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Development of Isokinetic and Iso-contractile Exercise Machine "MEM-MRB" Using MR Brake

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***Abstract*— Strengthening muscle force by training, e.g., an isokinetic exercise is used widely used method in the rehabilitation medicine and sports medicine. However, many conventional isokinetic exercise machines cannot be used safely and easily. In this study, we developed an isokinetic and iso-contractile exercise machine, named "MEM-MRB", using an "MR brake". This brake includes MR fluid. Because of the rapid response of the MR fluid, the MR brake shows superior response performance compared with conventional brakes. In other words, a simple and safe training machine with accurate rotational speed can be realized with this brake. At the same time, a high-speed (900 [deg/s] at an elbow joint) control was realized with this machine. Additionally, we experimented in isokinetic and iso-contractile exercise.**

I. Introduction

CURRENTLY, clinicians can use several types of muscle contraction, for example, isometric, isotonic and isokinetic contraction, in quantitative evaluation of muscle strength.

In the isometric contraction, the angle of the joint is fixed and the length of muscle is also fixed constantly. At the angle of joint, a subject efforts to generate one's muscle strength at one's best. In this contraction, we can measure maximal torque of muscles, but cannot measure dynamic properties. On the other hand, in the isotonic contraction, muscle lifts a constant load and a muscle tension is constant. In this contraction, we can measure dynamic properties of muscles, but cannot measure maximal torque. In the isometric contraction and isotonic contraction, we cannot measure both maximal torque of muscles and dynamic properties of muscles. In order to solve this problem, isokinetic contraction was suggested. In this contraction, we can measure maximal torque at any angle of joint dynamically, because subjects required to generate maximal torque during whole range of motion under restriction of velocity with special training machine which can develop exact velocity control.

In the isokinetic contraction, the constant velocity is not the velocity of the linear muscle contraction but joint angular velocity. This causes by the reason that the joint angular movements are affected of the length of the lever arm of the muscle origin and insertion. Little attention has been paid to these differences.

These days, isokinetic machines, for example, Cybex [2], Biodex [3], are widely used in the rehabilitation medicine and sports medicine. Those machines are used in many researches for the relationship between the muscle strength and the contraction velocity. This contraction is based on the research of the velocity of muscle contraction and muscle tension by Hill [1]. However, those machines cost expensive depending on its actuation device (actuator is usually servomotor with high torque).

In order to develop an isokinetic exercise machine with low-cost, high safety and high performance, we have developed isokinetic and iso-contractile exercise machine, named “MEM-MRB”, using a MR brake. The primary purpose of this study is to make the mechanical model of the human joint movement on the consideration of the length of the lever arm effect. The secondary purpose is to develop the isokinetic machine to enable to evaluate the muscle strength in the constant linear velocity of the muscle contraction.

In this report, we describe development of isokinetic and iso-contractile exercise machine, named “MEM-MRB”, using a MR brake. This brake includes MR fluid. Because of the rapid response of the MR fluid, the MR brake shows superior response performance compared with conventional brakes. In other words, a simple and safe training machine with accurate rotational speed can be realized with this brake. At the same time, a high-speed (900 [deg/s] at an elbow joint) control was realized with this machine. Additionally, we suggest experimental result in isokinetic and iso-contractile exercise.

II. Premise In This Paper

A. Model of Arm

Arm has several muscles which have various functions. The image of biceps brachii muscle is shown in Fig. 1. This

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time, we mainly considered an elbow flexion, and then we made an easy model of arm on the assumption that an elbow flexion depends on only biceps brachii muscle, as shown in Fig. 1. In this figure, θ and ω are an elbow angle and an angular velocity of elbow, respectively. Additionally, L, R, and r are a length of biceps brachii muscle, a length between the origin of the muscle and a rotational center of elbow, and a length between the rotational center and the insertion of the muscle, respectively. Under the assumption, L and ω are respectively expressed as the following equations:

$$L = \sqrt{R^2 + r^2 - 2Rr\cos\theta} \tag{1}$$

$$\omega = \frac{-Rr\sin\theta}{\sqrt{R^2 + r^2 + 2Rr\cos\theta}} \frac{dL}{dt} \tag{2}$$

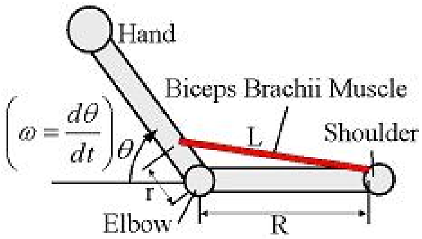

Fig. 1. Simple Model of Biceps Brachii Muscle

B. *Hill's Equation* [1]

It is known that the relation called a force-velocity curve is established between the output force of a muscle and a joint velocity. The model drawing of the force-velocity curve is shown in Fig. 2.

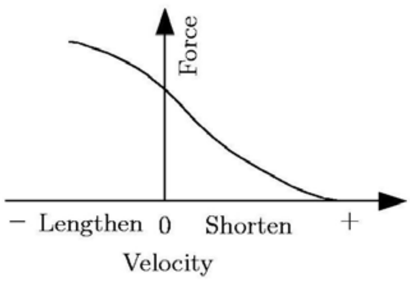

Fig. 2. Force-velocity Curve

The case of the zero joint velocity is called an "isometric contraction." In the isometric contraction, the angle of the joint is fixed, but inside the muscle, muscle fibers are shortened and elastic sites such as tendon are extended.

The case of the negative velocity of the joint while generating the force, that is to say, the state of the joint movement toward an opposite direction of the output force is called an "eccentric contraction." This corresponds to the negative zone of the velocity in Fig. 2. The maximum muscle force in the eccentric contraction is larger than the maximum muscle force in the isometric contraction, but forcing the joint to elongate leads to a rupture of the muscle fiber and a destruction of the joint.

On the other hand, the case of the positive velocity of the joint while generating the force, that is to say, the state of the joint movement toward the same direction with the direction of the output force is called a "concentric contraction." This corresponds to the positive zone of the velocity in Fig. 2. The output force decreases with the increase of the joint velocity and exceeding certain joint velocity leads to the zero output force. This curve under the concentric contraction is formulated by A.V. Hill (1938) as:

$$V = b(P_0 - P)/(P + a), \tag{3}$$

where P is the force, V is the velocity of a contraction of a muscle, P_0 is the force at the isometric contraction, and a and b are parameters depending on each muscle. This equation is called "Hill' s Equation."

As such a relationship holds between the output force of the muscle and the joint velocity, a quantitative evaluation might be possible if the maximum output force of the muscle at each joint velocity could be measured under the constant velocity of the motion.

III. Muscle Exercise Machine Using MR Brake

A. *MR Fluid*

Magneto-Rheological (MR) fluid is a kind of functional fluids that are attracting much attention these days. This fluid is composite material of non-colloidal solution and magnetic metal particles (e.g., iron particles). The diameter of the particle is 1-10 micrometers. The fluid changes its apparent viscosity (a rheological characteristic) when a magnetic field is applied to it [4]. The response of changing the viscosity is very rapid (about several milliseconds). The MR Fluid used in this study is MRF-132DG, which is developed by LORD Co., USA.

MR Fluid has such general characteristics as shown in Fig. 3. Fig. 3 shows how the shear stress changes with the shear rate as the magnetic field in the MR fluid. As shown by a dashed line in Fig. 3, the fluid presents the characteristics of Newtonian fluid when no magnetic field is applied ($H = 0$). As shown by a solid line in Fig. 3, when the magnetic field is applied ($H \neq 0$), the fluid has its viscosity greatly changed, presenting the characteristics of Bingham fluid. Specifically, shear stress is almost independent of the shear rate, but changes with the magnitude of the magnetic field. In other words, the magnetic field generates a force between two plates, which can be represented by a Coulomb friction model. Making use of this characteristic, we developed a brake and a clutch-type actuator [5].

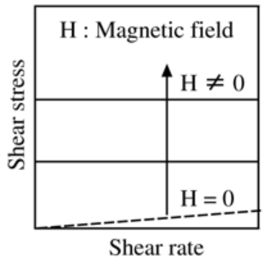

Fig. 3. Characteristics of MR Fluid

B. MR Brake

MR Brake consists of a disc with an output shaft, MR fluid, electromagnetic coil, and a fixed cover as shown in Fig. 4. In that case, we do not control the output shaft directly, but control the magnitude of current to the coil. When a current is applied to the coil, the magnetic field is generated in the MR fluid, and then the viscosity of the fluid increases. This increase of viscosity generates the braking torque and reduces the rotational speed. In other words, we control braking torque to the output shaft.

MR brake has high response because MR fluid has high response. Moreover, MR brake has good back-drivability. When a magnetic field is not generated in the MR fluid, MR brake generates little force because of the characteristics of MR fluid.

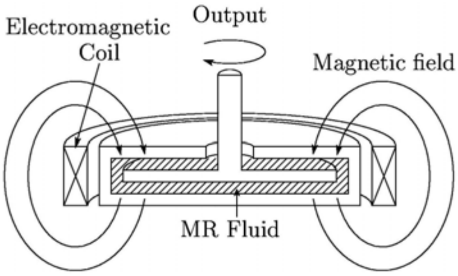

Fig. 4. Image of MR Brake

In this study, four C- type yokes are used on MR brake. The coils are twisted around each yokes. The yokes become the main path of magnetic flux. However, when the magnetic flux density passing through the electric conductor changes, electromotive force is induced and the eddy current passes through the conductor. Due to the eddy current, a counter-magnetic field that opposes the change in flux is produced and the response becomes slower. The magnitude of eddy current depends on the width of the conductor as shown in Fig. 5. In order to reduce eddy current, we use the yoke that is laminated thin silicon steel sheets as shown in Fig. 6. Each sheet is insulated from others.

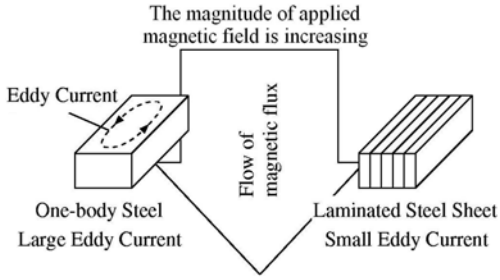

Fig. 5. The Magnitude of Eddy Current Depends on Width of Conductor

Fig. 6. C-Type Yoke Laminated Silicon Steel Sheet

The structure and specification of the MR brake are shown in Fig. 7 and table I, respectively.

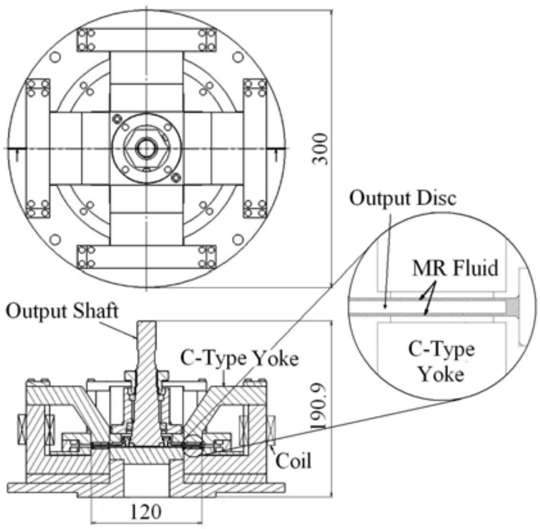

Fig. 7. Structure of MR Brake

TABLE I
SPECIFICATION OF MR BRAKE

Diameter of Casing	300 [mm]
Diameter of Output Disc	120 [mm]
Height	190.9 [mm]
Disc Gap	0.4 [mm]
Mass	26.4 [kg]
Num. of Yoke	4
Turn Num. of Coil	400 [turn]
Max. Current	2 [A]
Max. Brake Torque	27.5[Nm]

C. Muscle Exercise Machine Using MR Brake

We have developed an isokinetic exercise machine using an ER brake [6]. This time we developed an isokinetic exercise machine, named "MEM-MRB", using MR brake. The diagram and the appearance of MEM-MRB are shown in Fig. 8 and Fig. 9, respectively. By using MEM-MRB, isometric, isokinetic, and iso-contractile exercises can be realized. Moreover, at these exercises, we can train: for either flexion or extension; on either right or left arm.

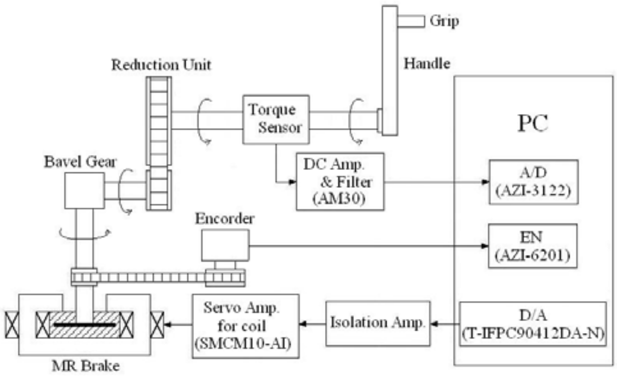

Fig. 8. Diagram of MEM-MRB

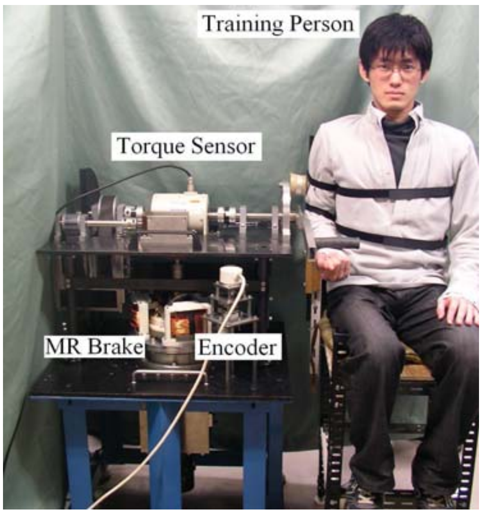

Fig. 9. Appearance of MEM-MRB

TABLE II
SPECIFICATION OF MEM-MRB

Reduction Ratio	4.41
Max. Braking Torque	120 [Nm]
Training Way	Both (Flexion, Extension)
Training Side	Both (Right, Left)

As shown in table I, the possible output torque of single MR brake is limited to 27.5 [Nm]. In other word, the output torque is not enough for training. Therefore we determined to install a speed reducer between the brake and an operation section. The speed reducer was designed using a belt-pulley mechanism. Reduction ratio has to be determined with considering possible maximum output force by human. In this time, we mainly considered an elbow joint exercise. Referring to data books of human engineering, it was designed for an average of men with age of 19 as target users. Because the exercise machine uses only brake, only concentric contraction training is targeted. The maximum output torque of the machine will need to exceed 90 [Nm] according to the data books with any margins. From this consideration, we determined the reduction ratio is 4.41. Because of the low reduction ratio and the specification of the MR brake, high-speed isokinetic exercises can be realized without changing its reduction ratio.

When a machine, which has large working area and large force, goes out of control, it is very dangerous. Therefore, the machine needs to be considered safety. MEM-MRB has much safety because MEM-MRB is a passive machine, not an active one. Machine design specification is shown in table II.

IV. ISOKINETIC EXERCISE SYSTEM

A. Isokinetic Exercise System

Isokinetic exercise can be realized by controlling the MEM-MRB. In this exercise, an angular velocity of elbow is kept constant with velocity control of instruments. The control system is shown in Fig. 10. PI controller is used for its velocity control. K_P and K_I mean a proportional gain [Nm•s/rad] and an integral gain [Nm/rad], respectively, and *G(s)* means a transfer function for the controlled object (MR brake). T_O, T_B, and ω mean an operation torque [Nm], the brake torque [Nm], and the angular velocity of elbow [rad/s], respectively. When the angular velocity exceeds the 0.3 [s] as fast as the reference angular velocity, the velocity control is started.

The output torque acts toward only an opposite direction to a rotational direction, and if an operator gives enough torque during the training, the output torque direction required for the brake is an opposite direction of the rotational direction.

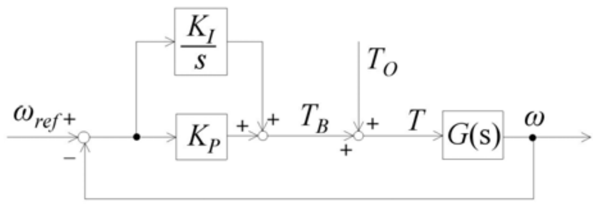

Fig. 10. PI Controller in Isokinetic Exercise System

B. Experiment of Isokinetic Exercise

An isokinetic exercise with the developed machine was carried out for a healthy subject (man, aged 22). He performed left elbow flexion from elbow angle of 45 to 140 [deg]. The reference velocity was changed from 100 to 900 [deg/s] with the interval of 100. Sampling time of the control was 1[ms].

Experimental result is shown in Fig. 11. Fig. 11 shows the result of the isokinetic exercise. We can see that the velocity was controlled constantly by the velocity control of the MR brake. The duration that the velocity was kept constant becomes short depending on the growing of the training speed because of the restriction of the range of motion. So the isokinetic training at such a high speed would have not been realized, if this MR brake has not been used in this machine.

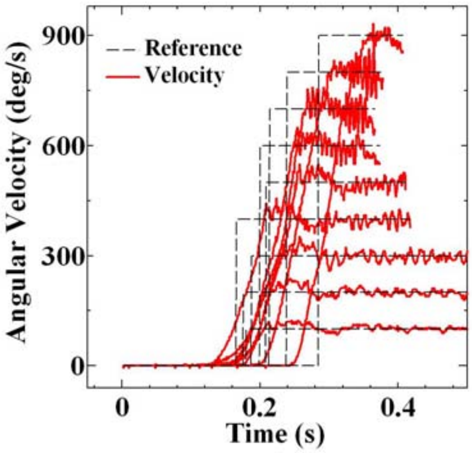

Fig. 11. Experimental Result of Isokinetic Exercise by using MEM-MRB

Hill's Equation can be made through the data of both the isometric and isokinetic exercise. After the isokinetic exercise, isometric one was performed at the elbow angle of 90 [deg]. The result of these exercises is shown in Fig. 12. The solid line in the figure means approximate Hill's Equation. The dashed line means a power, which is the product of the torque and angular velocity. According to the figure, we can see the peak of the power and the angular velocity of that.

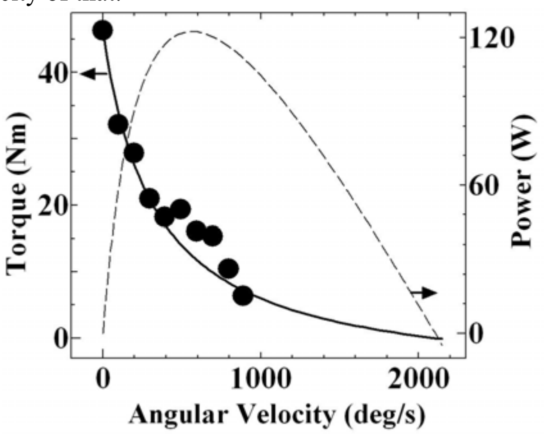

Fig. 12. Hill 's Equation in Isokinetic Exercise System

V. Iso- Contractile Exercise System

A. Iso-Contractile Exercise System

Iso-contractile exercise can be realized by controlling MEM-MRB. In this exercise, we can control the contraction velocity of the biceps brachii muscle. We call this system Iso-contractile exercise system in this paper.

The control system is shown in Fig. 13. On the Basis of Equation (2), the computer calculates reference angular velocity according to an elbow angle. Fig. 14 shows an example of the reference angular velocity curve of the constant contraction velocity of 200 [mm/s]. In this case, R and r of Fig.1 were set to 0.3[m], 0.03[m], respectively. A dashed line means a contraction velocity of the biceps brachii. As you see it, the contraction velocity is constant. On the other hand, a solid line means a reference velocity of the elbow joint. As you see in this line, the reference velocity becomes a concaved curve.

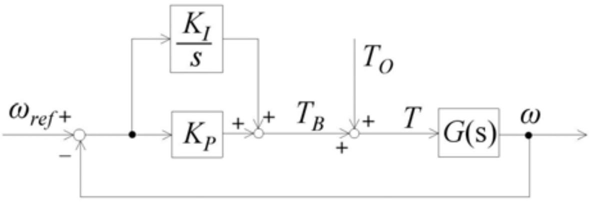

Fig. 13. PI controller iso-contractile exercise system

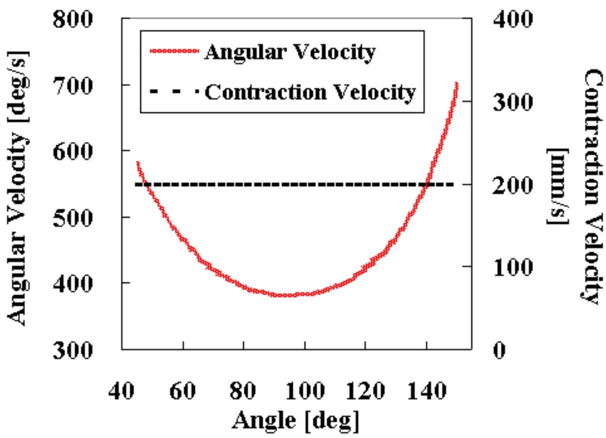

Fig. 14. Reference Curve of Angular Velocity at the Muscle Contraction Velocity of 200 [mm/s]

B. Experiment of Iso-Contractile Exercise

An iso-contractile exercise with MEM-MRB was carried out for a healthy subject (man, aged 22) to make sure a practicability of this machine. He performed left elbow flexion from elbow angle of 45 to 140 [deg]. The reference contraction velocity was changed from 50 to 550 [mm/s] with the interval of 50. Sampling time of the control was 1[ms]. In this case, R and r of Fig.1 were set to 0.3[m], 0.03[m], respectively. Experimental result of the iso-contractile exercise is shown in Fig.15. Fig.15 shows the contraction velocity of the biceps brachii on the simple model. As you see in these figures, we can control exactly angular velocity of the elbow depending on the reference curve.

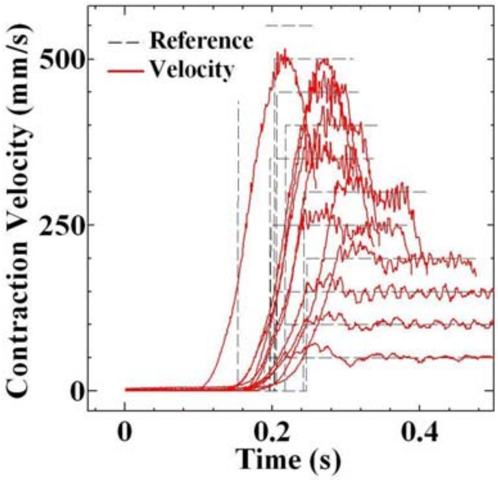

Fig. 15. Experimental Result of Iso-contractile Exercise

Hill's Equation can be made through the data of both the isometric and iso-contractile exercise. After the iso-contractile exercise, isometric one was performed at the elbow angle of 90 [deg]. The result of these exercises is shown in Fig. 16. The solid line in the figure means approximate Hill's Equation. The dashed line means a power, which is the product of the tension and contraction velocity. According to the figure, we can see the peak of the power and the contraction velocity of that.

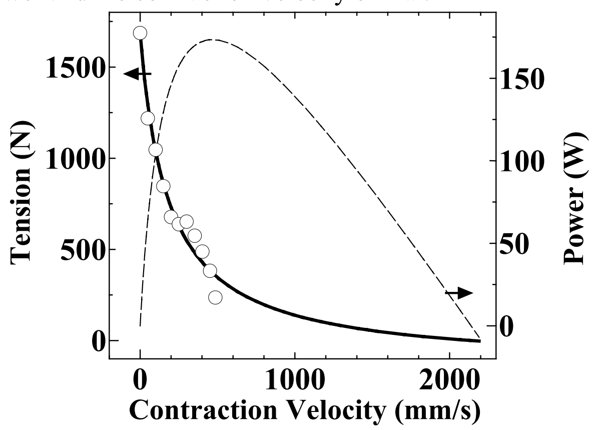

Fig. 16. Hill 's Equation of in Iso-contractile Exercise System

Finally, by utilizing this machine in the training, we can evaluate force-velocity relationship of the biceps brachii muscle directly. However, this method can be applied to only biceps brachii muscle. Further work is to develop methodologies to evaluate other part of the body.

VI. Conclusion

1) We developed the MR brake, which uses MR fluid and C-type laminated yokes. This device has quick and stable response characteristics.
2) We developed the exact and safe muscle exercise machine "MEM-MRB" using the MR brake.
3) The isokinetic exercise with MEM-MRB was carried out. Hill's Equation was made by measuring the generated muscle force and the velocity during training.
4) The high-speed training over 900[deg/s] at the isokinetic exercise was carried out safely and easily. Such a high-speed training cannot be realized by any other machines.
5) Iso-contractile exercise with MEM-MRB was carried out.

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