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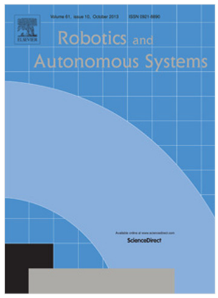

Waist-assistive exoskeleton powered by a singular actuation mechanism for prevention of back-injury

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Waist-Assistive Exoskeleton Powered by a Singular Actuation Mechanism for Prevention of Back-injury

Hun Keon Ko, Seok Won Lee, Dong Han Koo, Inju Lee and Dong Jin Hyun*

***Abstract*—This paper proposes the design of an electrically-powered waist assistive exoskeleton wire-driven only by one actuator and its control method. The developed exoskeleton is intended to reduce muscle fatigue and further prevent back-injury of industrial workers who undergo repeated, intensive waist motions. Considering requirements specially for industrial purposes, system performances related to cost, weight, operational time, and system endurance & maintainability of the robot have to be specially pursued. Therefore, reduction in the number of actuators without deteriorating the robot's main function can be an effective approach. Along with this concept, only the single actuator mounted on the back part of the robot is proposed to simultaneously drive both legs by wire through a differential gear mechanism. The applied differential mechanism allows natural motions generally observed in human walking with almost zero mechanical impedance, but the waist motion for lifting-up heavy objects can be assisted by the powered extension of both legs. A current control algorithm embedded in a micro-controller is specially designed to achieve objectives of the robot.**

In order to evaluate the waist assistance provided by the developed robot, activation signals of electromyography (EMG) on main muscles of working wearers related to waist motions were measured. Further, the usability was evaluated using the responses of a questionnaire survey. Thus, the proposed method for waist assistance by a singular actuator is verified to be conclusively effective.

***Index Terms*—waist assistance, lower-limb exoskeleton, under-actuation**

I. Introduction

Currently, many workers are suffering from musculoskeletal disorders caused by industrial tasks that involve repetitive motions. These disorders negatively affect the workers' work efficiency as their active daily lives. It is reported, according to a statistical analysis on industrial works, that approximately 40% of all work-causing illnesses are related to musculoskeletal disorders, and one of the representative symptoms is low-back pain [1]. Statistically, the incidence of back disorders is observed to be higher especially in areas of construction, transport, storage, human health, and social work activities. In these industries, workers frequently undergo repetitive movements such as heavy lift-up and load-carrying with a deeper forward bending posture, which is known to cause back-pain. Therefore, it is important to determine solutions that can prevent musculoskeletal diseases and further improve the working efficiency by reducing the muscle fatigue of industrial workers.

Recently, exoskeleton technology is being considered as a promising solution for prevention of musculoskeletal diseases especially in industries [2] [3] [4] [5] [6] [7]. Further, the researches on assistive torque generation methods utilizing various exoskeletons have been conducted to assist individuals with various disorders [8], [9], [10], [11]. To support this technological trend, various types of assistive exoskeletons are actually applied to real industrial environments, it is reported that they was able to make then to forty percentage reduction in back muscle activity [12]. Representatively, A 'Muscle suit' is one of the powered hip exoskeleton robots for lifting assistance [13]. It uses two McKibben-type artificial muscles for both hips as an actuation system, and can be applied to various fields such as logistics, nursing, and agriculture. In addition, the 'HAL Lumbar Support' is a good example of exoskeleton robots for lifting assistance. It has sensors attached to its back, which detect the bio-electrical signals of a muscle to determine when an assistive torque should be generated by motors located in both hip joints [14]. Despite a few successful cases on the application of wearable robots to rehabilitation, industrial exoskeletons have not been widely deployed yet due to performance limitations such as wearing discomfort due to the heavy weight and insufficient torque transmission.

For these reasons, the task of effective waist assistance is still an issue of great interest to engineers in the field of wearable robotics, and various types of devices are still being developed to tackle engineering problems. For instance, mechanical clutches were utilized to lock hip joints at static postures to achieve low power consumption [15]. In addition, a pneumatic muscle actuator was applied to implement a light-weight flexible endoskeleton-type device [16] [17]. Such waist-assistive devices, including the one with conventional design [18], generally have a mechanism that binds the upper body and both thighs in order to transmit torque generated by actuators located parallel to the joint, where assistance is required, without ground contact. Therefore, the total weight of the device is critically sensitive to a wearer. However, the actuation units need to be capable of large torque outputs, which requires heavy actuators or power sources [19]. To overcome this limitation and attain a tradeoff that maximizes the beneficial effects, minimal actuation could be the right approach for such types of modular devices.

This paper introduces a novel wire-driven singular actuation mechanism utilizing a differential gear. Comparing the mechanism with the conventional ones, the following characteristics can be provided. The proposed mechanism intends to transmit a large waist-assistive torque for a wearer's industrial tasks just by a singular actuator, which might allow the development of a low-cost, lightweight waist-assistive exoskeleton with simple electrical wiring. When a wearer is walking, almost

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Fig. 1: Overlapped photos describing operation of the H-WEX

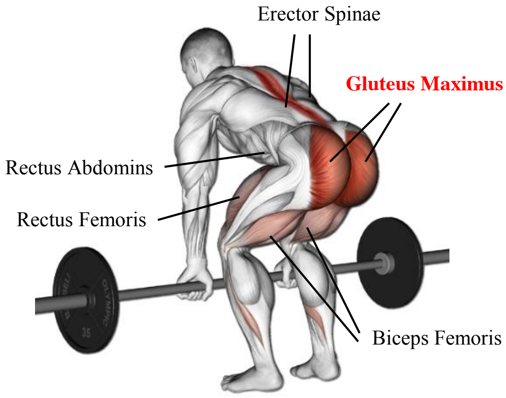

Fig. 2: Anatomical analysis of waist motion

zero mechanical impedance on both hips is allowed by the proposed mechanism even without utilizing the operation of actuator. Because there is little power consumption in walking motion, which occupies a portion of total consumption, the operating time for the assistance for the back muscle can be comparatively increased.

Furthermore, The Hyundai Waist Exoskeleton (H-WEX), shown in Fig.1, was developed to verify its performance. H-WEX is a lightweight (4.5 kg including batteries), electricity-powered mobile waist exoskeleton on which a embedded controller determines the proper torque to be transmitted according to a developed control algorithm. The experimental results with H-WEX indicate that the proposed mechanism effectively achieve waist assistance for various wearers, which implies that a low-cost, lightweight and power-saving but reliable solution for waist assistance can be achievable by the proposed singular actuation mechanism.

The remainder of this paper is structured as follows: Section II introduces the hardware design of H-WEX including the novel mechanism. Section III explains the control algorithm implemented on the robot. Subsequently, experimental procedures and evaluation data are provided in Section IV. Lastly, the key findings of the study are summarized in Section V.

II. Design of the Exoskeleton

A. Design Concept

Back injuries are caused mainly when an individual lifts an object repeatedly, holds the heavy object in the static posture, and twists his/her back owing to the heavy load. To reduce these injuries, it is helpful to apply a system that can assist the waist movement in the direction of anti-gravity. Generally, this system is configured to transmit assistive torque to a wearer's torso through actuators allocated at both hip joints. This configuration is quite simple but requires a large-sized motor combined with a high gear-ratio reducer in order to satisfy torque-velocity specification for the waist-assistive task. Therefore, the configuration frequently leads to increase in the total system weight and decrease in the system responsibility.

A novel system configuration is derived based on insight in biomechanics to tackle this problem. Considering the human anatomy, the main muscles related to motion of the waist and hip are *Gluteus Maximus* located on both hips as shown in Fig.2 [20]. During the flexion and extension of the waist, these two muscles synchronously act like one united muscle because the rotation direction of both hip joints is the same. This indicates that it is possible to assist movements of the waist only by a singular actuator that is analogous to this united muscle. Then, the developed exoskeleton is actually the power transmission system transferring generated torque by one actuator to both the hip joints.

Furthermore, for normal walking, the two muscles are independently activated because the direction of motion of both hip joints is opposite to each other except in a specific gait phase called the double stance [21]. Thus, power transmission systems must allow both hip joints to move with minimal mechanical impedance in the opposite direction for normal walking. For this, a differential gear is adopted in the middle stage of a power transmission system. The under-actuation system, consisting of a single motor and a differential gear, has been developed from this analysis. The actuator module was placed near the back side of the hip similar to the corresponding muscle position. For usability, the mechanical links were designed focusing on weight reduction and maximization of the contact surfaces for assistive forces.

B. Novel Actuation Mechanism for H-WEX

One of the important design parameters is the thickness of the actuator module when considering the location of the actuator module that is mounted on the back hip. If the thickness of the actuator module is designed to be large, a wearer might feel discomfort especially when having a seated or working posture. The combination of a flat motor and a harmonic gear can be an adequate solution to design a thin actuator module. The specification of the actuator module was targeted by referring to the guidance for manual handling in workplace [22]. According to the reference, it is recommended that the weight of the hand-handling object should be 15 kg or less when an individual has a posture with fully-extended arms. At this time, the length of the arm is assumed to be approximately 60 cm from the average human body dimension, and the required torque can be calculated as 90 N m from the values. It is assumed that the operating speed does not exceed 90 degree per second in the maximum load condition. A flat-type BLDC motor with rated output of 200 W is used as an actuator in consideration of the above described speed, torque, and friction loss. The harmonic drive is combined with the motor as a differential gear application. The developed actuator module is depicted in Fig.3. Two drive pulleys are connected to the flex spline and the circular spline of the harmonic gear, respectively. Therefore, the two drive pulleys are free when rotating in the same direction, and are affected in the opposite direction by the electric motor. The torque from the drive pulleys is transmitted to the hip joint pulley through a wire as described in Fig.4, which is mechanically guided by a set of rollers installed inside of the frame link along the hip line. The diameters of the drive pulley and the joint pulley are chosen to be same. Thus, two connected pulleys have the same amount of rotational movement.

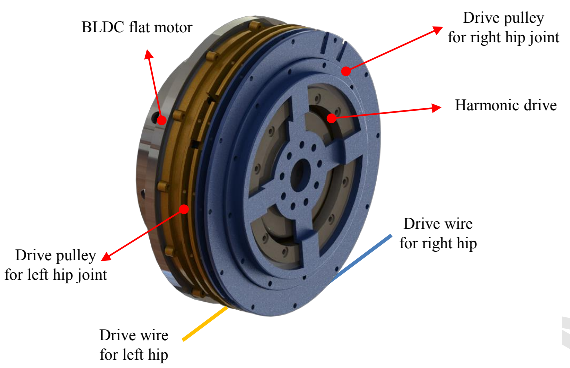

Fig. 3: Actuation unit: BLDC motor with harmonic drive

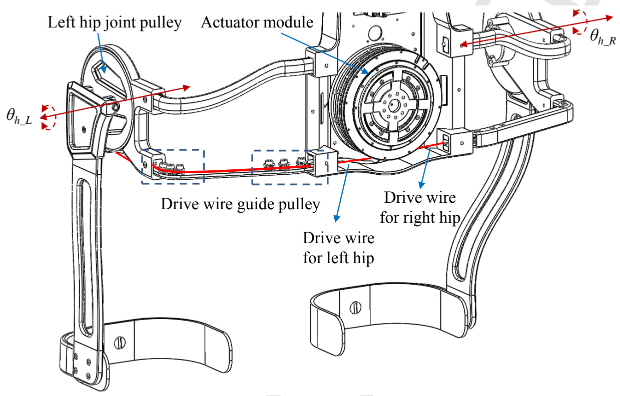

Fig. 4: Wire-driven torque transmission system

The operating principle of the developed drive system module is as depicted in Fig.5. The drive pulleys for the left and right legs are respectively marked with blue and red color lines to indicate the relative position of drive pulleys. Figure 5. (a) shows the position of the drive pulleys in the standing position corresponding to neutral status. The drive pulleys move in opposite directions with the same displacement as shown in Fig. 5. (b) when the waist is flexed. In the first step for walking, the two drive pulleys rotate in the same direction as both legs move in opposite directions. Simultaneously, relative rotation occurs because the displacement of the swing leg is greater than the displacement of the stance leg. The drive pulleys are located as shown in Fig. 5.(c) as a result of these movements. After that, both legs move almost symmetrically in walking [23], and so, the output pulleys rotate together in the same direction, as shown in the Fig. 5(d). The electric motor is stationary at this time, and so, the wearer can walk without resistance.

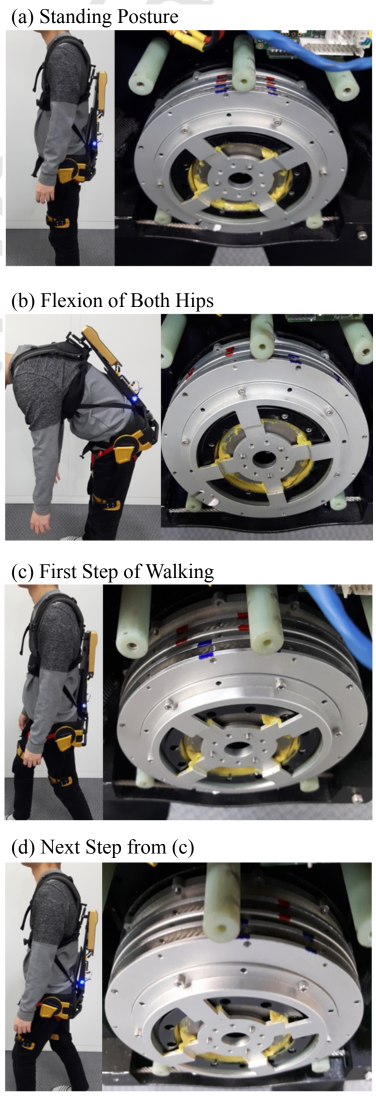

Fig. 5: Operation of the developed drive system: only when both hips have flexion together in (b), relative displacement between both drive pulleys occurs, which indicates that the motor shaft is rotated.

C. Design of Exoskeletal Structure

The first prototype, including the above-described actuation system, has been designed to prove the effectiveness of the proposed concept. Figure 6 shows the overall configuration of the developed robot with main components and degree of

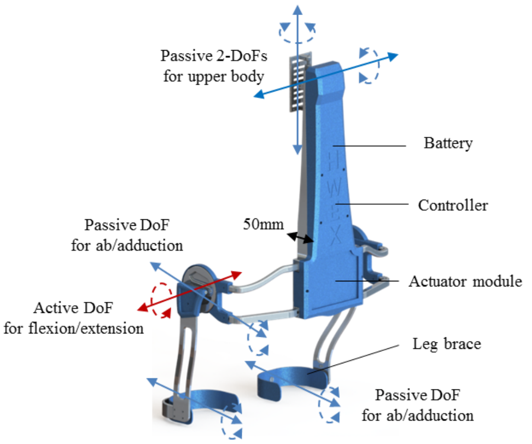

Fig. 6: Conceptual drawing for prototype hardware, H-WEX

Description	Value
weight (kg)	4.5
size (mm)	480(W)×780(H)×330(D)
Max. assist torque (Nm)	90
Max. hip joint velocity (deg/s)	320
Operational voltage	48V

TABLE I: Specification of the developed H-WEX

freedom. The exoskeleton has total eight degrees of freedom (DoFs) consisting of two one-directional active DoF for pitching of both hip joint, two passive DoF for yawing and pitch of upper body, two passive DoF for ab/adduction of each leg. The word 'one-directional active joint' implies here the joints that can be assisted along only one direction corresponding to extension motion. Such a configuration makes it possible for the robot to easily adapt to various operations such as bending and twisting of the waist, and ab/adduction of leg, thereby minimizing the inconvenience to the wearer. The robot is connected to the operator with straps in the shoulder, waist, and crotch. The crotch strap prevents the robot from moving up along the waist during the operation. The leg brace is simply placed on the thigh without a strap to allow free movement in the linear direction on the sagittal plane. This structure is a simple solution to release discomfort caused by misalignment between the rotation center of the human hip joint and that of the robot. The back side plate, including the battery, controller, and actuator module, is as thin as 50 mm, making it comfortable to sit on a chair while wearing the robot. The link is made of aluminum alloy for lighter weight, and the weight of the whole robot including electrics and harness is 4.5 kg. The main specifications for the H-WEX are summarized in Table 1.

III. Singular Motor Control

A. Configuration of Control Architecture

The electricity system for implementing a control algorithm consists of a 48 V Li-Po battery, a DC-DC converter, controller, an inertial measurement unit (IMU) sensor, and motor driver, as shown in Fig. 7. Each component is arranged vertically along the waist to minimize the interference between the robot and the wearer during waist twisting. The Mbed, an off-the-shelf micro-controller, is used as a main controller, and the sampling rate of the overall control system is set to 1 kHz. The controller communicates with motor drivers according to the Controller Area Network (CAN) protocol to transmit the current command and receive the hall sensor data for the brushless DC (BLDC) motor. Further, the IMU sensor sends data for the absolute inclination of the upper body in the sagittal plane to the controller via the universal asynchronous receiver-transmitter (UART) protocol.

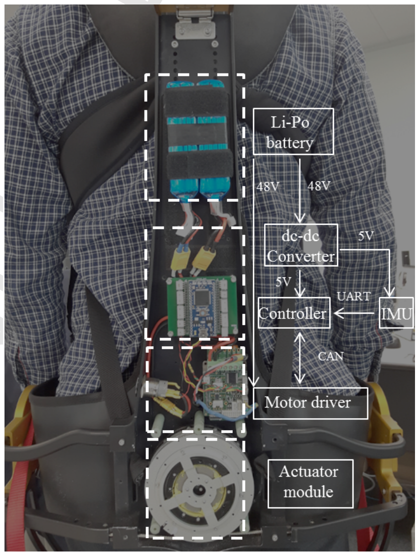

Fig. 7: Hardware architecture of the control system

B. Waist-Assistive Torque Generation Algorithm

A main control algorithm is developed such that the controller recognizes the wearer's motion and determines assistive torque according to a developed rule. Walking, stoop, squat and semi-squat are considered as basic states of a normal working motion and each motion is discriminated based on data given from both the IMU sensor and the motor hall sensor [24]. The overall concept of the control algorithm is depicted in Fig.8.

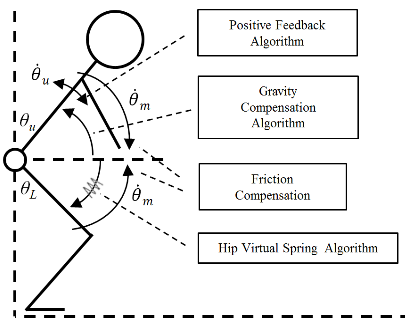

Fig. 8: Overall concept of control algorithm

θ_L denotes the summation value for angles of both hip joint relative to the vertical direction, and θ_u is the clock-wise angle between the torso link and the gravitational direction. We define both values to be non-negative values, and so, negative values for θ_L and θ_u are considered to be zero. θ_m implies the output angle for the actuator module, which is equivalent to the relative angle between two drive pulleys, and can be calculated by utilizing motor hole count considering the gear ratio (50:1) and the hole count per revolution (CPR) (36 CPR). Therefore, θ_m is derived as

$$\theta_m = \frac{\text{motor hole count}}{\frac{\text{hole count}}{\text{revolution}} \times \text{gear ratio}} \tag{1}$$

Based on the kinematics of the robot in Fig.8 and the consideration of the pulley sizes, θ_L can be estimated by a simple function Eq.2.

$$\theta_L = \theta_m - \theta_u \tag{2}$$

The block diagram in Fig.9 describes the developed control algorithm for determining the resultant assistive torque. Basically, the resultant assistive torque is the sum of the torque values given from four sub-algorithms below.

- Friction compensation torque τ_f to eliminate motion discomfort due to mechanical friction of the actuator.
- Virtual springy torque τ_{vs} to assist waist in squat or semi-squat postures in a manner similar to a torsion spring at both hip joints.
- Gravity compensation torque τ_g to provide anti-gravity force especially for static postures.
- Positive feedback torque τ_{pf} to assist motion according to the relative angular velocity of the torso with respect to both lower limbs [25]. This serves to weaken the summation assistive force given from both the gravity compensation torque and the virtual springy torque generation in the flexion mode. Therefore, it is intended to remove resistance for hip-flexion motion due to generated assistive torque.

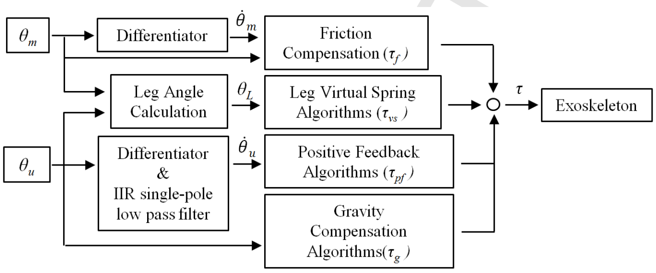

Fig. 9: Block diagram of control algorithm

The flow chart of the algorithm is described in Fig.9. Before turning on the power, the operator wearing the WEX must maintain an upright standing posture for the initialization process to determine the neutral position. Immediately after power-on, the controller begins to acquire data from the IMU and hall sensor, and the driving wire is wound by the actuator until the tension force on the wire is determined. When the wire tensioning is completed, the hole sensor count value at that time is saved as a zero neutral position. The robot is programmed not to generate assistive torque at positions larger than the neutral one for safe operation.

After the initialization process, the operation modes are determined according to a wearer's posture sensing.

Initially, it operates in the walking mode. In this walking mode, the actuator is intended to generate the minimally required torque for maintaining the tension on the wire by Eq.(3).

$$\tau_{walking} = \tau_f + \left(\frac{\theta_L}{b}\right)^2 \tau_{vs} + \left(\frac{\theta_u}{a}\right)^2 (\tau_{pf} + \tau_g) \tag{3}$$
$$\text{when } \theta_u \leq a \text{ and } \theta_L \leq b$$

'a' and 'b' are set to be constant threshold values of θ_L , θ_u to distinguish between two modes: the assist mode and the walking mode, respectively. According to the conditional

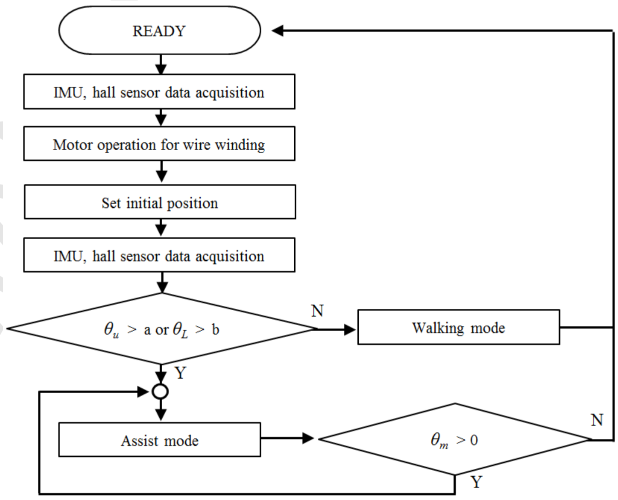

Fig. 10: Flow chart for developed control algorithm

statement for transiting from the walking mode to the assist mode in Fig.10, the walking mode always has $\theta_u \leq a$ and $\theta_L \leq b$. When the mode changes to the assist mode, Eq.(3) becomes Eq.(4), which is the torque generation algorithm in the assist mode, without discontinuity in the torque profile. The reason why the two modes are separated for torque generation is because of the difference in the control objectives for the two modes. Therefore, in order to eliminate discontinuity in the torque profile, the second and the third terms in Eq.(3) are added. Parameters such as 'a' and 'b' can be customized for each wearer, and they have the following physical meanings.

1) parameter 'a' is the margin required in order to prevent unintentional mode changes due to the shaking of the upper body during the walking.
2) parameter 'b' prevents the mode from entering the assist mode when a wearer is walking and stepping up/down.

It is noted that $\frac{\theta_u}{a} \leq 1$ and $\frac{\theta_L}{b} \leq 1$ in the walking mode have the quadratic forms in Eq.(3) such that the effects of small deviations from zero on the torque generation in the walking mode are smaller than the linear forms. When one of both θ_L

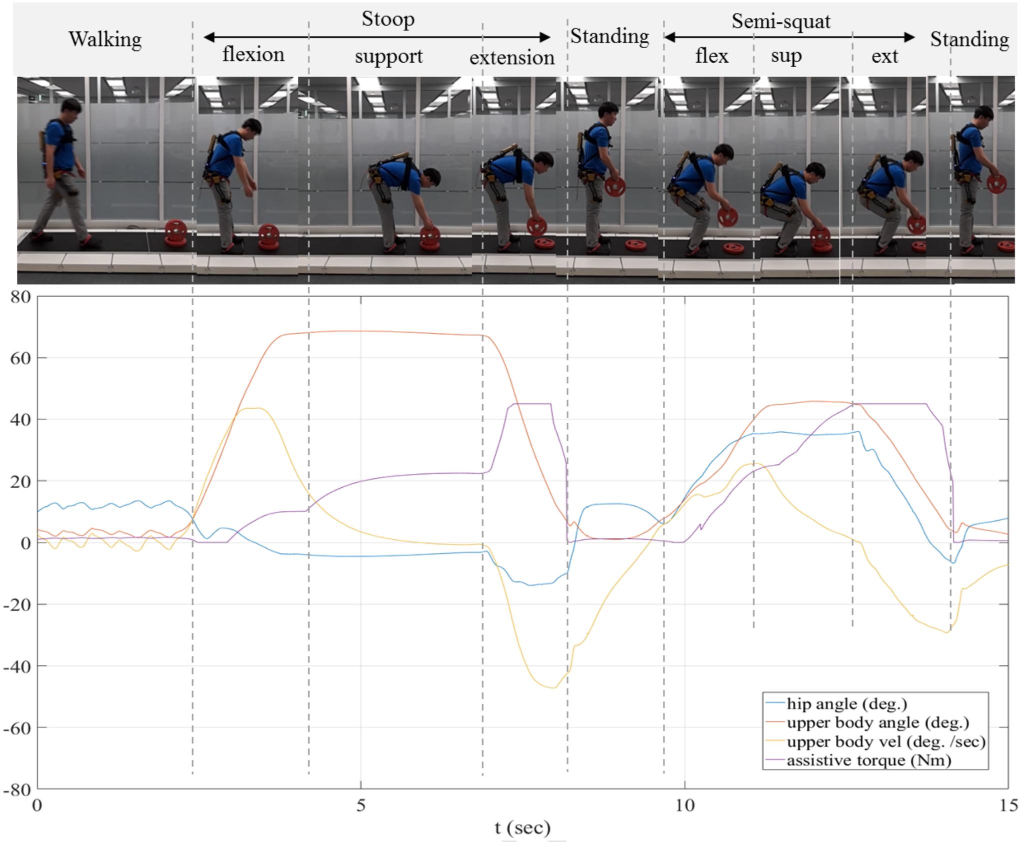

Fig. 11: Acquired values of sensor and the value of assistive torque determined based on the sensor value

and θ_u exceed the respective threshold value, the robot enters the assist mode, and the assist torque is determined by Eq.(4).

$$\tau_{assist} = \tau_f + \tau_{vs} + \tau_{pf} + \tau_g \tag{4}$$

In this assist mode, both the gravity compensation force for the upper body and the virtual spring force are canceled by the positive feedback algorithm during the flexion motion of a wearer. On the other hand, the extension motion is amplified by the feedback algorithm. After the wearer returns to the initial set position, the mode transits from the assist mode to the walking mode. Through this process, it is possible to relieve the burden on the worker by carrying out the movement operation and the work operation for the work without any discomfort. In the viewpoint of human machine interaction, several algorithms have been proposed to implement zero impedance on various exoskeletons [26], [27], [28]. On the other hand, this simple algorithm implements almost zero interaction force in the walking mode, taking advantage of the proposed mechanism. In the assist mode, the robot follows the movement based on the wearer's motion speed, but the interaction force can be assistive for their waist motion.

IV. Experimental Evaluation on H-WEX

A. Operation Experiment

Experiments were conducted to evaluate the operational performance of the robot when used by a wearer. Figure 11 shows the sensor values and the value of the assistive torque determined using these sensor values during various waist motions undertaken by a wearer. The gray dashed line is used to distinguish the acquired values according to each movement. The magnitude of the assistive torque was set to be limited under 45 N m for safety in this experiment. The main control parameters such as 'a' and 'b' are determined through a preliminary test with a wearer.

In the test, the upper body angles and hip joints angle of wearers were simultaneously monitored during activities such as walking, stair climbing and waist bending. Basically, 'a' and 'b' are boundary values for identifying assistive motions. Through a comparison of data obtained from wearers, the threshold values for 'a' and 'b' with a certain margin could be determined to prevent unintended transition into the assist mode during walking and stair climbing. Consequently, the values of 'a' and 'b' were set to 20° and 40°, respectively. After the end of the initialization process, the state machine enters the walking mode. At this time, the initial value of the hip angle, θ_L, is generally estimated to be approximately 10 deg due to decrease in the wire tension. In the walking mode, there is not much variation in the sum of the hip angle, θ_L and the upper body angle, θ_u. Therefore, according to Eq.2, the displacement of the actuator is almost zero in the walking mode.

The effect of the gravity compensative torque can generate impedance when a wearer bends his or her waist for the stoop posture. However, the motion assistive torque by the positive feedback algorithm is observed to partially compensate this impedance during the hip flexion movement. When a wearer has static posture with a bended waist, an assistive torque is generated to maintain the static posture. Moreover, it is verified that an assistive torque is provided for the extension of both hips until the state of the robot approaches that of the initial posture (i.e. $\theta_m \approx 0$). After completion of the hip extension, the hip angle. θ_L, is observed to decrease to 10 deg, as shown in Fig.11. The virtual spring force is shown to be activated on both hip joints proportional to the sum of both hip angles, semi-positive θ_L with the stiffness $k_p = 0.873$ Nm/deg. It is confirmed that the assistive torque is the resultant sum of the spring force and the gravity compensation torque together in the semi-squat posture.

B. Performance Evaluation by surface EMG test

An electromyography (EMG) test was conducted for nine male participants to evaluate the performance of the developed robot in terms of the degree of reduction attainable in the muscle activities of the main waist-motion related muscles [29]. The muscle activities were measured based on EMG signals from the muscles such as *Erector Spinae, Rectus Abdomins, Gluteus Maximus, Biceps Femoris and Rectus Femoris*.

The values of mean and standard deviation for age, height, and weight of the participants are listed in Table.II.

	Mean	Standard Deviation
age	33.4 years old	2.4
height	173.2 cm	4.5
weight	73.0 kg	9.0

TABLE II: Age, height, and weight of participants for the EMG test

The experimental procedure is such that each participant is requested to lift a load of 15 kg ten times, from the floor to the height of his pelvic position, whilst maintaining two postures: 1) semi-squat posture, 2) stoop posture, as shown in Fig.12. With this procedure, we examined four cases in which a wearer has a semi-squat posture with the robot, stoop posture with the robot, semi-squat posture without the robot, and stoop posture without the robot. Although the periods of one cycle (lifting and lowering) were shown to be different for each person owing to the variation in their physical abilities, most of the participants completed one cycle in 3 s. The maximum voluntary contraction (MVC) of each muscle was measured after a participant completed 40 cycles (for the four cases) to reduce intervention of muscle fatigue. The Delsys trigno wireless EMG system was used to acquire data at a 2000 Hz sampling rate. All of the data was processed using a Butterworth 4th order band-pass filter with frequencies ranging from 30 to 350 Hz. The values for each muscle activation signals were averaged with respect to one cycle. Subsequently, the maximum amplitude of data was normalized by the MVC. The results of the entire data analysis are shown in Fig.13. Compared with the data of the case without the robot, the muscle activity related to lifting was significantly reduced with the assistive torque of the robot. The muscle activity of Erector Spinae decreased by 23.5% for semi-squat and 10.5% for stoop. The muscle activity of Gluteus Maximus reduced by 18.6% for semi-squat and 15.8% for stoop. Further, the muscle activity of Biceps Femoris reduced by 30% for semi-squat and 10.1% for stoop. This decrease in muscle activity can help prevent musculoskeletal disorders of workers by reducing the muscle fatigue and preventing the overloading of their body. However, muscle activities of Rectus Abdomins and Rectus Femoris did not show a notable difference between the cases with or without the robot.

(a) Stoop lifting (b) Semi-squat lifting

Fig. 12: Two postures for the EMG test: (a) stoop, (b) semi-squat

C. Usability test on H-WEX by questionaire

The Usability of H-WEX, the developed robot, was evaluated for the same participant group through a questionnaire [30]. The set-up of the test for the questionnaire is depicted in Fig.14, and the experimental procedure is designed to be repeated in two steps.

- Step 1: Lift a 10 kg load up from the ground.
- Step 2: Then, walk 10 m away and put the load down.
- Repeat these two steps 10 times.

The participant performs this process with a robot, and then repeats it without the robot. The total time and working posture was not regulated in this test to reflect a variety of workers at a real working field. Subsequently, the participants were asked to answer the following questions to determine their experience and opinion regarding the robot.

- Q1. Do you feel the robot is lightweight?
- Q2. Do you feel comfortable in walking and ascending stairs wearing a robot?
- Q3. Do you feel comfortable in lifting and lowering a load wearing a robot?
- Q4. Do you feel assisted by the robot?
- Q5. Do you think that the assistive force by the robot is adequate?
- Q6. Do you think that the robot can help the workers in a real field?

Each participant was requested to score each question on a scale of 0 (disagreement) to 5(agreement). Figure 15 describes the average score and standard deviation for each question. The score for the first question indicated that the weight of the robot is moderate. The answers for Q2 and Q3 indicated that users did not feel discomfort upon moving and working with

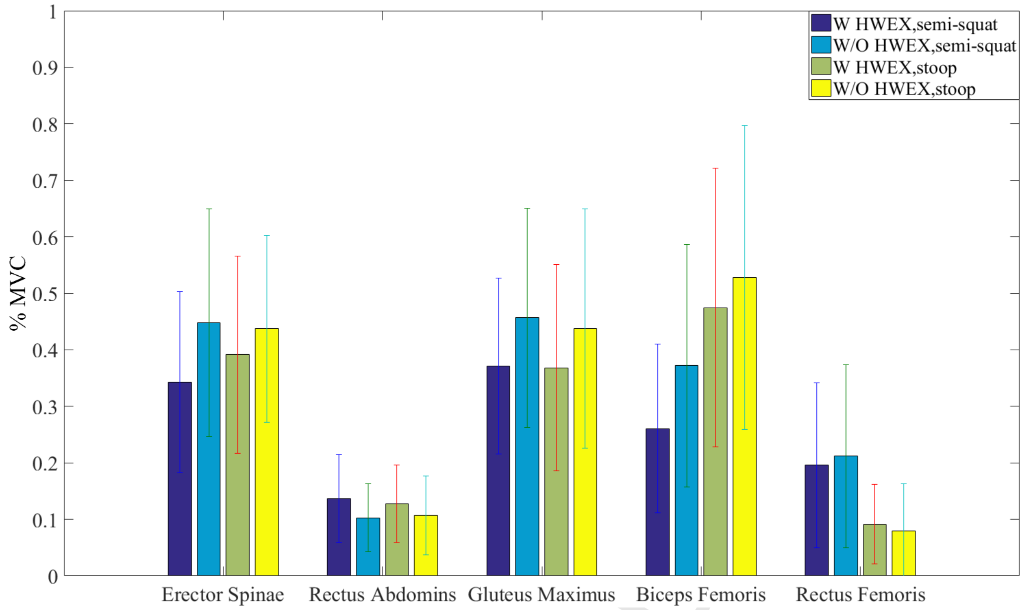

Fig. 13: Test results of measurement of muscle activity

Fig. 14: Sequential procedure for usability test

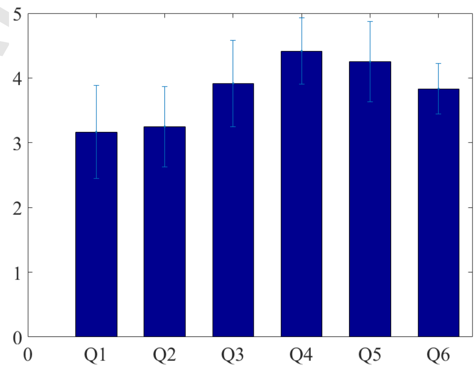

Fig. 15: Resultant scores for evaluative qeustionnaire

the robot. In addition, all wearers could perceive the assistive effect provided by the robot, and answered that the assistive force was sufficiently effective. Answers to the last question confirmed a positive evaluation of practicality.

V. Conclusion

This paper presents the mechanical design concept, based on bio-mechanical approach, of an electrically-powered waist assistive exoskeleton driven by only one actuator, and its control method. The prototype, H-WEX, was developed to verify this conceptual mechanism, and further, the control algorithm was designed for the robot to effectively assist the waist motion of wearer. Through an EMG test conducted on nine participants wearing the H-WEX, the it was noted that the activities of major muscles related to waist motions were reduced by 10% to 30% while the participants were performing an experimental procedure of lifting a load up. In addition, a usability test was carried out to study the actual applicability related to appropriateness of the robot's weight, effectiveness of the assistive force, and wearing comfort. Our proposed concept was verified through this study; this concept can reduce the cost and weight of an assistive product, and it will help expand the applicability of wearable robots in real fields. Currently, we have been developing a new model that reduces the maximum assistive force and the weight based on the analysis that the assistive force used in the test is sufficient. In addition, an actual field test is being prepared for implementation in manufacturing, logistics, and nursing fields, and we will continue to improve H-WEX based on the obtained test data.

REFERENCES

[1] Health and Safety Executive, "Work related Musculoskeleton Disorder (WRMSDs) Statistics," http://www.hse.gov.uk/statistics/causdis/musculoskeletal/msd.pdf.

[2] Linda Seward, "Noonee testing Chairless Chair exoskeleton at Audi production plants," http://robohub.org/noonee-testing-chairless-chair-exoskeleton-at-audi-production-plants/.

[3] Andrew Krok, "Ford's exoskeleton could help factory workers in a big way," https://www.cnet.com/roadshow/news/fords-exoskeleton-could-help-factory-workers-in-a-big-way/.

[4] ATOUN, "Power Assist Suit ATOUN MODEL As," http://atoun.co.jp/products/atoun-model-as.

[5] Robo-Mate, "Modular exoskeleton for industry: Active Trunk," http://atoun.co.jp/products/atoun-model-as.

[6] EXOSKELETON REPORT, "Exoskeletons for work and industry," http://exoskeletonreport.com/product-category/exoskeleton-catalog/industrial/.

[7] F. Giovacchini, F. Vannetti, M. Fantozzi, M. Cempini, M. Cortese, A. Parri, T. Yan, D. Lefeber, and N. Vitiello, "A light-weight active orthosis for hip movement assistance," *Robotics and Autonomous Systems*, vol. 73, pp. 123–134, 2015.

[8] H. A. Quintero, R. J. Farris, and M. Goldfarb, "A method for the autonomous control of lower limb exoskeletons for persons with paraplegia," *Journal of medical devices*, vol. 6, no. 4, p. 041003, 2012.

[9] A. Esquenazi, M. Talaty, A. Packel, and M. Saulino, "The rewalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury," *American journal of physical medicine & rehabilitation*, vol. 91, no. 11, pp. 911–921, 2012.

[10] Y. Long, Z.-j. Du, W.-d. Wang, and W. Dong, "Robust sliding mode control based on ga optimization and cmac compensation for lower limb exoskeleton," *Applied bionics and biomechanics*, vol. 2016, 2016.

[11] Y. Long, Z.-J. Du, W.-D. Wang, G.-Y. Zhao, G.-Q. Xu, L. He, X.-W. Mao, and W. Dong, "Pso-svm-based online locomotion mode identification for rehabilitation robotic exoskeletons," *Sensors*, vol. 16, no. 9, p. 1408, 2016.

[12] M. P. de Looze, T. Bosch, F. Krause, K. S. Stadler, and L. W. O'Sullivan, "Exoskeletons for industrial application and their potential effects on physical work load," *Ergonomics*, vol. 59, no. 5, pp. 671–681, 2016.

[13] T. Aida, H. Nozaki, and H. Kobayashi, "Development of muscle suit and application to factory laborers," in *Mechatronics and Automation, 2009. ICMA 2009. International Conference on*. IEEE, 2009, pp. 1027–1032.

[14] CYBERDYNE, "HAL LUMBAR TYPE FOR LABOR SUPPORT," https://www.cyberdyne.jp/english/products/Lumbar_LaborSupport.html.

[15] X. Yong, C. Wang, C. Wang, W. Feng, X. Wu, and Y. Wang, "Development of a low-power wearable powered waist exoskeleton with mechanical clutch," in *Information and Automation (ICIA), 2017 IEEE International Conference on*. IEEE, 2017, pp. 177–182.

[16] H. Inose, S. Mohri, H. Arakawa, M. Okui, K. Koide, Y. Yamada, I. Kikutani, and T. Nakamura, "Semi-endoskeleton-type waist assist abwear suit equipped with compressive force reduction mechanism," in *Robotics and Automation (ICRA), 2017 IEEE International Conference on*. IEEE, 2017, pp. 6014–6019.

[17] F. Cho, R. Sugimoto, T. Noritsugu, and X. Li, "Improvement of wearable power assist wear for low back support using pneumatic actuator," in *IOP Conference Series: Materials Science and Engineering*, vol. 249, no. 1. IOP Publishing, 2017, p. 012004.

[18] H. Yu, I. S. Choi, K.-L. Han, J. Y. Choi, G. Chung, and J. Suh, "Development of a stand-alone powered exoskeleton robot suit in steel manufacturing," *ISIJ International*, vol. 55, no. 12, pp. 2609–2617, 2015.

[19] S. Toxiri, J. Ortiz, J. Masood, J. Fernández, L. A. Mateos, and D. G. Caldwell, "A powered low-back exoskeleton for industrial handling: considerations on controls," in *Wearable Robotics: Challenges and Trends*. Springer, 2017, pp. 287–291.

[20] D. P. Byrne, K. J. Mulhall, and J. F. Baker, "Anatomy & biomechanics of the hip," *The open sports medicine Journal*, vol. 4, no. 1, 2010.

[21] E. Ayyappa, "Normal human locomotion, part 1: Basic concepts and terminology." *JPO: Journal of Prosthetics and Orthotics*, vol. 9, no. 1, pp. 10–17, 1997.

[22] Health and Safety Authority, "Guidance on the Management of Manual Handling in the Workplace," http://www.hsa.ie/eng/Publications_and_Forms/Publications/Retail/Management_Manual_Handling.pdf.

[23] M. P. Kadaba, H. Ramakrishnan, and M. Wootten, "Measurement of lower extremity kinematics during level walking," *Journal of orthopaedic research*, vol. 8, no. 3, pp. 383–392, 1990.

[24] L. Del Vecchio, "Choosing a lifting posture: Squat, semi-squat or stoop," *MOJ Yoga & Physical Therapy*, vol. 2, 2017.

[25] J. A. Norris, A. P. Marsh, K. P. Granata, and S. D. Ross, "Positive feedback in powered exoskeletons: improved metabolic efficiency at the cost of reduced stability," in *International design engineering technical conferences & computers and information in engineering conference; September 4*, vol. 7, 2007.

[26] J. F. Veneman, R. Kruidhof, E. E. Hekman, R. Ekkelenkamp, E. H. Van Asseldonk, and H. Van Der Kooij, "Design and evaluation of the lopes exoskeleton robot for interactive gait rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 379–386, 2007.

[27] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The roboknee: an exoskeleton for enhancing strength and endurance during walking," in *Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on*, vol. 3. IEEE, 2004, pp. 2430–2435.

[28] Y. Long, Z. Du, C. Chen, W. Wang, L. He, X. Mao, G. Xu, G. Zhao, X. Li, and W. Dong, "Development and analysis of an electrically actuated lower extremity assistive exoskeleton," *Journal of Bionic Engineering*, vol. 14, no. 2, pp. 272–283, 2017.

[29] K. Huysamen, M. de Looze, T. Bosch, J. Ortiz, S. Toxiri, and L. W. O'Sullivan, "Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks," *Applied Ergonomics*, vol. 68, pp. 125–131, 2018.

[30] Y. Muramatsu, H. Kobayashi, Y. Sato, H. Jiaou, T. Hashimoto, and H. Kobayashi, "Quantitative performance analysis of exoskeleton augmenting devices–muscle suit–for manual worker," *International Journal of Automation Technology*, vol. 5, no. 4, pp. 559–567, 2011.

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