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Working Posture Control of Robot Suit HAL for Reducing Structural Stress

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Abstract— **The advent of the super aged society and decline in earning power makes it critical to develop technologies that can support the limitations of our human abilities. We have developed Robot Suit HAL to support human physical capabilities. A wearable robot expected to work in human society is required to have a high structural safety, with a tough and compact structure and a human outline. To achieve this, this paper focuses on the control method for a wearable robot based on the structural safety. We suggest that HAL autonomously leads a wearer to a known appropriate working posture to reduce the structural stress based on prior FEM analysis. This is called Working Posture Control. The purpose of this paper is to propose a working posture control method and to verify the effectiveness of the proposed method. The target motion is the holding of a load with both forearms, such as is done during heavy work. The heavy work assistance means a higher workload for HAL than ever before, compared to usages such as the walking assistance. FEM analysis shows the waist component becomes stressed especially. Therefore, the reference working posture is defined as one where the upper body is inclined backwards using the principle of reducing the structural stress by shortening the moment arm. To this end, the control algorithm switches from control by bio-electrical signals to proportional and derivative control based on the angles and the angular velocities of the joints at the right time. When this method was applied in an experiment, the angles of the hip and knee joints follow the reference angles for changing to the appropriate working posture of the load holding motion and it was shown that the structural stress of the waist component was reduced. This confirmed the effectiveness of the proposed method.**

I. INTRODUCTION

Most of the developed countries are facing a difficult future due to an extremely low birth rate and a rapid aging population. According to a white paper on the aging society reported by Japan's Cabinet Office in 2008, those aged 65 or older already account for 20 percent of the population and is forecasted to be 40 percent by 2055. That means the working generation will bear a great social burden. In the extreme case, aged people must support aged people. There will be labor shortage, care problems, decline in economic growth, a bigger share of the medical bill for each, low quality of life and solitary death problems. The advent of the super aged society and decline in earning power makes it critical to develop technologies that can support the limitations of our human abilities.

Utilizing Cybernics technology, which is a range of solutions to support and/or increase human capabilities, we have developed the exoskeletal Robot Suit HAL (Hybrid Assistive limb), which can expand and support the wearer's physical capabilities [1]-[6]. Figure 2 shows an overview and system configurations of the HAL-5 full-body version which is the experimental object of this study. This HAL has six types of segments: forearm, arm, trunk, thigh, leg and foot. Each segment consists of several exoskeletal frames. Everything is connected to the feet of the robot which are in contact with the ground. Therefore, HAL can support its own weight, as well as part of the wearer's weight and any extra loads carried. Power units are attached on each elbow, shoulder, hip, and knee joint, and have one degree of freedom each, flexion and extension. Wearing equipments fasten the wearer's body to HAL. Joint torpues generated by power units are transmitted to the wearer through these equipments. The sensors used by HAL are explained later. HAL, which is a human support technology, can be applied to many areas; training for physically challenged people, care assistance and heavy work support such as construction or disaster rescue.

A wearable robot expected to work in human society is required to have a high structural safety, with a tough and compact structure and a human outline. At the same time, it is difficult to balance a tough structure with a compact one because of the trade-off between strength and size. Furthermore, the structure of the wearable system has severe design limitation. An endoskeletal frame like a humanoid robot can have high mechanical strength, however, an exoskeletal framwork like HAL is bound by the presence and the shape of the wearer's body. Any mechanical failure of HAL while working in a human living environment could harm not only the wearer but also the people around him/her. Thus, HAL needs higher structural safety than industrial robots, which are working in limited environments like unmanned factories. On the other hand, an oversized wearable robot has limited applications in our daily environments. Therefore, thickening the components is not a desirable method for this wearable robot to increase the mechanical strength.

This paper focuses on the control method for a wearable robot based on the structural safety. There have yet been few examinations of this idea that the mechanical strength of a robot depends on its posture. Therefore, HAL can be tougher than before by changing to an appropriate working posture, even if the exoskeletal frames are compact. D. Isobe et al. have studied motion planning of manipulators using real-time FEM (Finite Element Method) analysis [7]. They investigated the effectiveness of controlling a manipulator's posture for reducing structural stress. Our research target however is a wearable system, not a manipulator. The HAL-5 full-body

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version has 8 controllable joints limited by human joint range of motion. It is difficult to apply the real-time FEM analysis method to posture control of HAL because of the calculation cost. We suggest that HAL autonomously leads a wearer to a known appropriate working posture for reducing structural stress based on prior FEM analysis. This control method is called Working Posture Control of HAL.

The purpose of this paper is to propose a working posture control method and to verify the effectiveness of the proposed method. The development of the working posture control consists of the following stages;

A) Defining the target motion for utilizing functions of HAL
B) Performing FEM Analysis for determining the appropriate working posture of high mechanical strength depending on the working situation
C) Designing a control algorithm for the complete Human-HAL system

Chapter 2 explains the working posture control method, which includes the target motion, the FEM analysis and the control algorithm. Chapter 3 shows the experimental results of holding a load. Chapter 4 discusses and verifies the effectiveness of the proposed method. Finally, Chapter 5 gives the conclusions.

II. METHODS

A. Target Motion

The target motion involves holding a load with both forearms, such as during heavy work. Figure 2 shows an example of a wearer who lifted up a heavy load using HAL. There are two reasons why we select this motion.

One reason is that heavy work assistance with HAL is very important for reducing the physical burden of many workers. Especially, as is acknowledged by many researchers, the care motion is one of the heaviest tasks [8]-[13]. Most of the caregivers suffer from some chronic sickness such as backache due to cumulative physical damage, which led the Ministry of Health, Labour and Welfare in Japan to also take measures against this problem. Because HAL can support human physical capabilities, care assistance with HAL is also useful for the health care field and thus important to support any super aged society.

The other reason is that heavy work assistance means a higher workload for HAL than ever before, compared to usages such as the walking assistance. HAL now needs to handle not only the weight of the wearer but also that of the heavy load. Therefore, it is crucial to examine the structural safety of HAL regarding to the load holding motion.

In the next section, Section 2.2, the results of the FEM analysis are investigated to determine the appropriate working posture for the target motion. In addition, the target motion is looked at from the perspective of the control algorithm in Section 2.3.

B. FEM Analysis

The results in our past FEM analysis suggest the waist component of the trunk segment becomes especially stressed.

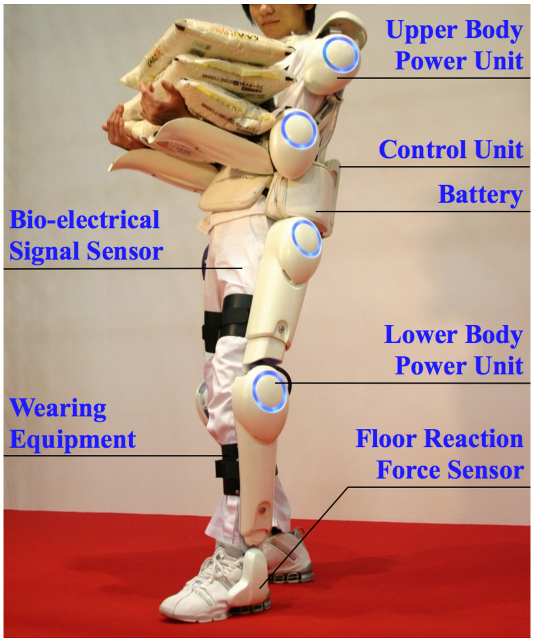

Fig. 1. The fundamental system of HAL-5 full-body version. This HAL has six types of segments: forearm, arm, trunk, thigh, leg and foot. Each segment consists of several exoskeletal frames. Everything is connected to the feet of the robot which are in contact with the ground. Therefore, HAL can support its own weight, as well as part of the wearer's weight and any extra loads carried. Power units are attached on each elbow, shoulder, hip, knee joint, and have one degree of freedom, flexion and extension. Wearing equipments fasten the wearer's body to HAL. Each sensor is used to control.

Fig. 2. An example of a wearer who lifted up a heavy load (e.g. a care receiver's weight) using HAL. The target motion involves holding a load with both forearms, such as during heavy work. The heavy work assistance means a higher workload for HAL than ever before, compared to usages such as the walking assistance.

We consider this trend to be characteristics of an exoskeletal structure and to be caused by the load holding posture.

The structural stress is affected to a great deal by bending moment, not shear force or axial force such as tension and compression. This fact is not surprising because the bending moment is an integration value of shear force and distance, or moment arm, from the reference point to the working point. The longer the moment arm, the bigger the bending moment. Additionally, the waist component is located posterior to the wearer's waist. When HAL bends forward in the load holding posture, the moment arm from the care receiver's weight on the forearm frame to the waist component is often the longest of all moment arms. As a result, it becomes particularly stressed. Thickening the waist component for increasing the mechanical strength means it is difficult to sit down. Therefore, it becomes necessary to apply the working posture control.

For FEM analysis, the model of HAL's exoskeletal frames was constructed using three-dimensiononal CAD (Computer Aided Design). The size of this model is equal to a HAL-5 full-body version for a wearer who is 180 cm tall. It was possible here to analyze only the exoskeletal frames in different static postures, because the power units attached on each joint move slowly in a near static way and are themselves subject to a different analysis that considers commercially available components. For determining the reference posture of the proposed method, FEM analysis of the model is run using CAE (Computer Aided Engineering). The analysis conditions are the following.

1) A concentrated load acts on a fixed point of each forearm frame.
2) The model has both feet fixed to the ground.
3) All joint angles are changed based on the results of prior experiments using HAL in order to refer to human joint angles during load holding postures.
4) The joint angles of the elbow and the shoulder are constant in accordance with the proposed load holding control method for HAL.

Table 1 shows the result of FEM analysis using the HAL model to check the maximum structural stress around the left side of the waist component based on the upper body inclination. In the table, Upstand means that the model is standing up straight and both of the hip joint angles are set at 0 rad. Forward means the model is inclined forward at 0.17 rad (10 deg) angle and Backward means the model is inclined backward at 0.17 rad angle. Both knee joints are at full extension, that is 0 rad angle. Though we confirmed that the flexion of knee joints often reduces the maximum structural stress of the waist component, the full extension of the knee joints keeps the load holding posture without energy loss in the knees because of the mechanics of the knee joints. For quick comparison, the structural stress of Upstand and Standing with both feet together is defined as 1.00.

The principle of reducing structural stress is to shorten the moment arm from the working point. In table 1, we can confirm that the backward inclination of the upper body is effective to reduce the structural stress of the waist component. Changing to 0.34 rad (20 deg) angle for the hip joints reduces approximately the stress by about 40 percent before changing the posture. It should be pointed out that putting the right foot forward results in a higher mechanical strength of the left side of the waist compared to putting the left foot forward. Thus, thickening of just one side of the waist component is suggested to increase the structural safety of HAL. In addition, the shoulder component tends to have an increased maximum structural stress when the upper body is inclined backward. For that reason we need to be careful of the total structural stress.

TABLE I

THE RESULT OF FEM ANALYSIS USING THE HAL MODEL TO CHECK THE MAXIMUM STRUCTURAL STRESS AROUND THE LEFT SIDE OF THE WAIST COMPONENT BASED ON THE UPPER BODY INCLINATION. THE INCLINATION IS 0.17 RAD ANGLE. FOR QUICK COMPARISON, THE STRUCTURAL STRESS OF UPSTAND AND STANDING WITH BOTH FEET TOGETHER IS DEFINED AS 1.00.

	Backward	Upstand	Forward
Standing with both feet together	0.71	1.00	1.18
Putting the left foot forward	0.81	1.06	1.27
Putting the right foot forward	0.63	0.88	1.07

From these results, the reference working posture for the proposed method is determined in this paper to be as follows.

1) The upper body is inclined backward at 0.17 rad based on the FEM analysis and human joint range of motion.
2) The knee joints is at full extension because of energy conservation.
3) The elbow and shoulder joint angles are determined by the intention of the wearer. In this regard, however, moving forearms and arms closer to the trunk is better for reducing structural stress of the waist component.

C. Control Algorithm

The methods used to control HAL are the Cybernics Voluntary Control and the Cybernics Autonomous Control. Power assist based on human intention is achieved by mixing these two control methods.

The Cybernics Voluntary Control provides physical support based on the wearer's voluntary muscle activity. The power units of HAL generate assistive torque by amplifying the wearer's joint torque estimated from his/her BES (Bio-Electrical Signals) and the support motions are consequently controlled by signal adjustments. To detect the BES, two sensors are attached on the wearer's skin near the flexor and the extensor driving the targeted joint. A sensor unit consists of two electrodes and an instrumentation amplifier. There, the two BES from the flexor and extensor are filtered and amplified.

The Cybernics Autonomous Control autonomously provides a desired functional motion generated according to the wearer's body constitution, conditions and purposes of motion support. While bioelectrical signals are mainly used in the Cybernics Voluntary Control, various kinds of information, such as floor reaction force and joint angles, can be used by the Autonomous Control to provide appropriate physical support. Preventing the movement of HAL from conflicting with the human's intention is still important however. At first, we focus on the situation that the wearer remains stationary. The load holding posture is suitable for this aim.

Figure 3 shows the control algorithm. The control algorithm of the proposed method consists of two tasks. Task 1 is applied to the Bio-Electrical Signal Control to assist all 8 controllable joints, which are elbow, shoulder, hip and knee. The assist torque of each joint is obtained from the following equation.

$$\tau_1 = \alpha_{gain}(\alpha_{flex}\mu_{flex} - \alpha_{ex}\mu_{ex}) \tag{1}$$

Here, α_{gain} is defined as the assist ratio based on the wearer's request, μ_{flex} and μ_{ex} are the signals obtained by the BES sensors. α_{flex} and α_{ex} are coefficients for relating the BES to the torque. Task 2 is applied to proportional and derivative control in order to achieve the reference working posture of the load holding motion. The assist torque of the hip and knee joints is therefore obtained from the following equation.

$$\tau_2 = K_P(\theta_{reference} - \theta_{joint}) + K_D(\dot{\theta}_{reference} - \dot{\theta}_{joint}) \tag{2}$$

Here, K_P is a proportional gain and K_D is a derivative gain, θ_{joint} and $\dot{\theta}_{joint}$ are the joint angles obtained by joint angular sensors attached to each power unit, $\theta_{reference}$ and $\dot{\theta}_{reference}$ are their respective reference values. The angles of the elbow and shoulder joints are maintained to support the load holding posture when the wearer holds a heavy load.

There are three estimations for switching Task 1 to Task 2 or vice versa. Referring to figure 3 and considering that the shown algorithm is run many times a second, they are given as follows.

$$\dot{\theta}_{ma-joint} > \dot{\theta}_{minimum} \tag{3}$$

$$t_2 < T_{latency} \tag{4}$$

$$\theta_{upper-body} < \theta_{threshold} \tag{5}$$

Equation 3 is the Movement Estimation. It checks the moving average of the angular velocities of the hip and knee joints, $\dot{\theta}_{ma-joint}$, for switching from Task 1 to Task 2. In this equation $\dot{\theta}_{minimum}$ is nearly 0 rad/s. In the case that $\dot{\theta}_{ma-joint}$ is more than $\dot{\theta}_{minimum}$, the BES Control starts. In case the angular velocities of all joints are below $\dot{\theta}_{minimum}$, the time is suitable for applying Cybernics Autonomous Control because the movement is so slow that it is nearly static. Therefore, Task 2 starts in this case.

Equation 4 is the Stillness Estimation, which checks whether the wearer is nearly static for a certain latency

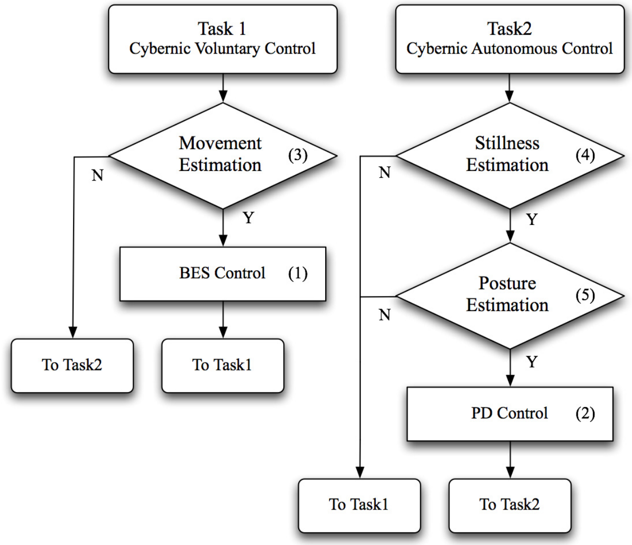

Fig. 3. The control algorithm of the proposed method. Three estimations switch from control by bio-electrical signals to proportional and derivative control by the angles and the angular velocities of the joints. Each number at the figure shows the number of the equation from the context.

time to make sure that PD control can be applied. If not, Task 2 switches back to Task 1. In this condition t_2 is the elapsed time since Task 2 started, and $T_{latency}$ is a short time period. In case t_2 is less than $T_{latency}$, Posture Estimation starts, and is kept running for a maximum time of $T_{latency}$, under the assumption that the wearer does not move during this time because the movements were measured to be slow in equation 3. If the equation does not hold, Task 1 starts.

Equation 5 is the Posture Estimation and it checks whether the reference working posture is attained based on the upper body inclination with respect to the ground and the present motion and thus decides to keep at Task 2 or go back to Task 1. In this equation $\theta_{upper-body}$ is calculated from the angles of the hip and knee joints. Furthermore, $\theta_{threshold}$ is a parameter for distinguishing between a load holding posture and a lifting up posture, and is defined as the minimum upper body inclination from which can be concluded that the wearer lifts up something. Therefore, in case $\theta_{upper-body}$ is less than $\theta_{threshold}$, PD Control starts to lead a wearer to the reference working posture. If not, Task 1 starts again because HAL judges that the wearer remains stationary temporarily before lifting up the load. It would be possible to add another Posture Estimation depending on the target motion.

III. EXPERIMENT

This chapter shows the experimental results of an experiment in which a load was being held by a person wearing a HAL-5 full-body version. A stress sensor is attached on the waist component to detect the bending moment in the direction of the gravitational force. The experimental protocol was the following.

1) The wearer stands with both feet together.
2) He puts 20 kilograms weight on his forearms.

3) He adjusts his posture and stands still.
4) We verify the timing of Task switching and reduction of structural stress by the working posture control.

Figure 4 shows the directions of the hip and knee joint angles: counterclockwise is positive in this figure. Each joint angle is defined as the relative angle between its adjacent segments, and each zero point is defined as the fully stretched position. The estimated parameters in this experiment are defined as $\dot{\theta}_{minimum} = 0.01$, $T_{latency} = 1.0$ and $\theta_{threshold} = 0.5$.

Figure 5 shows the result of this experiment. The horizontal axis is the time (in seconds). The vertical axes are the angular velocities of hip and knee joints (in rad/s) in the first graph, the angles of hip and knee joints (in rad) in the second, and the number of the current Task in the final graph. The angular velocities and angles on the left side are shown because the wearer stands with both feet together and the motions on both sides are similar.

At the dashed circle we can find that the present angular velocities of hip and knee joints $\dot{\theta}_{joint}$ is less than $\dot{\theta}_{minimum}$ and Task 1 is switched to Task 2. After that, the hip and knee joints follow the reference angle. During the shaded region on the angle data posture control is not applied because Task 1 was active. One second, equal to $T_{latency}$, after from Task 2 started, Task 1 starts again.

Figure 6 shows the effect of reducing the average structural stress. The stress before using posture control is defined as 1.00. After applying the working posture control, the reduction rate is 13 percent. Not good angle tracking is an example in which the hip and knee joints do not follow the reference angle enough. At that time, the reduction rate is 6 percent.

IV. DISCUSSION

Judging by the result of the experiment, we can confirm the effectiveness of the proposed method. There are three reasons as follows.

1) Each estimation (equations 3-5) can switch Task 1 to Task 2 or vice versa at the any time.
2) The angles of the hip and knee joints follow the reference angles for changing to the appropriate working posture of the load holding motion.
3) Compared with the initial posture before controlling, 13 percent reduction rate of the structural stress of the waist component is achieved by the proposed method.

It is worth noting that the proposed method is effective to reduce the structural stress even if the initial posture, which is stable and comfortable for the wearer, is similar to the reference posture. There is some allowance between the wearer and the wearing equipment of HAL. Therefore, small angular variations of HAL's joints have an insignificant effect on the wearer. If the proposed method is applied to another initial posture such as an extreme forward inclination of the upper body (0.8 rad), 80 percent reduction can be achieved in FEM analysis. However, in case of extreme initial posture like that, the proposed method should lead the wearer to the appropriate working posture in stages. A fast and furious posture control would make the wearer uncomfortable and puts a heavy load on the components of HAL. We suggest the advanced working posture control should depend on the difference between initial posture and the final reference. In addition, a high performance in arriving at the reference angle is needed to achieve enough effect for reducing the structural stress.

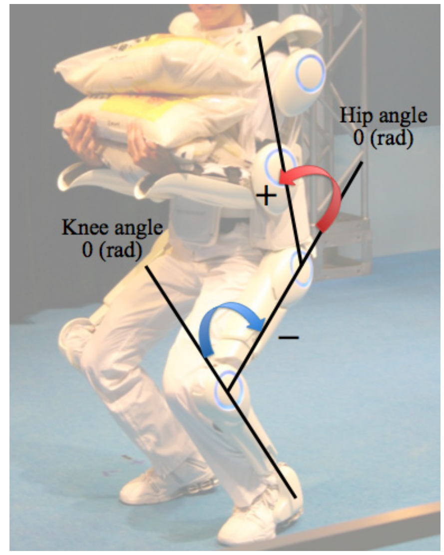

Fig. 4. The directions of the hip and knee joint angles: counterclockwise is positive in this figure. Each joint angle is defined as the relative angle between its adjacent segments, and each zero point is defined as the fully stretched position.

Although the three estimations operate as planned, it is necessary to review them.

1) The Movement Estimation should switch Task 1 to Task 2 after a certain period of time when the wearer stands still. If a joint is quickly flexed and extended repeatedly, the moving average of the joint angular velocity is nearly 0 rad/s despite the fact that the wearer is moving.
2) The Stillness Estimation should use the bio-electrical signals to estimate the wearer's intention directly. The values of each BES sensor is memorized as the thresholds when the wearer stands still. Then, if the present values differ enough compared to the memorized ones, the estimation should switch Task 2 back to Task 1.
3) The Posture Estimation should use more information of the available sensors, such as floor reaction force sensors, to estimate the various motions of the wearer.

V. CONCLUSION

Based on the above experiment, in which a load was being held in the desired posture, it can be concluded that the effectiveness of the proposed working posture control method is verified. The results of this study will thereby further contribute to increasing the structural safety of wearable systems.

The effectiveness of the working posture control has already been investigated by the fundamental experiment

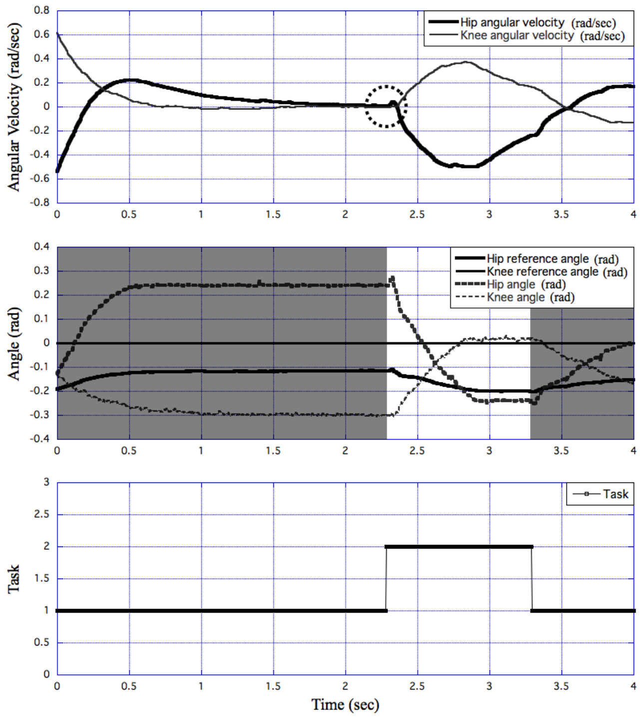

Fig. 5. The result of this experiment. This figure shows the angular velocities, the angles and the Task transitions during holding a load. The angular velocities and angles on the left side are shown because the wearer stands with both feet together and the motions on both sides are similar. Each estimation (equations 3-5) can switch Task 1 to Task 2 or vice versa at the any time. At the dashed circle we can find that the present angular velocities of hip and knee joints are nearly 0 rad/s. The angles of the hip and knee joints follow the reference angles for changing to the appropriate working posture of the load holding motion. During the shaded region on the angle data posture control is not applied because of Task 1 was active.

described in this paper. In the following phases of this research, HAL should lead the wearer to the appropriate working posture in stages to make it comfortable for the wearer and suitable for the structure of HAL. In addition, the proposed method will be applied to existing heavy work situations where a human weight, or more, needs to be handled. The HAL under development for heavy work assistance such as for caregivers has a larger lifting capacity than the present HAL-5 used in this experiment. At the same time, we need to discuss about the structural safety based on both control and mechanical design.

The merging of new technologies into the social system in order to support the super aging society are seen as a matter of pressing urgency for the developed countries. Wearable robots are required to have not only assistive functions but also structural safety. We therefore expect that HAL, which gained high structural safety by applying the proposed methods, will become well suited to human society in the near future.

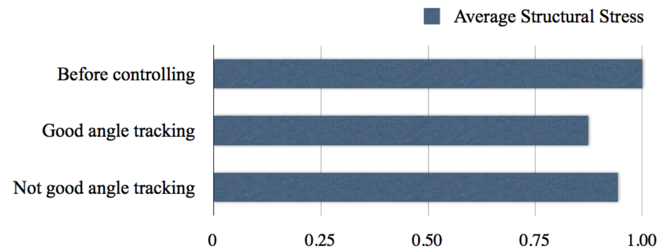

Fig. 6. The effect of reducing the average structural stress. The stress before using posture control is defined as 1.00. Compared with the initial posture before controlling, 13 percent reduction rate of the structural stress of the waist component is achieved by the proposed method.

VI. ACKNOWLEDGMENTS

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