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Low-profile Two-degree-of-freedom Wrist Exoskeleton Device using Multiple Spring Blade

Tomohito Higuma, Kazuo Kiguchi and Jumpei Arata

Abstract—Robotically assisted rehabilitation therapy, which is therapy performed using a robotic device that guides or assists motion and frequently triggered by a biological signal (such as a myoelectric signal or brain signal) is effective in recovering motor function following impairment. In the field of rehabilitation robots and human support robot, exoskeleton robots have been widely studied both for upper and lower limbs. Applying the exoskeleton to a wrist joint remains challenging because the wrist has two degrees of freedom in a structure smaller than the structures of other upper and lower limb joints and the center of rotation moves according to motion owing to the complex anatomical structure. To tackle this problem, we developed a wrist exoskeleton mechanism that consists of two elastic elements that largely deform during motion in transmitting forces from two linear actuators implemented on the user's forearm and in transforming the forces to wrist flexion/extension and adduction/abduction. The advantages of the presented device are the device's compactness, low weight and inherent flexibility due to the elastic structure. The present paper presents an overview of the newly developed wrist exoskeleton mechanism, prototype implementation and preliminary mechanical evaluations. Evaluation tests revealed the feasibility of safely introducing the mechanism to rehabilitation therapy or support for activities of daily living.

I. INTRODUCTION

Approximately 15 million people worldwide suffer a stroke each year [1]. Active or passive movement therapy is generally performed to improve motor impairment following a stroke [2], with active movement therapy having recently been found to be more effective than passive movement therapy in promoting recovery [3]. To further improve the effectiveness of active movement therapy, rehabilitation robots have been widely studied in the field of robotics [4]. Robotically assisted rehabilitation therapy, which is therapy performed using a robotic device to guide or assist motion and frequently triggered by a biological signal (e.g., a myoelectric or brain signal) has recently been found to be effective in promoting recovery from impairments of motor function. The effectiveness of rehabilitation robots has been positively reported in previous works [5], [6].

Motor function of the upper limb largely affects activities of daily living (ADL) and thus the quality of life of stroke survivors. As pioneering works on upper-limb rehabilitation robots, MIT-MANUS [7] and Haptic Knob [8] have been presented. These are grounded end-effector-based rehabilitation robotic devices that the patient grabs the tip of and

manipulates in therapy. In contrast, wearable exoskeleton robots for rehabilitation have been widely studied in the field of robotics for both upper and lower limbs [9],[10].

The advantage of exoskeleton robots is that the device can guide or assist the human limb at the joint-to-joint level, and the robots thus potentially provide more accurate guidance or assistance than end-effector-based devices. Furthermore, as the device can be worn by the user, rehabilitation therapy can be incorporated with conventional movement therapy. However, the development of exoskeleton robots remains challenging because the mechanical requirements are higher than those of the grounded end-effector-based rehabilitation robot. A great challenge in the development of an upper-limb exoskeleton is that the device should be lightweight and compact so as to not prohibit the user's motion. Against this background, we have developed a hand exoskeleton device actuated by an underactuated mechanism, to guide and support finger motion [11]. To further extend the hand exoskeleton device, we developed a wrist exoskeleton system that will be integrated with our previously presented hand exoskeleton.

Applying the exoskeleton to a wrist joint is challenging in terms of mechanical implementation because the wrist has two degrees of freedom (DOFs), namely flexion/extension and adduction/abduction, in a structure smaller than that of other upper- and lower-limb joints, and the center of rotation moves according to motion owing to the complex anatomical structure. The wrist joint is a collection of eight carpal bones and the surrounding soft-tissue structure. Gopura et al. suggested that the two DOFs have in fact four axes, two axes for each DOF, slightly pivoted in relation to each other [9], [12]. The deviations on flexion/extension and adduction/abduction have been reported as approximately as 5 mm [13], [14]. This suggests that a fully rigid wrist exoskeleton with fixed rotation centers may result in an excess load being applied to the wearer's wrist joint because of the discordance of rotation centers. Considering that stroke patients with motor impairments often have accompanying paralysis to some degree, the excess force may damage the limb and must therefore be considered in the mechanical design.

To tackle this problem, we developed a wrist exoskeleton mechanism that consists of two elastic elements that are largely deformed in motion to transmit the force from two linear actuators implemented on the user's forearm and to transform the force to wrist flexion/extension and adduction/abduction. Advantages of the presented device are its compactness, low weight and inherent flexibility due to its

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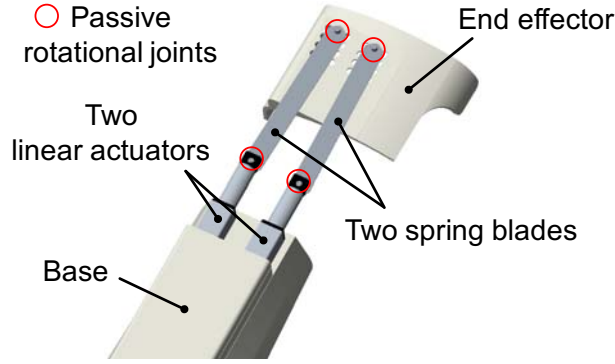


Fig. 1. The proposed mechanism consists of a base, an end-effector and two spring blades. The base and end-effector are fixed to the user's forearm and back of the hand, respectively. The ends of the spring blades are attached to the base and end-effector by passive rotational joints.

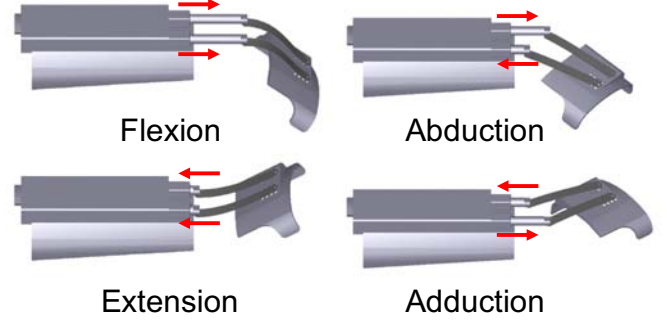


Fig. 2. Two spring blades are independently actuated along the long axis of the base to provide two-DOF (flexion/extension and adduction/abduction) motion of the user's wrist.

elastic structure. This paper presents an overview of the newly developed wrist exoskeleton mechanism, prototype implementation and preliminary mechanical evaluations.

II. RELATED WORKS

As previously mentioned, the mechanisms of upper-limb exoskeletons have been widely explored [10], and some previously presented robots include a wrist joint mechanism. However, most robots have been implemented using a rigid chain of mechanisms with a fixed rotational center(s) for the wrist, and the load applied to the joint due to structural discord between the user and robot has not been widely discussed. Kiguchi et al., for example, presented a robot by introducing a circular guided slider with its rotation center fixed at the center of the circle [9].

Devices with a similar implementation often have a gap between the robot and user, allowing the user's wrist to slightly shift according to the motion and thus avoiding an excess loading on the wrist due to the discordance of the rotational center. However, this makes the user's motion cumbersome and potentially damages the joint around the end of the range of motion (ROM), where the joint motion is inherently limited in other directions. Furthermore, the gap between the human limb and robot enlarges the robot, making the motion cumbersome and possibly prohibiting the user's motion.

Exoskeleton devices have been specifically developed for the wrist joint. Spencer et al. presented a three-DOF wrist exoskeleton device using four servomotors [15] providing pronation/supination, flexion/extension and adduction/abduction joint motion. Hasegawa et al. presented a wrist exoskeleton device based on a five-bar spherical linkage mechanism [16]. Allington et al. presented a device based on a pneumatic actuator combined with a link mechanism, providing two DOFs: pronation/supination and flexion/extension [17]. Sasaki et al. proposed a rubber pneumatic actuator that can be worn by the user to actuate wrist flexion [18].

The present paper presents a new mechanism for the wrist exoskeleton device, using two elastic spring blades. The

elastic elements can be actively slid back and forth, allowing the transmission of a bidirectional force and the design of a compact mechanism with a low profile. Deformation occurs according to how the wrist structure fits on the human wrist structure in motion, and the device thus does not prohibit the user's motion. The elasticity also allows the shift of the joint center according to the anatomical wrist structure.

III. WRIST EXOSKELETON MECHANISM

A. Requirements

The mechanism was designed to be used for rehabilitation therapy and to be further extended as an ADL support device in the future. The required ROM was thus determined as 90 degrees in flexion, 70 degrees in extension, 40 degrees in adduction and 15 degrees in abduction by considering the average physically unimpaired person. The required torque was experimentally determined to support the weight of the user's hand (0.54 Nm, computed as an average value for the Japanese elderly [19],[20]).

B. Overview

Figure 1 is an overview of the proposed mechanism. The proposed mechanism consists of a base, an end-effector and two elastic spring blades. The base and end-effector are fixed to the user's forearm and back of the hand, respectively. The ends of the spring blades are attached to the base and end-effector by passive rotational joints. Figure 2 shows the movement of the proposed mechanism. The two spring blades are independently actuated along the long axis of the base. When the two spring blades move in the same direction, the wrist joint performs flexion (from proximal to distal) and extension (from distal to proximal). Differential motion of the two spring blades allows the end-effector to move in the lateral direction, providing adduction/abduction of the wrist joint.

Note that the mechanism itself does not provide a rotation center. As illustrated in Figure 3, when the mechanism is worn by a user, the user's wrist joint provides mechanical constraints along with the rotation center of the wrist joint.

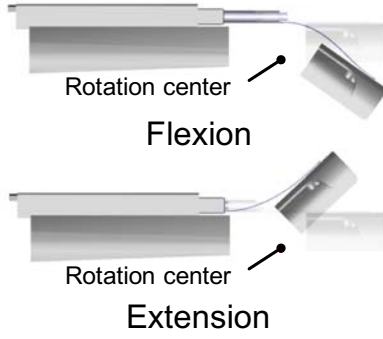


Fig. 3. The input linear force is transmitted to the rotational wrist torque by considering the user's wrist joint as part of a lever mechanism.

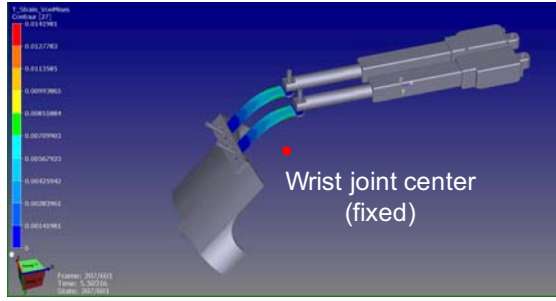


Fig. 5. A representative result of FEA for flexion is presented. FEA was performed in the range of elastic deformation of the spring blades, choosing spring steel as the material.

The mechanism provides the external force that actuates the wrist joint, as a linear motion along with the user's skin surface. The input linear force is then transmitted to the rotational wrist torque with the user's wrist joint being a pivot point. For instance, the end-effector simply moves back and forth when the mechanism is not worn by a user because of the lack of mechanical constraint. This largely contributes to simplifying the mechanism. However, a certain load is supposedly added to the user's joint structure, because the mechanism works as a lever mechanism, with a user's joint being a pivot point. This is mechanically evaluated and described in the following section.

In contrast to wire-driven mechanisms, the use of spring blades allows the mechanism to transmit the force not only in the forward direction but also backward, and the force is thus bidirectionally transmissible along the spring blade. The elastic spring blades largely deform with motion, and their deformation fits the human limb structure so as not to prohibit the user's motion.

C. Kinematic model

For flexion/extension, the two spring blades must move in the same direction and thus move back and forth at the same time. This motion largely involves spring deformation as shown in Figure 2. However, for adduction/abduction, the

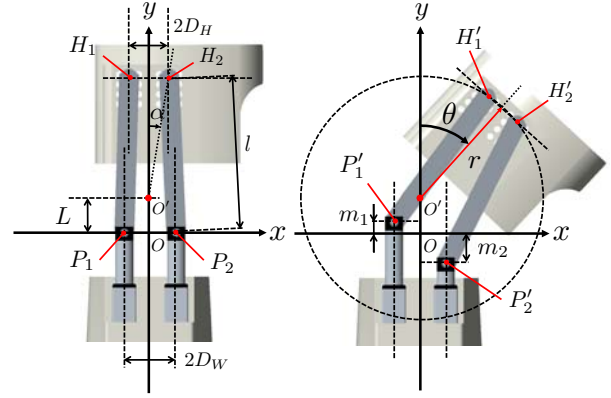


Fig. 4. A kinematic model of the mechanism is given by the parameters in the figure.

proposed mechanism can be simply described by equations of the general kinematic model.

Figure 4 shows the kinematic parameters, where the length of each spring blade is l , $2D_H$ and $2D_W$ are the distances between the two springs at the distal (H_1-H_2) and proximal (P_1-P_2) ends, respectively, and L is the distance between the wrist joint (O') and the original position of the linear motor (corresponding to both DOF angles being zero degrees).

If r is the length of $O'-H_1$ and $O'-H_2$, then

$$r^2 = D_H^2 + (\sqrt{l^2 - (D_W - D_H)^2} - L)^2 \quad (1)$$

If α is the angle between the y axis and $O'-H_1$, then

$$\sin \alpha = \frac{D_H}{r} \quad (2)$$

The coordinates of H'_1 and H'_2 after adduction/abduction through an angle θ can thus be expressed as

$$\begin{aligned} H'_1 &= (r \sin(\theta - \alpha), L + r \cos(\theta - \alpha)) \\ H'_2 &= (r \sin(\theta + \alpha), L + r \cos(\theta + \alpha)) \end{aligned}$$

If the linear motor displacement is given as m_1 and m_2 , the coordinates of P_1 and P_2 are expressed as

$$\begin{aligned} P_1 &= (-D_W, m_1) \\ P_2 &= (D_W, -m_2) \end{aligned}$$

As the lengths $P_1-H'_1$ and $P_2-H'_2$ equal l ,

$$l^2 = \{r \sin(\theta - \alpha) + D_W\}^2 + \{L + r \cos(\theta - \alpha) - m_1\}^2 \quad (3)$$

$$l^2 = \{r \sin(\theta + \alpha) - D_W\}^2 + \{L + r \cos(\theta + \alpha) + m_2\}^2 \quad (4)$$

A forward kinematic model for adduction/abduction is therefore

$$m_1 = L + r \cos(\theta - \alpha) - \sqrt{l^2 - \{r \sin(\theta - \alpha) + D_W\}^2} \quad (5)$$

$$m_2 = -L - r \cos(\theta + \alpha) + \sqrt{l^2 - \{r \sin(\theta + \alpha) - D_W\}^2} \quad (6)$$

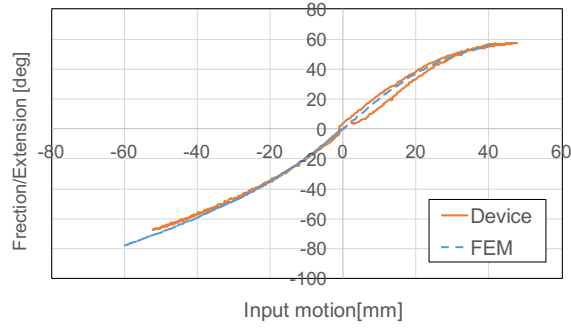


Fig. 6. Flexion/extension is provided by the motions of linear motors in the same direction. The graph shows the flexion/extension trajectory computed in FEA and measured in the evaluation experiment, with flexion corresponding to a positive angle and extension to a negative angle.

D. Simulation employing finite element analysis

Finite element analysis (FEA) was conducted using a computer-aided-design model of the proposed mechanism and DAFUL version 5.2 [21], while the model was pre-processed using FEMAP version 10.0.2 [22]. For the spring material we selected hardening carbon steel (having a Young modulus of 205 GPa) with thickness of 0.3 mm, by a series of preliminary analysis.

Note that the stroke length of linear motors are configured as 100 mm, taking into consider the prototype implementation described in the following section.

Figure 5 shows representative results of FEA. Note that the wrist joint center was determined as a virtual fixed point in the analysis because the mechanism requires a rotational center for the motion that would be determined by a human wrist joint in practice.

Figure 6 shows results of FEA for flexion and extension. It is seen that a sufficient ROM of 133.3 degrees is possible in flexion/extension within the range of elastic deformation.

In contrast to the case for flexion/extension, adduction/abduction can be described using a general kinematic model because the kinematic relationships are only given by the geometric distribution of joints. Figure 7 shows the angle of adduction/abduction while varying the differential motion between the two linear motors, expressed as m_d . Note that the flexion/extension was fixed at zero degrees. As the mechanism contains elastic material that deforms according to the motion, the input energy is stored in the mechanical structure. This suggests that the presented mechanism requires a force stronger than that required by commonly used link-driven mechanisms, to resist the reaction force from the spring blades. FEA gave the expected output torque applied to the wrist joint in flexion/extension, for the proper selection of an linear actuator according to requirements (Figure 8).

From the results of FEA, this selection provides a maximum angle of flexion of 55.3 degrees in, 78.0 degrees in extension, 34.8 degrees in adduction and 12.2 degrees in abduction. The limitation of ROM is mostly due to the limitation of stroke length of linear motors except for flexion, thus

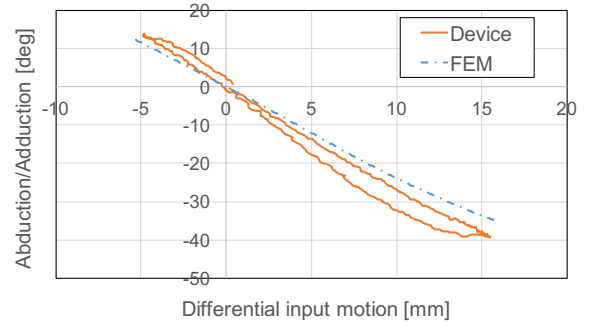


Fig. 7. Adduction/abduction is provided by the differential motion between two linear motors. The graph shows the abduction/adduction trajectory computed in FEA and measured in the evaluation experiment, with adduction corresponding to a positive angle and abduction to a negative angle.

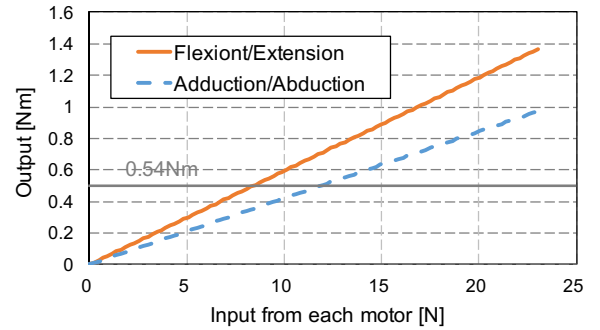


Fig. 8. The graph shows the expected output torque of the mechanism at different motor inputs for each linear actuator, computed by FEA.

can be further extended. Our preliminary analysis revealed that the harder spring enables a larger transmission, allowing a larger ROM in flexion. However, for a ease of prototype implementation, we determined the prototype design for a feasibility study as the model analysed in FEA described in this section.

IV. PROTOTYPE IMPLEMENTATION

We developed the prototype according to the analytical results described in the previous section, as shown in Figure 9. The prototype was fabricated from Acrylonitrile Butadiene Styrene (ABS) resin, using a three-dimensional printer (UPrint SE PLUS, Stratasys Ltd., USA). The spring blades were fabricated by a laser cutting machine from hardening carbon steel with thickness of 0.3 mm. The wrist exoskeleton was 310 mm in length and weighed 288.3 g, and the total weight of the system, including the control box, battery and cables, was 509.5 g.

The wrist exoskeleton can be attached to the user's forearm and wrist using Velcro straps. The internal side of the device is ergonomically curved and covered by a soft texture to provide comfort and to avoid dislocation between the robot and limb. All mechanical parts are implemented on the user's back side of the hand so as to not prohibit physical contact

when handling objects while wearing the device. The device was designed to have a low profile (with thickness of 2.0 to 22.5 mm) so as not to prohibit the user's movement.

The control box consists of a microcomputer (Coron, Techno Road Co., Ltd., Japan) and a mobile battery (QE-PL103, Panasonic Co., Ltd., Japan) and controls the two linear motors (L12-100-100-6-R, Actuatorix Motion Devices Inc., Canada) implemented in the prototype. Each linear motor provides a maximum of 42 N of force at a stroke of 100 mm. The current prototype is only equipped with simple buttons for the motion trigger, but will in future receive a biological signal, such as an electromyography signal, to get the trigger from the user.

V. EVALUATIONS

A. Range of motion

The ROM was tested for the prototype by monitoring the motion using a camera system (Motion Analysis Microscope VW-6000, Keyence, Japan) while the frequency of image acquisition was set as 250 fps. The motion was tested on a testbed wrist joint (Figure 10(a)) that comprised a rigid forearm and wrist connected by a universal joint. The total weight of the testbed wrist joint was 296.4 g, with the forearm part weighing 86.4 g, the hand part 83.2 g and the universal joint 126.8 g. Note that the testbed wrist joint was introduced to conduct a quantitative assessment, while the rotation center of the wrist joint was fixed in contrast to human anatomy.

Figures 6 and 7 show the experimental results for flexion/extension and adduction/abduction, respectively, together with the results of FEA. Overall, the prototype motion was in good agreement with the FEA results. Hysteresis was observed in the experiment, supposedly because of a difference in the deformation of the two springs due to the backlash of linear actuators and passive joints, but not in FEA. The maximum observed angle of flexion was 56.7 degrees, that of extension was 68.1 degrees, that of adduction was 39.5 degrees and that of abduction was 13.8 degrees. The results show the ROM mostly covered that of the healthy subjects, and 63 % in flexion. The ROM in flexion can be further extended by harder spring blades as previously mentioned in the section III. D.

B. Output Force

The output force of the prototype was measured using a three-axis force sensor (USL06-H5, Techgihan, Japan) fixed on a base, while the motion was performed against the sensor (as shown in Figure 10(c)). The prototype was set on the testbed wrist joint during motion. The force was measured for flexion/extension and adduction/abduction at different five positions in each direction.

Results are given in Table I. The maximum output force depended on the position because the deformation of springs largely affected the output. When the wrist joint was flexed, the output force was limited at most for both flexion and extension. This largely relates to the spring characteristics. The spring blades are compressed for wrist flexion and

TABLE I
RESULTS OF OUTPUT FORCE ASSESSMENT

Direction	Position				
	Flexed	-	Straight	-	Extended
Flexion [N]	3.2	7.7	15.6	16.6	9.7
Extension [N]	5.3	4.8	17.4	22.8	29.5
Direction	Adducted	-	Straight	-	Abducted
Adduction [N]	9.8	7.4	7.2	6.9	6.5
Abduction [N]	6.8	7.0	7.2	7.5	7.8

extended for wrist extension as illustrated in Figure 3. When the spring is compressed toward its long axis, there is deformation perpendicular to the long axis outwardly and energy is stored in the spring as elastic energy, thus decreasing the efficiency as a force transmission system. When the spring is extended, there is no deformation perpendicular to the long axis because the spring is guided by the device. This can be minimized by adding a mechanical guide or stopper to control the spring deformation in flexion; however, this may increase the mechanical complexity. The authors' previous work showed that a stiffer spring can transmit a stronger force but requires a larger input force. This suggests that the input/output relation of the proposed mechanism is determined by not only the motor specifications but also the mechanical configuration, and can further trade-off in its implementation. The output force observed for adduction/abduction did not change greatly in the range of motion, showing only a minor variation due to the angles of mechanical linkages changing in motion.

C. Load applied to the wrist part

An experiment was conducted using the same testbed wrist joint used in the previous experiments to assess the load applied to the user's wrist joint due to the device motion. A force sensor (USL06-H5, Techgihan, Japan) was placed between the wrist fixation part and the end-effector to measure the applied force from the prototype while the flexion/extension and adduction/abduction motion was independently performed. Contrary to human anatomy, the testbed wrist joint has a fixed rotation center on the wrist joint. The experiment was therefore performed as a preliminary assessment, taking advantage of the fact that the testbed wrist joint has fairly low joint impedance and thus making a quantitative assessment of the mechanical properties of the prototype.

As the experimental results, the maximum resultant forces recorded by the force sensor were 10.24 N for flexion/extension and 4.26 N for adduction/abduction. The observed force was larger in the direction that the device exerts a force. The resultant force was sufficiently weak so as not to harm the user's joint and limb. However, further user-based assessment is required to evaluate the interaction force between the device and human limb, to ensure safety.

D. Rigidity

Rigidity was measured by applying a displacement by a linear motor (RCA2-RP3N-I-10-1-30-A1-N, IAI Corporation, Japan) with a force sensor (LUR-A-200NSA1, Kyowa



Fig. 9. An overview of the developed prototype is shown. The prototype has total weight of 509.5 g, length of 310 mm and thickness of 2.0 to 22.5 mm and can thus be worn by a user without excess effort.

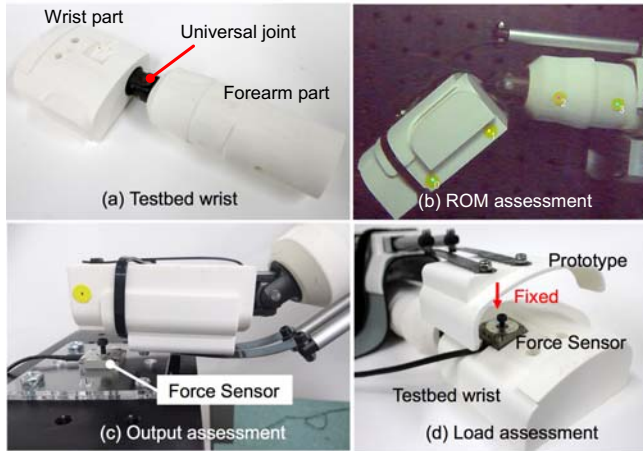


Fig. 10. The experimental setup is shown; (a) the testbed wrist joint that consists of a rigid forearm and wrist parts connected by a universal joint, (b) the experimental setup for the ROM test, (c) the experimental setup for the output force measurement and (d) the force sensor implemented in the wrist part to evaluate the load applied to the user's wrist by the device.

Electronic Instruments Co., Ltd., Japan) attached at the tip, while the prototype fixed on the testbed wrist joint. A motion speed of the linear motor was set as 1 mm/s in velocity, and displacement as 10 mm. The measurement was performed in the same positions of prototype with the experiment performed for output assessment (Table I) by applying the displacement to the tip of wrist part from different four angles (palmar, dorsal, adduction and abduction). The rigidity was then computed by averaging the measured rigidities.

The experimental results revealed that the averaged rigidity was 1.03 N/mm. It was shown that the rigidity was smallest at the flexed position (0.47 N/mm) and largest at the extended position (1.35 N/mm). In the extended position, the spring blades are guided by the prototype body and largely deformed, thus the rigidity was supposedly increased. The deviations on flexion/extension and adduction/abduction have been reported as approximately as 5 mm [13], [14], thus the reaction force from the robot is supposed to be 5.15 N at maximum. Note that the prototype was fixed on a rigid testbed wrist joint in this experiment, thus the result shows the worst case in terms of the reaction force from the robot,

because the stiffness of human limb is lower than that of the testbed wrist joint. This suggests that the structure of proposed prototype is fairly soft, thus allows the movement of wrist rotation center caused by human anatomy without having an excess load.

VI. DISCUSSION AND CONCLUSIONS

A new wrist exoskeleton mechanism was proposed and a prototype introduced. Furthermore, preliminary evaluations regarding the ROM, output force and load applied to the user's limb were presented. The presented mechanism consists of rigid wrist and forearm parts connected by two spring blades. The device has two DOFs on the wrist joint for flexion/extension and adduction/abduction. A series of preliminary evaluations revealed the feasibility of the mechanism as a wrist exoskeleton mechanism.

The contribution of the paper is the proposition of a wrist exoskeleton mechanism that elastically deforms to fit to the human body in motion and thus does not impede the wearer's motion. The elasticity was found to be effective in terms of avoiding excessive loading of the user's wrist, which is a possibility for previously presented rigid systems owing to the discordance of joint centers. The simple mechanism based on spring blades largely contributes to reductions in weight and size. The prototype has total weight of 509.5 g, length of 310 mm and thickness of 2.0 to 22.5 mm and it can thus be worn by a user without excess effort.

We plan to further improve the device according to the evaluations described in the present paper and to assess the device on human subjects. Our primal goal is providing the presented device as a tool for robotic rehabilitation. The device can be extended for use as an ADL support device.

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