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Development of Load-lifting-assist Mechanism Using Lower Limbs

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The increasing average age of agricultural workers owing to the declining birth rate and aging population is becoming a serious problem worldwide. To harvest and transport products, it is necessary to lift, lower, and move containers when transporting them, but this work is a heavy burden not only for the elderly but also for young people. Thus, several electric assistive devices have been developed for carrying this load, including some in the field of long-term care. However, because of the complexity and high cost of the equipment, they are not widely used on private farms and in ordinary households. To solve these problems, we have developed a motorized auxiliary device for lifting and transporting goods. It has a simple structure, few failures, and low cost. Instead of conventional motors, hydraulics, or pneumatic pressure, the energy source for this device is the worker's thigh muscles, which generate the greatest force in the human body. In addition, instead of using arm muscles to support the load, the device causes the load to be supported with the shoulders. In this study, we demonstrate the basic structure and mechanism of the device, analyze the dynamic characteristics of some mechanisms, and propose effective mechanical elements for lifting the load.

1. Introduction

Serious problems have arisen in agriculture as a result of the decline in birth rate, population aging, and the increase in the average age of workers worldwide.(1) The average age of agricultural workers is increasing owing to the declining birth rate and aging population and has become a serious problem worldwide. For example, according to statistics from the Ministry of Agriculture, Forestry and Fisheries,(2) the average age in the Japanese agricultural sector is over 65 years. In agricultural production, to harvest and transport produce, containers must be lifted, lowered, and moved during transport. This task is very difficult even for young people and, of course, it is a heavy burden for the elderly. Thus, several studies and developments on power-assisted devices for transporting such loads, including in the field of long-term care, have been conducted.(3) For example, Yoshimitsu and Yamamoto developed a motorized assistive garment

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for long-term care.(4) The usefulness of this assistive suit was tested by transmitting an assistive torque to each joint. Noritsugu *et al.* developed an artificial muscle made of pneumatic rubber and applied it to a wearable motorized assistive device. They also developed a small, lightweight artificial muscle made of pneumatic rubber suitable for making safe human-sized actuators.(5,6)

Rahman *et al.* developed a robotic assistive device.(7,8) The robot is controlled by inertia and gravity. In addition, it was evaluated from the viewpoints of sensing weight, force, kinematic properties, safety, and stability, taking into account human-centered force control methods.(7,8) However, these robots are complex and expensive to operate. In addition, since these robots are not specialized for agriculture, they have not yet been widely used by private farmers or in ordinary households. In this study, we designed an electrically powered assistive device for lifting and transporting goods, which is simple to operate, less problematic, and less expensive than conventional devices. To power the device, we used the energy produced by the worker's thigh muscles, which generate most of the force of the human body, instead of conventional electric motors, hydraulics, or pneumatic pressure. In addition, the device causes the load to be held with the shoulders. There are multiple examples of muscle utilization that combine control engineering and ergonomics.(9,10) In this study, we demonstrated the basic structure and mechanisms of the device, analyzed the dynamic properties of certain mechanisms, and developed effective mechanical elements to lift the load. We also conducted experiments to faithfully reproduce the concept of the lifting technique.(11) In the discussion, we also summarize what was learned through the results obtained from this experiment.

2. Methods

2.1 Equipment overview

Figure 1 shows a schematic diagram for lifting, holding, and walking with a load. Two wires, one for lifting the load and the other for holding it in place, for each of the left and right shoulders are attached to the device. The device is also equipped with a contraption for lightening the load utilizing the principle of leverage. Each wire is equipped with an electromagnetic ratchet that can be activated and deactivated and a wire winder. A wire cable used to assist in lifting the load is attached to the ankles, while the wire rope for securing the load is attached to the waist.

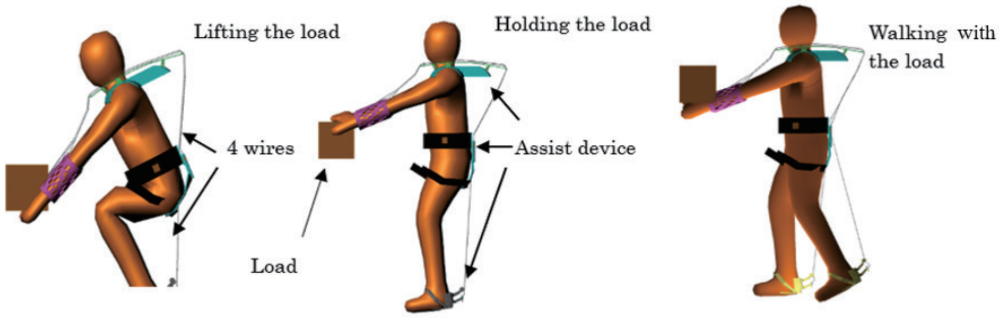


Fig. 1. (Color online) Schematic of device.

2.2 Principle of device operation

Figure 2 shows the load-lifting condition. The two wires of the device are connected to a cylinder attached around the wrist. After bending the knees and supporting the weight with the hands, the distance from the waist to the ankles is increased (L1 < L2), and the load is lifted if the wires are fixed. At this point, the load is lifted not by the strength of the arms, but by the strength of the lower limbs (lifting force). If the lifting height is insufficient, the knees are repeatedly bent and stretched.

Two wires, one to lift the load and the other to hold it, were connected to an electromagnetic ratchet and a device with an internal wire winder. The device connected to the lower back is shown in Fig. 3. Only the lifting wire was connected to the device at the heel, as shown in Fig. 4.

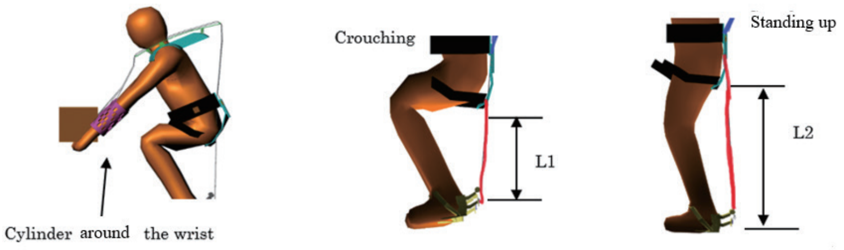


Fig. 2. (Color online) Operating principle for lifting load.

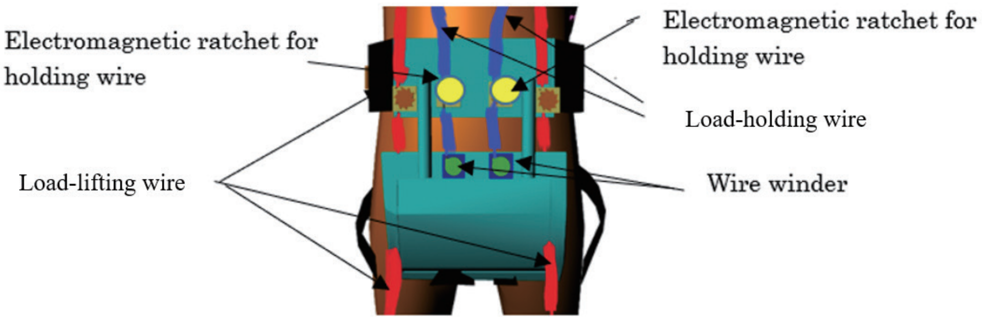


Fig. 3. (Color online) Waist-mounted device.

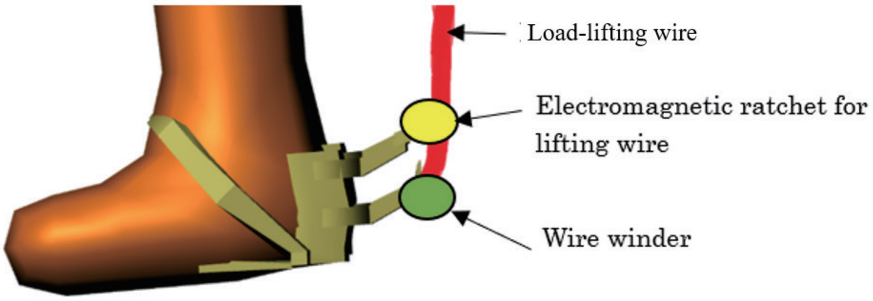


Fig. 4. (Color online) Device attached to the heel.

We should follow points (1)–(3) to operate the unit.

(1) All ratchets must be free when bending the knees and placing the hands on the load. A loose wire is wound by the winder.

(2) When standing and lifting the load, the lifting wire ratchet connected to the heel is activated and the fixed wire ratchet is deactivated. Since the lifting wire is secured, the load can be lifted.

(3) To lift the load further, turn the fixed wire ratchet ON, turn the heel lifting wire ratchet OFF, squat down, and stand up. Repeat the above steps as necessary. Since the fixing wire is secured, the load does not fall, but is lifted from the position in step (1).

The load-lifting wire extends through the waist unit to the heel unit. With the above operation, a heavy load that would otherwise be lifted and supported by the arm muscles can be carried by the shoulders.

2.3 Other details of device mechanism

As shown in Fig. 5, some parts of other devices take advantage of the lever principle to reduce load-lifting forces. The shoulder section is an example. Our device reduces the force on the lower limb by setting the distance L1 < L2. Springs are also fitted to reduce shock. To prevent the load from swinging during walking, a damper has been mounted, as shown in Fig. 6. The part attached to the wrist is cylindrical, as shown in Fig. 7, to allow the load to operate to be lifted.

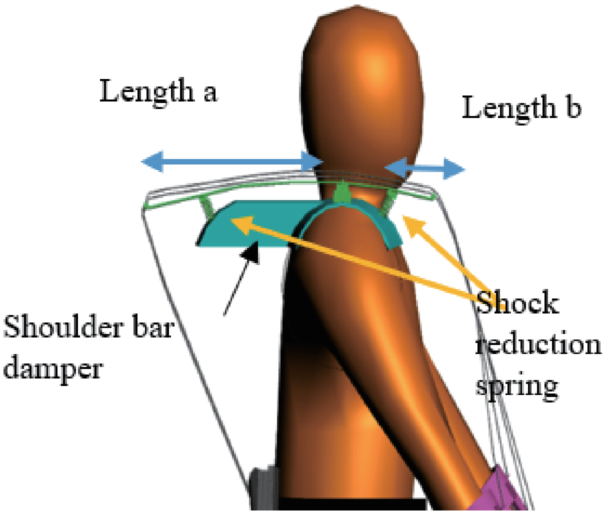


Fig. 5. (Color online) Schematic of shoulder device attached to the shoulder.

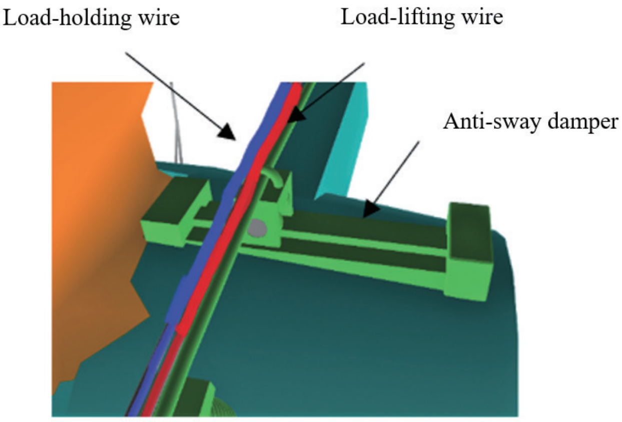


Fig. 6. (Color online) Shoulder device connected to the heel viewer from above.

Fig. 7. (Color online) Cylinder around the wrist.

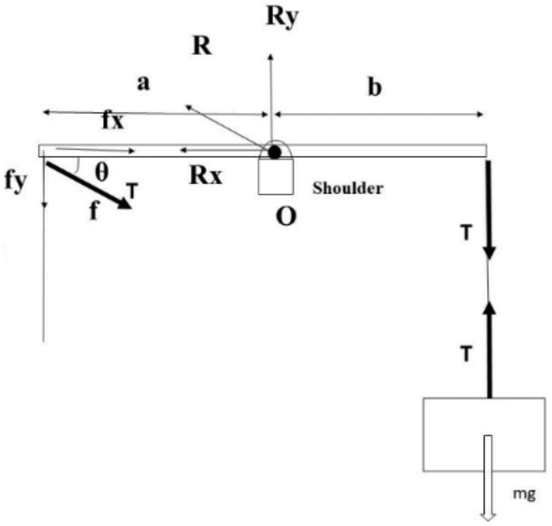
3. Shoulder Device

3.1 Ratio of wire angle to bar length in shoulder devices

Three patterns (A, B, and C) were devised for assembling the load-lifting equipment.

(a) Basic system A

The lengths a and b of the shoulder unit and the angle of the wire are considered as shown in Fig. 8 As seen in Fig. 8, R is the reaction force generated by the shoulder, T is the wire tension, and the hinged part is the upper shoulder. f is the wire tension from the waist.



T:Tension
θ: Angle
R : Force on the shoulder
Rx: Force in x direction at the shoulder
Ry: Force in y direction at the shoulder
a:Length between shoulder and tip of the stick
b:Length between shoulder and end of the stick
f: Force on tip of the stick
fx: Force in x direction at tip of the stick
fy: Force in y direction at tip of the stick
mg: Gravity of the weight

Fig. 8. Cylinder around the wrist in basic system A.

The equations of equilibrium for the moments in the x- and y-directions and around the hinge O are

$$R_y - mg - f_y = 0\,, \tag{1}$$

$$f_x - R_x = 0\,, \tag{2}$$

$$f_y \cdot a - mg \cdot b = 0\,. \tag{3}$$

Inserting $f_y = f\sin\theta$ into Eq. (3), we obtain $f = \dfrac{mgb}{\sin\theta \cdot a}$ ($0 < \theta \leq 180°$). f reaches its minimum at $\theta = 90°$.

The shoulder reaction force R is as follows.

$$R^2 = R_x{}^2 + R_y{}^2 \tag{4}$$

From Eqs. (1) and (2),

$$R_x = f_x\,, \tag{5}$$

$$R_y = mg + f_y\,, \tag{6}$$

$$f = \frac{mgb}{\sin\theta \cdot a}, \tag{7}$$

$$R^2 = R_x{}^2 + R_y{}^2 = m^2 g^2 \left(\frac{b^2}{\sin^2\theta \cdot a^2} + 2\frac{b}{a} + 1 \right). \tag{8}$$

R^2 is minimized at $\theta = 90°$ and $\sin\theta = 1$. Then,

$$R^2 = m^2 g^2 \left(\frac{b^2}{a^2} + 2\frac{b}{a} + 1 \right). \tag{9}$$

Therefore, by setting $\theta = 90°$ and $a >> b$, the shoulder load is minimized.

(b) Basic system B (attachment of a fixed pulley)

Basic system A is best considered as a simple lifting-assist mechanism, but it applies a force twice the weight in the vertical direction of the shoulder. Therefore, it is not practical. To improve this situation, we devised basic system B.

A rod with a fixed pulley attached to each end and a wire hanging from a clamp is attached to the top of a weight. The wire passes through the two pulleys and then through the clamp at the top of the weight. Next, the wire again passes through the two fixed pulleys and is attached to the waist. Figure 9 shows a conceptual diagram of this process.

The equations of equilibrium for the moments in the *x*- and *y*-directions and around the hinge O are

$$R_y - 2T - T - f_y = 0, \tag{10}$$

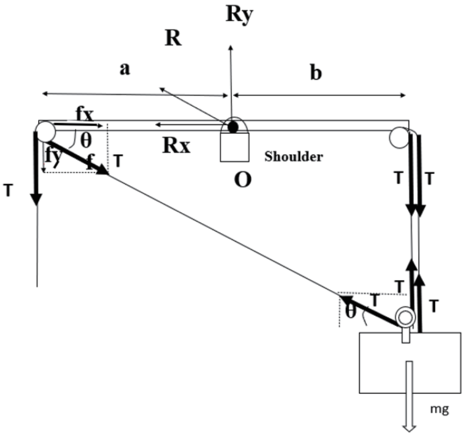


Fig. 9. Pulley system connected to the cylinder around the wrist in basic system B.

$$R_x - f_x = 0, \tag{11}$$

$$(T \cdot \sin\theta + T) \cdot a - 2T \cdot b = 0. \tag{12}$$

The force f on the weight is $f = mg - 2T - T\sin\theta$, where $F = 0$, assuming zero acceleration at rest. Then,

$$mg - 2T - T\sin\theta = 0. \tag{13}$$

From Eq. (13),

$$T = mg / (2 + \sin\theta), \tag{14}$$

$R_x = T \cdot \cos\theta$ and $R_y = (3 + \sin\theta)T$, and

$$R = \sqrt{10 + 6\sin\theta} \cdot T \tag{15}$$

The relationship between shoulder force and θ is $R = \sqrt{10 + 6\sin\theta} \cdot T$ on the basis of Eq. (15). This is the force on the shoulder when the mass m = 1.0 kg. When the angle θ is 50° during lifting, 13.53 N, that is, the same force as when lifting a weight of 1.38 kg, is applied to the shoulder. k kg is the same force applied to the shoulder when lifting a weight of 1.38 k kg. Since the burden on one shoulder is 1.38 k kg / 2 = 0.69 k kg, the burden on the shoulder is less than in basic system A and is a practical value.

(c) Basic system C (combination of fixed and dynamic pulleys)

Figure 10 shows a conceptual diagram of a combination of fixed and dynamic pulleys. The equations of equilibrium for the moments in the x- and y-directions and around the hinge O are

$$R_y - 3T - T - f_y = 0, \tag{16}$$

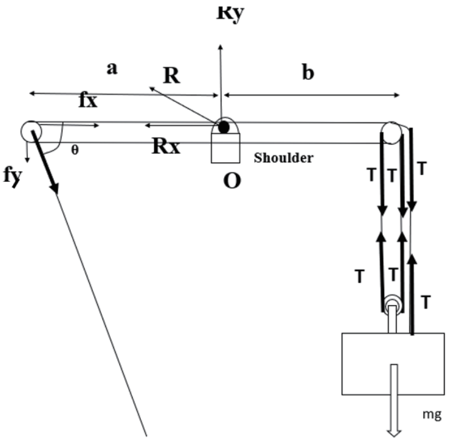


Fig. 10. Cylinder around the wrist in basic system C.

$$R_x - f_x = 0, \tag{17}$$

$$T\sin\theta \cdot a - 3T \cdot b = 0. \tag{18}$$

Then,

$$\begin{gathered} 3T = mg, \\ T = mg/3, \end{gathered} \tag{19}$$

and with $R_x = f_x = T \cdot \cos\theta$, $R_y = 3 \cdot T + T \cdot \sin\theta = (3 + \sin\theta) \cdot T$,

$$R = \sqrt{10 + 6\sin\theta} \cdot T. \tag{20}$$

Figure 11 shows the change in force on the shoulder versus angle θ for the three basic systems A, B, and C. From Fig. 11, C was considered to have the least burden on the shoulder and to be the easiest to maintain a static stable state. Therefore, to reduce the burden on the shoulder the most, a model combining dynamic and fixed pulleys was considered suitable in this study. In addition, systems A and B would be suitable for use as simple models, but the system of A would be suitable for carrying a load with a smaller θ (in a higher posture) and that of B would be suitable for carrying a load with a larger θ (in a lower posture).

3.2 Model of shoulder shock absorber

The effects of springs and dampers installed in the shoulder unit were studied. Figure 12 shows a schematic of the study and the variables and constants used. The spring constant k in the diagram is the elasticity constant of the rod connecting the shoulder and the associated spring. The spring constant k_1 and the damping coefficient c_1 are constants for the springs and dampers of the shoulder.

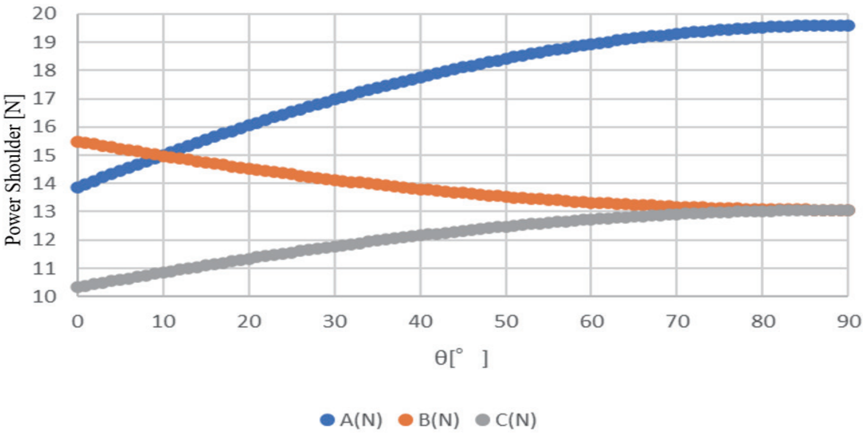


Fig. 11. (Color online) Forces on the shoulder.

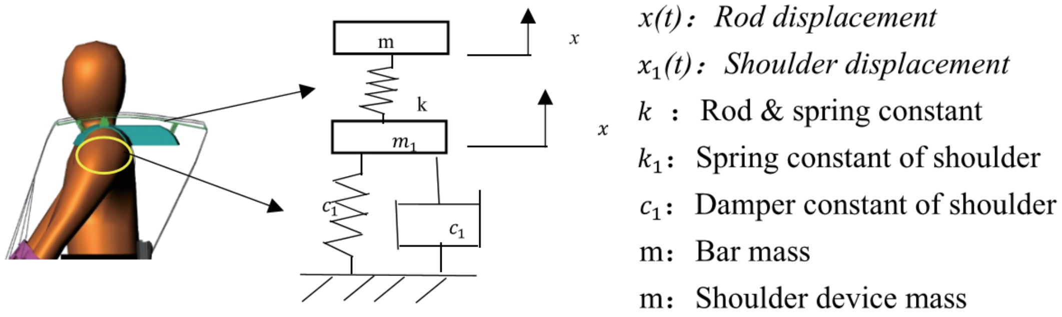


Fig. 12. (Color online) Schematic of shoulder device model.

The equations of motion based on the variables and displacements shown in Fig. 9 are the equations of motion for a 2-DOF system in Eqs. (21) and (22). [Note that *F*(*t*) is the load applied to the bar.]

$$M\ddot{x}(t) = F(t) - k\{x(t) - x_1(t)\} \tag{21}$$

$$M_1\ddot{x}_1(t) = -k_1x_1 - c_1\dot{x}_1 - k\{x_1(t) - x(t)\} \tag{22}$$

The Laplace transform of Eqs. (21) and (22) with *F*(*t*) = 0 yields

$$Ms^2X(s) = -kX(s) - X_1(s)\}\,, \tag{23}$$

$$M_1s^2X_1(s) = -k_1X_1(s) - C_1SX_1(s) - kX_1(s) + kX(s). \tag{24}$$

Now, if the input is x and the output is x_1, the transfer function *G*(*s*) is quadratic, as

$$G(s) = \frac{X_1(s)}{X(s)} = \frac{-Ms^2}{M_1s^2 + c_1s + k + k_1 + 1}. \tag{25}$$

3.3 Shoulder shock absorber simulation results and discussion

Using the model equation in Sect. 3.2, we investigated the effects of the bar, the spring constant of the bar, and the damper coefficient for the shoulder on the shoulder. Figure 13 shows the basic results. The vibration was examined when the load was lifted after 2 s and placed after 4 s. In the figure, the displacement of the bar and the force on the shoulder are shown.

On the basis of the findings shown in Fig. 13, the spring constant *k* of the bar in the model shown in Fig. 10 was increased from 100 to 500 N/m, and the results are shown in Fig. 14. The

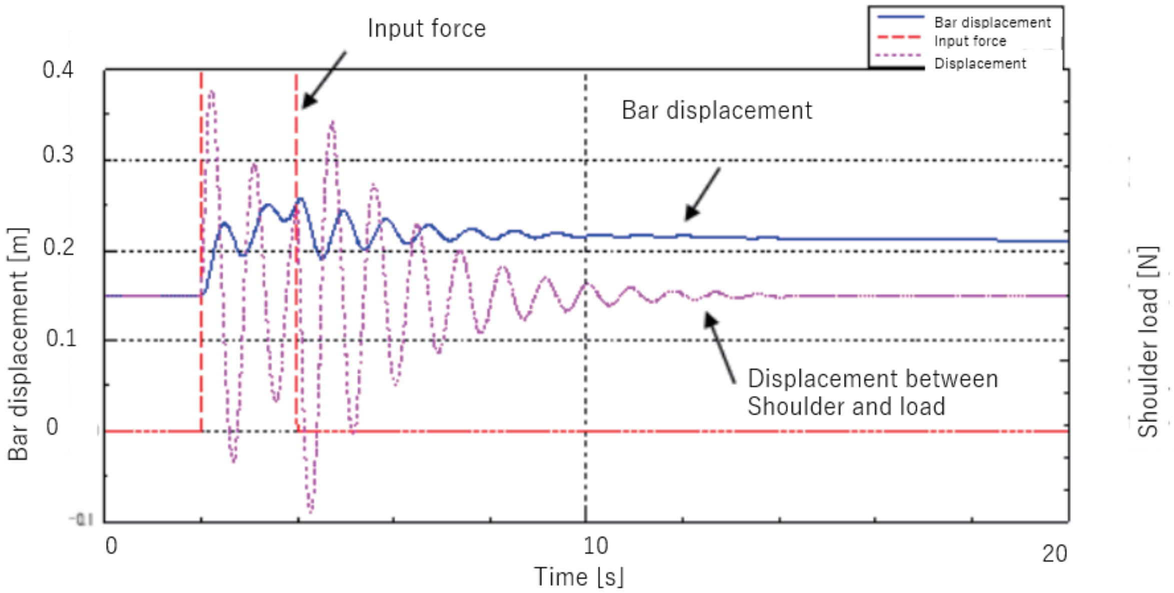


Fig. 13. (Color online) Results of calculation using the fundamental model.

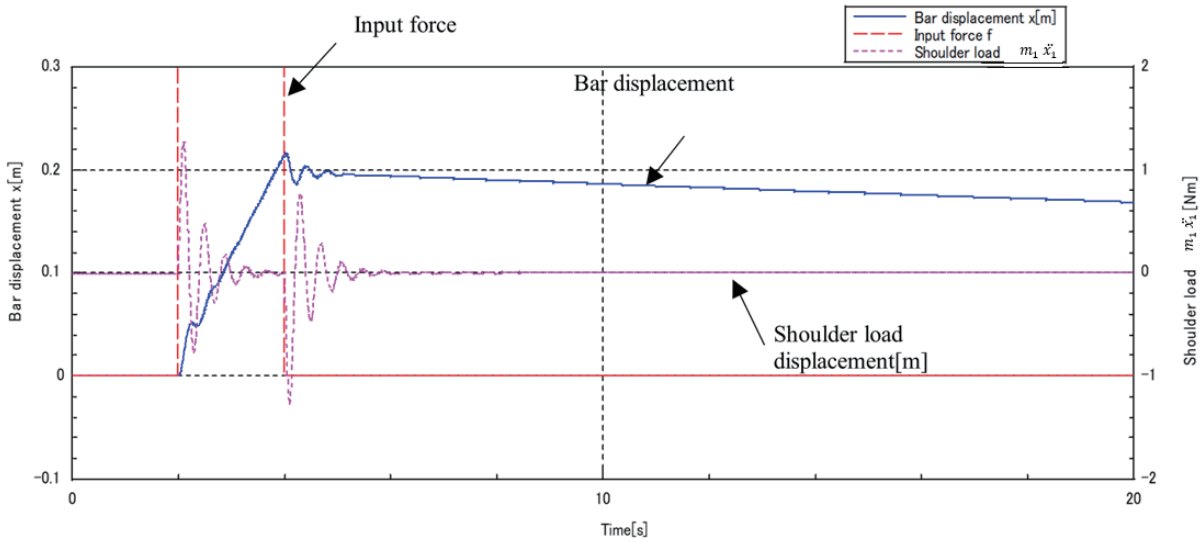


Fig. 14. (Color online) Calculated changes in bar displacement and shoulder load with increasing spring constant of the bar in the device mode.

vibration of the bar displacement rapidly decays, but the maximum load on the shoulder increases from about 0.7 to 1.2 N.

Again, on the basis of the data in Fig. 13, the damper coefficient c inside the shoulder was increased from 100 to 200 kg m/s. The results are shown in Fig. 15. Although it took time for the vibration to converge, the shoulder load was about 0.4 N, which is the smallest.

Figures 15 and 16 show the results of increasing the spring constant k from 100 to 500 N/m. Although the displacement of the bar is reduced, the burden on the shoulder, which was seen to be reduced in Fig. 15, is observed to increase again.

Figure 17 shows the results of increasing the spring constant of the shoulder k_1 from 1 to 100 N/m under the same conditions as in the case of Fig. 15. Compared with the results shown in Fig. 15, where the shoulder load was minimized, there is no significant difference. The effect of the shoulder spring constant on the shoulder load seems to be small.

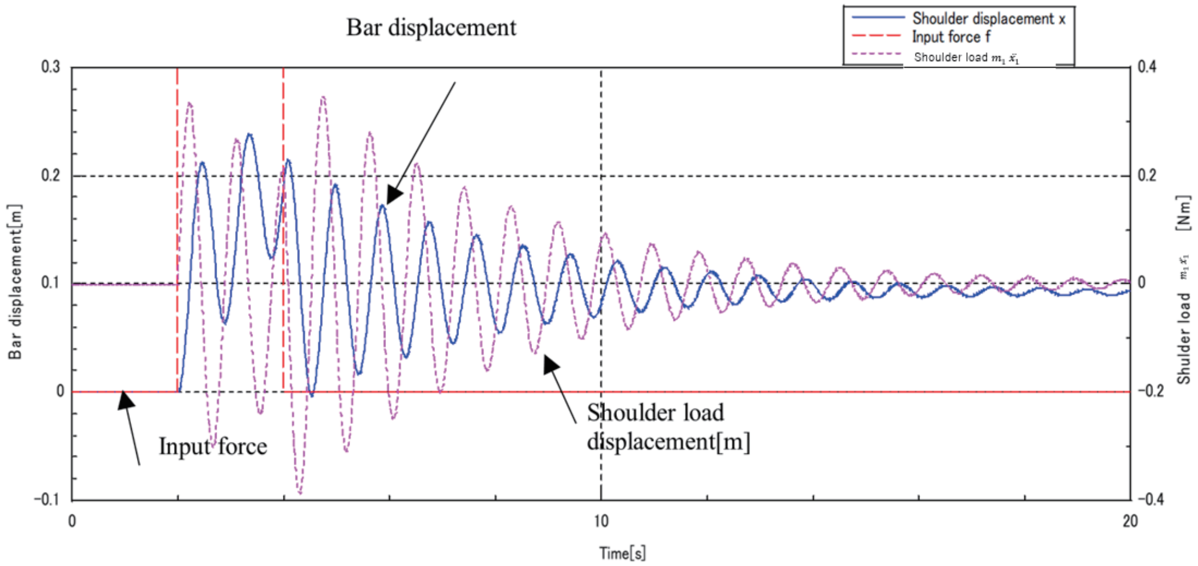


Fig. 15. (Color online) Calculated changes in bar displacement and shoulder load with increasing damper constant of the bar in the device mode.

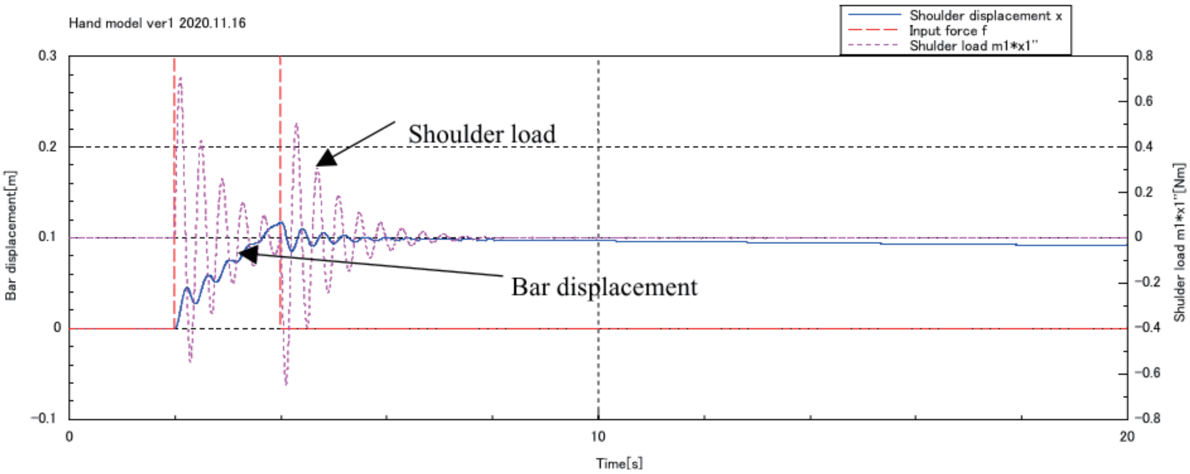


Fig. 16. (Color online) Calculated changes in bar displacement and shoulder load with increasing spring constant k of the bar in the device mode.

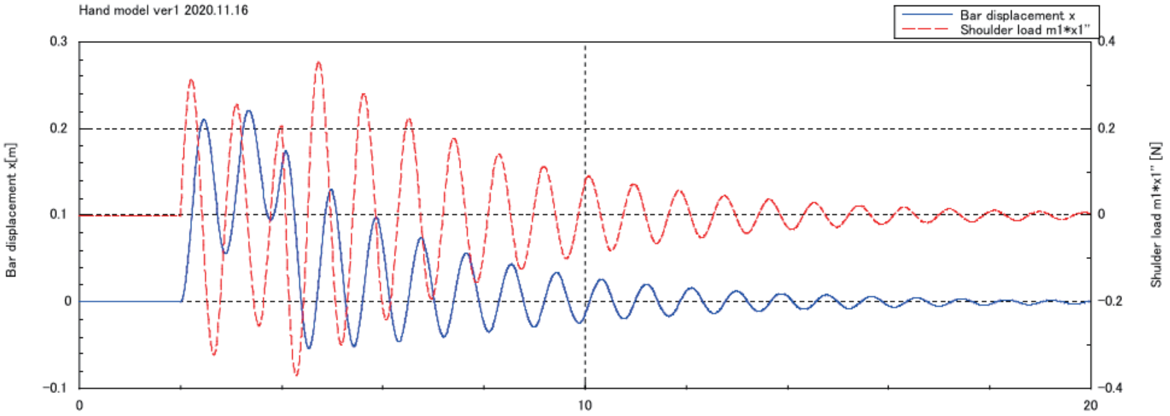


Fig. 17. (Color online) Calculated changes in bar displacement and shoulder load with increasing spring constant k_1 of the bar in the device mode.

4. Experiments to Demonstrate the Usefulness of Lower Limb Strength

4.1 Comparison of lifting with arm force only and lifting using thigh muscles

Generally, when lifting a load above the abdomen, only arm strength is used. On the other hand, when the device is used, the load can be lifted above the abdomen using the thigh muscles. Therefore, an experiment was conducted to compare lifting a load using only arm strength with lifting a load using the thigh muscles. In this study, we measured the forces when the load was actually lifted using only the arms and using the thigh muscles, employing a pneumatic circuit pressure-measuring device. Note that by lifting the load in a sitting position, the conditions when lifting the load using only arm strength were reproduced. In addition, by fixing the elbow with a stick, the condition of lifting the load with the force of the thigh muscles only was reproduced. This experiment was approved by the Research Ethics Committee of Kurume Institute of Technology.

4.2 Schematic of experimental apparatus and method

In this section, we describe the schematic of the experimental apparatus and method used in this study. Note that the subject of this experiment was an adult male in his sixties. Figure 18 shows the circuit diagram of the experimental apparatus. Figure 19 shows the state of the load when it was lifted by the force of the arms only. Figure 20 shows the conditions when the load was lifted using the thigh muscles.

Experimental method

(1) Apply the pressure adjusted by the pressure-reducing valve to the cylinder rod side.
(2) Lift the handle attached to the end of the rod.
(3) Measure the pressure on the pressure gauge.

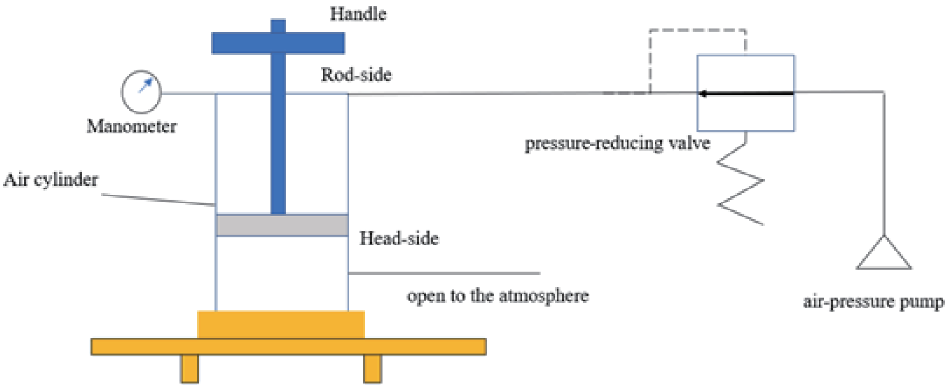


Fig. 18. (Color online) Circuit diagram of the experiment.

Fig. 19. (Color online) Lifting a load using only the arms.

4.3 Experimental results

As shown in Fig. 21, when the load was lifted using the thigh muscles, the maximum force produced was 119.8 N greater than that produced in lifting using only the arms. Therefore, it is considered that this lifting-assist device can be used to reduce the burden on the body and save labor by utilizing the force of the thigh muscles.

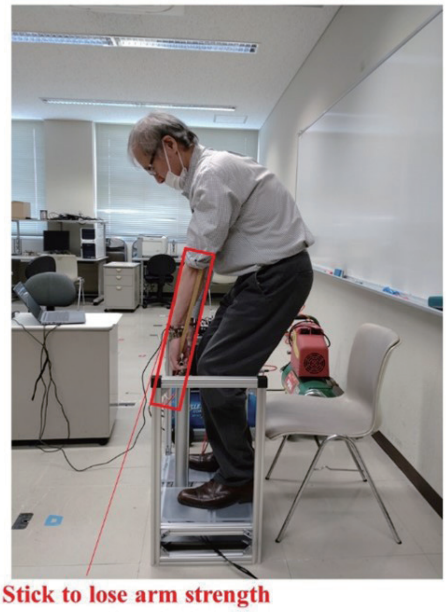


Fig. 20. (Color online) Lifting a load using the thigh muscles.

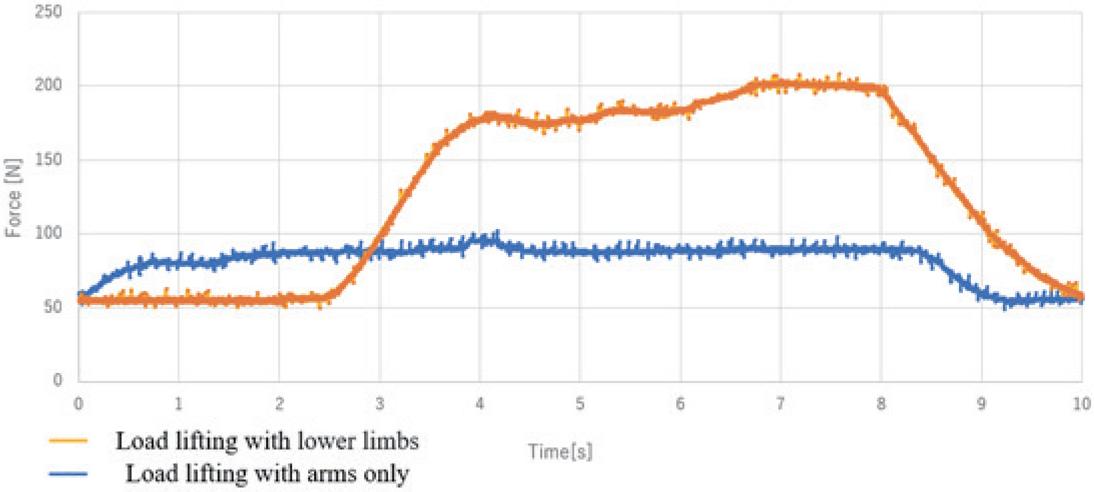


Fig. 21. (Color online) Forces produced when lifting a load using thigh muscles and using arms.

5. Discussion

5.1 Forces on the shoulder and arm

Because the shoulder forces are too high for the mechanism of the simplified basic system A, basic systems B and C were designed. Both are basic models that include fixed and dynamic pulleys. When handling objects, it is important to minimize the size of the pulleys and design a mechanism that distributes the forces well, as the wire simply passes through the pulleys. The cylindrical strap that covers the wrist has a small hole to prevent the wire from breaking when it is lifted.

5.2 Simple but powerful power supply

The power source of the device is not a conventional electric motor or hydropneumatic pressure, but the muscles of the human thigh. As a result, the device is simple in construction and requires minimal force, which is applied mainly to the shoulders and arms. When the hands used to lift the load have no vertical swing, the tension of the rope in the vertical direction and the gravity of the weight are negligible. In other words, the force exerted on the hands is minimal.

5.3 Reducing the load on the shoulder (elastic constant and damping factor)

By increasing the elastic constant, the displacement of the bar during weight lifting decreases, but the load on the shoulders increases. On the other hand, increasing the damping factor reduces the load on the shoulders. In other words, it is desirable to install a mechanism with a damper at an intermediate position between the bar and the shoulder. Similarly, it has been found that the load on the ankle and knee joints can also be reduced by increasing the damping factor,(9,10) which suggests that the model based on shock absorbers is applicable to the human physiology.

5.4 Experimental results

The main difference between this and the previous study(11) is that an experiment was attempted to confirm reproducibility. The results of the experiments with this device confirmed the effectiveness of the thigh muscles as the source of power. In general, the field of mechanical engineering focuses on reducing the force expenditure of the thigh muscles by using actuators such as motors. Our device makes maximum use of the human's natural strength by exploiting the power of the thigh muscles, thereby saving labor without waste. In addition, actively utilizing the lower limb strength helps to prevent muscle weakness.

6. Conclusions

We presented a device and mechanism for lifting and holding heavy loads with the shoulders without the need to use much energy owing to using mainly the thigh muscles. Our device transfers loads conventionally supported by arm muscles to the shoulders. While this method does not reduce the load, it helps keep the load on the shoulders and makes it feel lighter to the bearer. We devised three methods: lifting the load by tension alone, using a fixed pulley, and using a combination of a fixed pulley and a dynamic pulley. It was found that the combination of fixed and dynamic pulleys reduced the load on the shoulders the most. To further reduce the load on the shoulders, the orientations of the wires of the mechanism were also calculated. The mechanism was further developed and simulated. By increasing the elasticity constant of the shoulder bar, the displacement of the shoulder bar when lifting the load could be reduced. However, it was found that the load on the shoulder increased. By using a spring damping system for the shoulder muscles and other internal structures, it was found that the coefficients of the shoulder dampers helped to reduce the shoulder load. However, there was no significant difference in shoulder burden when the shoulder spring constant was varied. Since it is not practical to increase the damper coefficient for the shoulder, a new device with a damper may be attached between the bar and the shoulder to reduce the shoulder burden. The results discussed in this paper can be applied to not only this device, but also other situations such as attaching a miniaturized damper to the shoulder harness of a backpack. The reproducibility of the experiment, as described in the discussion, was again confirmed in this work. In particular, the maximum force generated when lifting with the thigh muscles was 119.8 N (approximately four times the force generated when lifting with the arms only). This suggests that utilizing the power of the thigh muscles can reduce the load on the body and save work. In this study, new results were obtained by adding repetitive experiments to the methodology of previous studies. We hope to develop a device that allows humans to actuate their thigh muscles more independently, so that people all over the world can lead healthy and comfortable lives.

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