2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Development of a Non-Exoskeletal Structure for a Robotic Suit *

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Abstract— **In recent years, various robots have been developed that can be worn on the body. These can be used to assist older people and people with disabilities by either providing extra power or helping them with walking. These robots usually form an external skeleton around the frame of the body. Although the external skeletal structure has the advantage of supporting the robotic mechanism, an adjustment mechanism to match it to the contours of the wearer's body is necessary, and this mechanism increases the weight of the robot. In this study, we propose a non-exoskeletal structure that uses the skeletal system of the human body, and develop a lightweight robotic suit that produces few feelings of restriction.**

I. Introduction

In 2014, Japan will become a super-aged society with 24.1% of its population classed as older people. The number of older people requiring nursing care in everyday life and the ratios of older people among the labor force has increased rapidly. In such a background, various robots have been developed for the purpose of care and rehabilitation and support in daily life.

There is also strong interest in wearable robots, and various robots of this type have been developed [2,3,4]. Examples include a "stride management assistance system" to help improve the walking function of older people [5], a "hybrid assistive limb" (HAL) wearable robot for rehabilitation support and independent movement support for people with disabilities [6], a wearable walking rehabilitation support robot "KAI-R" for people who received artificial knee joint replacement surgery [7], a "muscle suit" developed by the Tokyo University of Science [8], and a "wearable power suit" developed by the Kanagawa Institute of Technology, which reduces the burden of dependence on a caregiver [9].

These wearable robots usually form an external skeleton that complies with the frame of the human body, and the advantage to this is that the weight of the robot can be carried by this exoskeleton. However, the movement of the wearer is restricted to the flexibility of the rigid robot links in the structure. In daily life, where various types of movement are required, this feeling of restraint might be a burden to the wearer.

*Resrach supported by the Japan Science and Technology Agency's (JST) Adaptable and Seamless Technology Transfer Program through target-driven R&D (A-STEP) with Seeds Validation type.

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In this study, as a solution to these problems, we devised a lightweight, flexible robotic suit that uses the skeletal system of the human body rather than an externally linked skeleton [10]. We developed a model that adheres to a human body, not only while the users are walking, but also when they are performing various movements of everyday life, and this allows the flexibility of human movement to be maintained.

II. Exoskeletal and Non-Exoskeletal Robots

A. Definition

In this report, we define a wearable robot that assists the movement or muscular strength of the wearer by transmitting the movement of the robotic frame to the frame of the human body as an exoskeletal robot.

Conversely, we define a robot assisting the movement of the joints using the skeletal system of the human body as a non-exoskeletal robot, which does not have a rigid link between each joint. An example of this is the robotic suit that we developed in this study.

B. Differences between Exoskeletal and Non-Exoskeletal Robots

To explain the differences between the two types of robot, we present a typical exoskeletal robot that was used in a previous study [11] and the non-exoskeletal robot that was developed in this study in Fig. 1.

The exoskeletal robot forms a frame-like structure with a rigid link connecting each part. The weight of the robot is supported at the bottom of the foot. In contrast, the non-exoskeletal robot does not have links between the parts. In other words, the major difference is the absence of a rigid external skeleton to support the robot. Therefore, the weight of the robot can be reduced to a level that can be maintained by the human body. It is not necessary to consider how the framework needs to adapt to body movements, or to have a mechanism to adjust the length of each link to the build of the wearer.

However, since the non-exoskeletal robot uses the skeletal system of the human body, it cannot provide power assistance to its human operator; this is impossible because the robot would cause damage to the frame of the human body. For an exoskeletal robot, such power assistance is possible, so we categorize such robots as "ability increasers." We categorize non-exoskeletal robots as "ability compensators," i.e., those that provide assistance and compensate for body functions that are weak or impaired.

(a) Exoskeletal robot (b) Non-Exoskeletal robot

Figure 1. Difference between two types of robot

C. Possible Applications for Non-Exoskeletal Robots

The non-exoskeletal robot can maintain very high exercise flexibility with few feelings of restriction while it is worn. It can be worn for long periods of time, and allows various movements. In addition, because of its simpler structure and lighter weight, the non-exoskeletal robot is easier to wear than a conventional exoskeletal robot. Thus, for the purpose of ability compensation (not ability increase), we can expect the non-exoskeletal robot's to have applications in a wide number of fields where high flexibility during regular use is valued.

III. The Robotic Suit

A. Characteristics of the Robotic Suit

The robotic suit does not use a myogenic potential signal, but rather a torque detection method based on a torque sensor built into the harmonic drive speed reducer and a synchronization-based motion control method that was demonstrated in a previous study. Therefore, attaching electrodes to the human body is unnecessary, which makes the suit easier to wear. Another characteristic is that motor units to assist the movement of individual joints can be added or removed easily.

B. Constituent Units of the Robotic Suit

Figure 2 shows the non-exoskeletal robotic suit that we developed. The suit comprises three units in total. The left and right hip-joint units are coupled onto the hip belt of the hip unit. A motor unit is connected to each hip-joint unit and to the left and right knee-joint units. The weight of the hip-joint motor unit rests on the hips, and the weight of the knee-joint motor unit is on the lower thigh. In addition, these joint units and thigh supports, as well as the lower thigh plates, are all made of flexible resin rather than metal.

Table I shows the weight of the robotic suit. The exercise support for the flexion and extension of the hip and knee joints is powered by these motor units.

Figure 2. View of robotic suit

TABLE I. Weight of robotic suit

Hip Unit	650 g
Knee Unit	290 g (×2)
Motor Unit	701 g (×4)
Total	1,931 g

C. Basic Structure of the Joint Unit

Figure 3 shows the basic structure of a joint unit. The joint unit is made up of two plates positioned to comply with the body frame in the upper and lower parts of the joint. This is the structure that transmits the rotary power of the motor to the movement of the joint by attaching a motor unit to the combination axis (joint axis) of these plates. Figure 3 shows a hip-joint unit, but the knee-joint unit has the same structure.

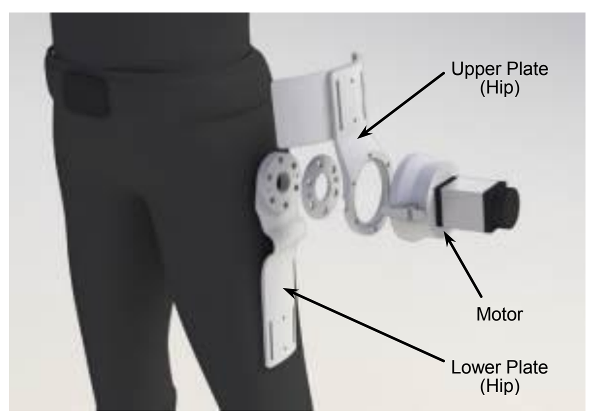


Figure 3. Structure of Joint Unit

D. Hip Unit and Adjustment Mechanism

The upper part (called the T-bar) of the left and right hip-joint units is fixed to the hip belt and constitutes the hip unit. This hip belt makes an umbrella shape in the same way as for backpacks for mountain climbing, and is constructed to hold the pelvic iliac crest from the diagonal top. With this structure, the pelvis supports the hip unit weight, including the weight of the motor unit, and the unit is completely prevented from slipping down. In addition, a front buckle makes the hip belt easy to put on and remove. Similarly, a hook-and-loop fastener makes the right and left thigh supports easy to put on and remove. Figure 4 shows the hip unit, and Figure 5 shows the positional relationship between the hip unit and the human skeleton.

However, the distances between the pelvic (iliac crest) and hip joints (greater trochanter) depend on the body of the wearer. In other words, it is necessary to match the position relationships of the hip-joint-unit axis to the hip belt with the wearer and to adjust it. The hip unit comprises of three parts (Fig. 6) to allow the system to be adjusted based on the individual differences of the human frame. The plate for the hip-joint unit is made of a tough, lightweight nylon composite material, ASPEX-PA. The thigh supports are made of foaming polyvinyl chloride board, which is also lightweight and highly flexible (FOREX/t = 3 mm). Vinyl chloride board 1 mm thick is used for the two hip-belt matrices. On the inside of the inner belt against the body, 10 mm-thick urethane sponge rubber is attached. The urethane sponge rubber has high cushioning characteristics, and it does not slip easily. For fixation, the entire outside surface of the inner belt, the inside of the outer belt, and both sides of the T-bar of the hip-joint unit have a hook-and-loop fastener attached to them.

A characteristic of the hip-unit adjustment mechanism is that the adjustment is completed as it is put on. First, the wearer attaches an inner belt to their body, covering the iliac crest. Then the inner belt is joined to the T-bar with the hook-and-loop fastener to match the greater trochanter with the joint-axis center of the hip-joint unit. Finally, the outer belt is put over the inner belt and the T-bar. By making its adjustment part of the process of putting it on, anyone can fit the robot to the build of the wearer easily and naturally without using any tools. Furthermore, it is not necessary to perform this adjustment every time, and the robot can easily be put on and taken off using the buckle on the front of the hip belt. Figure 7 shows the adjustment mechanism. In addition, the T-bar and the two belts are weakly joined by the hook-and-loop fastener, but the pressure of putting a T-bar between them by closing the outer belt becomes higher, strongly fixing the hip-joint unit to the hip belt. Thus, position gaps from walking movements and weight do not occur.

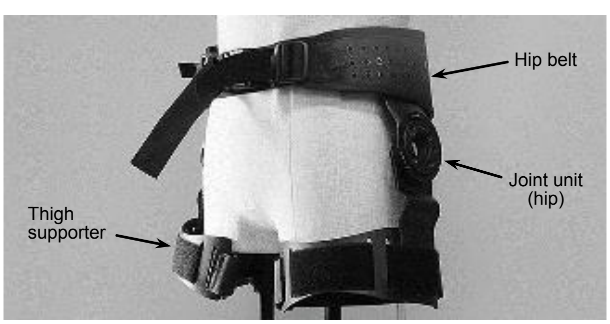


Figure 4. View of hip unit

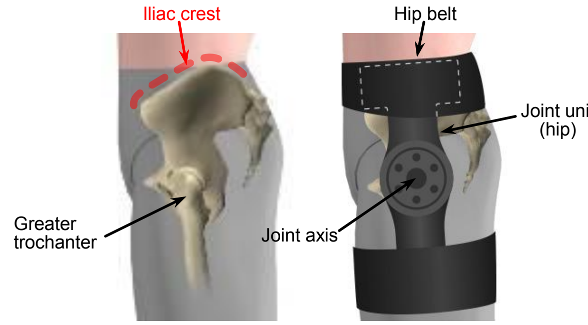


Figure 5. Human skeleton and hip-joint unit

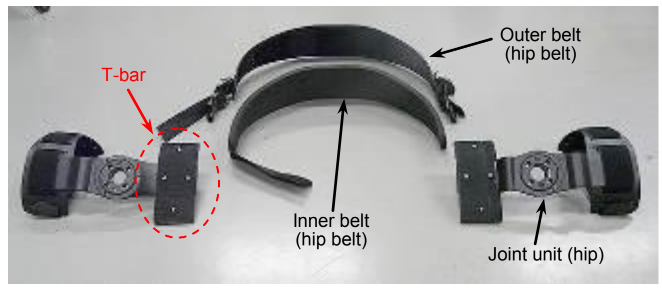


Figure 6. Component parts of hip unit

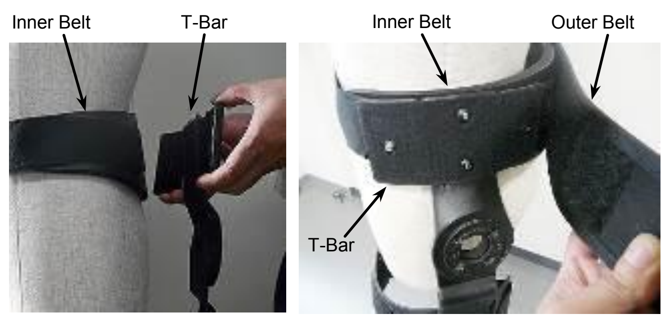


Figure 7. Adjustment Mechanism

E. Shape of the Knee-Joint Unit

In our previous study [10], one significant problem was the swinging that occurred on a knee-joint unit during exercise. To solve this problem, we extended the lower thigh plate to the top of the ankle and switched to a structure that holds the entire lower thigh. By making this structure, we were able to fix a knee-joint unit to the entire lower thigh and improve the solidity of the unit considerably. We used the same tough, lightweight nylon composite material used for the plates, ASPEX-PA.

F. The Motor Unit's Detachable Mechanism

Each joint is designed so that a motor unit can easily be attached and detached. Figure 8 shows a motor unit junction. When the motor unit is attached to the joint unit, a positioning pin (A) outside the central part of the motor unit is inserted into a positioning socket (a) in the joint unit top plate. A power transmission pin (B) inside the central part of the motor unit is joined to a corresponding passive socket (b) in the lower joint unit plate. The power transmission pin (B) turns as the motor turns, and the lower joint unit plate is moved by this power. In addition, the motor unit is prevented from falling off through the use of two connectors to the joint unit. The motor unit can easily be removed by opening this connector, and tools are not necessary for putting it on or removing it. The advantage of this mechanism is that the burden on the body is reduced by the wearability improvements and the light weight of the structure. In other words, the joint unit can be attached to the body in the same way as putting on a garment if a bulky motor unit is removed, and the weight on the body can be reduced by removing a motor unit if assistance at a particular joint is unnecessary.

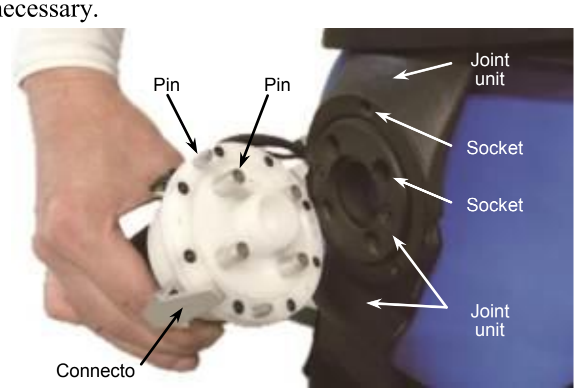


Figure 8. Removable motor unit

IV. Using the Template

A. Degrees of Freedom of Motion

According to previous biomechanical research [12, 13], we understand that movement, such as pelvic slant and rotation, is important for human ambulation. However, because it aims to assist flexion and extension movements of the hip and knee joints, the robotic suit in its current design (and many exoskeletal robots) cannot positively assist such movement. Because the non-exoskeletal robot does not have rigid links between the joints, the robotic suit rarely disturbs such important movements. Many exoskeletal robots, however, reduce the wearer's movement and flexibility other than the movements that they are designed to support. Therefore, for comparison, we prepared a limb model (Fig. 9) with knee and hip joints united by a rigid link. We evaluated the exercise flexibility in the hip and knee joints for a subjective sense of how the participant attached these models. Table II and Table III show the results of the comparison experiment.

(a) Limb model (b) Robotic suit

Figure 9. Experimental model of robotic suit

TABLE II. FLEXIBILITY OF HIP-JOINT

(RS: Robotic suit / LM: Limb model)
○: Workable △: Hard to work ×: Unworkable

	Hip Joint					
	Flexion	*Extension*	*Extorsion*	*Adduction*	*External rotation*	*Internal rotation*
LM	0~60°○	△	△	△	△	△
	60~90°△					
	Over90°×					
RS	0~60°○	○	△	○	○	○
	60~90°○					
	Over90°×					

TABLE III. FLEXIBILITY OF PELVIC AND KNEE-JOINTS

(RS: Robotic suit / LM: Limb model)
○: Workable △: Hard to work ×: Unworkable

	Knee joint		Pelvic			
	Flexion	*Extension*	*Anteversion*	*Retroversion*	*Inclination*	*Rotation*
LM	○	○	△	△	△	△
RS	○	○	○	○	○	○

B. Fit of the Joint Unit and the Human Body

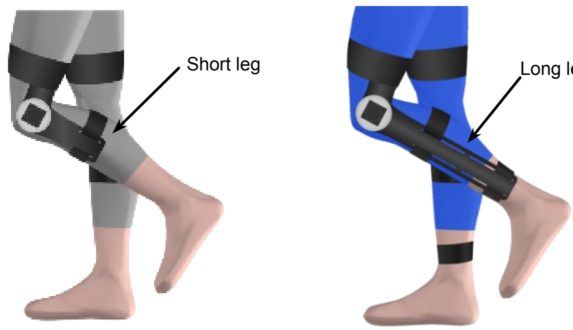
We measured the state of the joint unit during a walking exercise using a motion sensor to judge quantitatively that it was fixed on the body, while the hip-joint and one knee-joint unit of our non-exoskeletal robotic suit carried the weight of the motor unit. For comparison, we carried out the measurements while the model was not wearing the robotic suit. In addition, to check if there was less swinging of the knee joint unit, which was considered to be a problem in the previous study [10], we prepared a model that fixed only the lower thigh, as in the model in the previous study (see Figure 10). For an exoskeletal robot model, we used a limb model (Fig. 9) and the ankle-foot orthosis (AFO) model that was attached to a short lower limb harness (shown in Figure 11).

We fixed a motion sensor to the hip-joint unit and the knee-joint unit of the robotic suit and measured the angular velocity while a participant was walking on a treadmill. We set the speed of the treadmill to 4 km/h. Figure 11 shows the position of the motion sensors. A motor unit was connected to add weight, but it did not provide power assistance during this experiment. To this end, we removed the power transmission pins, thus preventing the joint unit from increasing the resistance of the motor reduction gears. The mass of each motor unit was about 700 g.

We used a treadmill (LS8.0T; Horizon Fitness) that allowed speed adjustments in 0.1 km/h increments and set the floor angle of inclination to 0°. We used four small 8ch radio motion recorders as motion sensors (MVP-RF8-GC-2000; Microstone Corp.), set the sampling frequency to 100 Hz, and measured angular velocity in the same period. The external dimensions of the motion sensor were 45 × 45 × 12 mm, and its mass was about 25 g.

Figures 13 and 14 show the results of the angular velocity analysis for the hip and knee joints. These are RMS levels for

30-second data from 10 to 40 seconds after the start of walking. Series Gx shows the angular velocity of the anteroposterior horizontal axis rotation. Series Gy shows the angular velocity of the plumb axis circumference. Series Gz shows the angular velocity of the right and left horizontal axis circumference.



(a) Old model (b) Robotic suit

Figure 10. Previous study's model (old model)

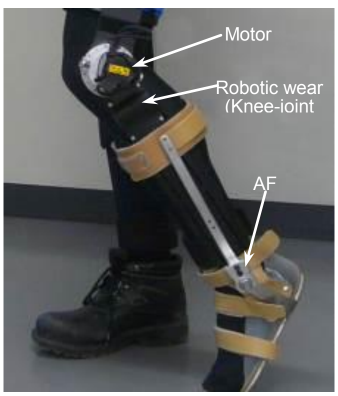


Figure 11. AFO model (robotic suit with AFO)

Figure 12. Position of the motion sensors

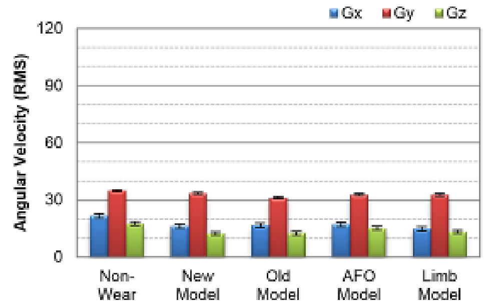


Figure 13. Angular Velocity of the hip-joint

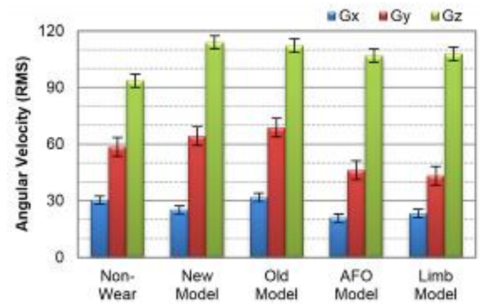


Figure 14. Angular Velocity of the Knee Joint

C. Effects of the Use of the Motor Drive

In our previous study [10], one significant problem was the swinging that occurred on a knee joint unit during exercise. To solve this problem, we extended the lower thigh plate to the top of the ankle and switched to a structure that holds the entire lower thigh. By making this structure, we were able to fix a knee-joint unit to the entire lower thigh and improve the solidity of the unit considerably. We used the same tough, lightweight nylon composite material used for the plates, ASPEX-PA.

We tested whether the power from a motor unit attached to the robotic suit could communicate with the body. Table IV gives the specifications of the motor unit. We carried out a natural floor-walking experiment using a walk assistance program with synchronization-based control, as in a previous study [11]. There were four drive motors in total, one on each of the left and right hip and knee joints. We found that walking was still possible and the walking assistance power from the robotic suit could be felt in the hip, but we also confirmed that supplementary help was required in the knee joint area.

TABLE IV. MOTOR UNIT SPECIFICATIONS

Motor	AC Servo Motor R2FA4008H (80W) made by Sanyo Denki Co., Ltd.
Reduction gear	SHG-14-50 (Reduction Ratio 1/50) made by Harmonic Drive®Systems Co., Ltd.
Max torque	74.2 Nm
Rated torque	26.7 Nm

V. DISCUSSION

In terms of wearability, the robotic suit could be adjusted flexibly and easily to each different participant's physique, and participants did not feel pain from restriction even if the suit was worn all day. Therefore, the robotic suit is very wearable and can be worn regularly in everyday life.

Our experiment revealed that the range of motion of the robotic suit is high. In other words, the robotic suit produces few feelings of restriction. It is thought that the feelings of restriction in an exoskeletal robot stem from the fact that the flexibility of the body is dampened by the fixed-length links between the joints. However, we think that the restriction in movement direction is essentially unreduced if the actuator does not have back drivability through the use of a gear with a high ratio. In addition, for the flexion of a hip and knee joint in ranges over 90 degrees, the cause of the restriction is from the shape of the joint, and further improvement is possible through changes in shape.

For the solidity of the joint unit, based on the fact that the results were the same with or without the robotic suit, we found that, in the hips at least (Fig. 13), the motor weight and the fixation to the body could easily be compensated for. In the knee joints, the reason that the Gx component of angular velocity follows the form Old Model > Non-Suit > New Model > Lim Model > AFO Model (Fig. 14) may be caused by the solidity (i.e., the direction influencing Gx) of the knee joint unit. The Gy swing angle was better than that found with the model in the previous study, but did not reach the same level as when the suit was not worn. In addition, the other Gz swing angles were greater than that when nothing was worn. The reason is because steps became smaller and turns of the knee became quicker. Swinging was felt most in Gy, the cause of which was probably the weight of the motor unit, and it will be necessary to make the unit smaller and lighter to reduce swinging. At the same time, the shape of the unit and how it is attached to the body can still be improved. In addition, the limb model and the AFO model restrict movement because there is less swinging than when nothing is worn.

The power transmission performance when the motor drives the knee joint unit is still a problem, and we hypothesize that looseness at the thigh is the cause. Exercise support similar to that provided at the hip joints is low if the unit is too snug, and we believe that it will be necessary to find a way of keeping it firmly in place while controlling feelings of restriction.

VI. CONCLUSION

In this study, we devised and developed a lightweight, flexible, non-exoskeletal robotic suit that uses the skeletal system of the human body. Because the robotic suit does not have the rigid external skeleton links that an exoskeletal robot has, there is very little movement restriction, and the system is very lightweight. Swinging in the knee joint unit, a problem in a previous study, was decreased by supporting the entire lower thigh. The system is not yet perfect, but it is a wearable, non-exoskeletal robotic suit that does not restrict the movement of the human body during walking and various other movements that are part of everyday life, and it can be used for long periods of time. In the future, we intend to develop this system further for practical use, including improvements such as structural improvements in the knee joint unit and the small, lightweight motor unit.

ACKNOWLEDGMENTS

We carried out this study in coordination with Shinshu University, Sanyo Denki Co., Ltd., and Harmonic Drive Systems Co., Ltd. It was supported by the Japan Science and Technology Agency's (JST) Adaptable and Seamless Technology Transfer Program through target-driven R&D (A-STEP) with Seeds Validation type "Research and Development of a High-Performance, Lightweight, Wearable Robotic Suit using Synchronization-Based Control," adopted in 2011.

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