch reflex, the protective behavior can be seen with stretch reflex, as the joint angle does not reach the limit.

In Section IV-C, we verified the effectiveness of stretch reflex for postural stability by bending the elbow and adding the sudden impact while changing parameters. With stretch reflex, the change in joint angles before and after the sudden impact decreases compared to without stretch reflex. Because the muscles of the musculoskeletal humanoid have hysteresis caused by friction, the joint angle gradually changes by the impact force without stretch reflex. On the other hand, by embedding stretch reflex, the joint angle changed by the impact force is reverted, and the same joint angle can be constantly kept. While the muscle tension decreases by decreasing $\Delta l^{stretch}$, the effect of stretch reflex becomes weak. While the robot can quickly respond to the next impact by decreasing $\Delta t^{loose}$, the effect of stretch reflex becomes weak if $\Delta t^{loose}$ is too short, and $\Delta t^{loose}$ should be long to a certain degree in terms of feedback control explained subsequently. Thus, there is a tradeoff of parameters of stretch reflex.

In Section IV-D, we verified the effectiveness of stretch reflex with joint angle feedback control for postural stability when suddenly receiving a heavy object. With stretch reflex, the maximum change in joint angle when the sudden impact is added is inhibited compared to without stretch reflex. Also, when $\Delta t^{loose}$ is short, the muscle length is quickly reverted after stretch reflex, the joint angle feedback control is executed as without stretch reflex, and the convergence time becomes longer. On the other hand, when $\Delta t^{loose}$ is sufficiently long, after the joint angle is suddenly reverted to $\theta^{ref}$ by stretch reflex, $\theta^{ref}$ can be constantly kept with the joint angle feedback control. The longer $\Delta t^{loose}$ is, the higher the contribution of the joint angle feedback becomes compared with stretch reflex. Thus, by setting $\Delta t^{loose}$ appropriately, quick postural stability after the impact or burden is enabled.

In Section IV-E, as an example of inducing stretch reflex on purpose, we verified the effectiveness of stretch reflex when lifting a heavy object. With stretch reflex, while the muscle tension increases for a moment, the final muscle tension decreased. By adding excessive force to the heavy object, stretch reflex is induced and muscle tension suddenly increases. Due to the hysteresis of muscles caused by friction, while large muscle tension is necessary to exceed the friction without stretch reflex, by embedding stretch reflex, the muscle quickly moves for a moment, the friction is exceeded, and the final muscle tension is reduced. Thus, by adding large force to the environment and inducing stretch reflex on purpose, the robot can realize the task by reducing the final muscle tension.

From these experiments, stretch reflex avoids the joint angle limit and enables the fast convergence of joint angles when combined with joint angle feedback control. Also, stretch reflex overcomes the hysteresis of muscles, inhibits the change of posture by sudden impact, and contributes to the reduction of muscle tension by making use of it actively. While previous studies have discussed stretch reflex mainly in simulation or for postural stability of lower limbs, these results can be obtained for the first time when the characteristics of the actual robot (e.g. friction) are included.

In this study, while we consider the difference of behaviors by the change of parameters, we need to automatically determine the parameters for desired behaviors. The parameters of human stretch reflex are known to be changed by the task or environment [16], and we need to embed this mechanism into the musculoskeletal humanoid.

## VI. CONCLUSION

In this study, we embedded stretch reflex into the upper limb of the actual musculoskeletal humanoid and verified its effectiveness. We classified the applications of stretch reflex into passive and active. Regarding passive applications, we handled the protective behavior, and postural stability with or without joint angle feedback control, when sudden impact is added. Regarding active applications, we handled the motion of lifting a heavy object by inducing stretch reflex on purpose. By embedding stretch reflex, the robot can cope with the sudden impact around the joint angle limit and inhibit the burden to the joint. Also, when the sudden impact is added, stretch reflex can inhibit the change in joint angles caused by hysteresis, and realize the fast convergence of joint angles with joint angle feedback control. When lifting a heavy object, by making use of stretch reflex with excessive force added to the environment, the robot can finally realize the task with smaller muscle tensions. Thus, we succeeded in discovering multiple effective applications of human stretch reflex for the upper limb of the actual musculoskeletal humanoid.

In future works, we would like to verify the effectiveness when combining this study with goldi tendon reflex and reciprocal innervation, and conduct more human-like motions.

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