Compound Movement Support by an ULSS Based on a Bioelectrical Signal for Upward High Load Works

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Abstract –

Upward high load works such as the installation of ceiling boards are severe work. We have developed an upper limb support system (ULSS) for the works. The purpose of this study is to develop compound movement support algorithm for the ULSS, and to confirm the effectiveness of the ULSS with the algorithm. The installation of the ceiling boards is compound movement. The workers move a tool vertically with one arm while holding the heavy board with another arm. The ULSS is a powered exoskeleton and has enough range of motion (ROM) for the works. The developed algorithm controls each arm part of the ULSS separately and achieves the compound movement support based on a bioelectrical signal (BES). The BES is detected on the surface of the human skin covering the muscle when the human is going to move their muscle. Volunteers perform the compound movement simulating the actual work in the evaluation experiments. As a result, the ULSS with the algorithm had a positive effect on the support. The average number of the compound movement with the ULSS increased 2.0 times compared to the average number without the ULSS.

Keywords –

Compound movement; Upward high load works; Powered exoskeleton; Bioelectrical signal

1 Introduction

At demolition or construction sites, workers have to perform upward high load works. Examples are installation of ceiling boards, cutting of metal pipes, and chipping of cement [1]. The workers hold heavy loads overhead, and move heavy loads vertically. It is difficult to sustain such the upward high load works, and working environment will be severe. For this reason, actual working time of whole working time decreases, and work efficiency will be reduced. In addition, the severe working environment causes decrease of the workers in the construction industry [2]. Therefore, It is necessary to improve the working environment, and movement support for upper limbs is required.

A wearable system with a sufficient degree of freedom (DOF) and support power will be effective to sustain these upward high load works for a long time. Many wearable systems for the movement support have been researched and developed [3]-[9]. However, these studies focus on the high power support for the works performed under the wearer's head, or light power support for the works performed on the wearer's head. In this study, we focus on the upward high load works, and have developed an upper limb support system (ULSS) [10]. The ULSS is a powered exoskeleton and follows complex movements of the wearers by redundant DOF. In the actual work sites, it is necessary for the ULSS to perform voluntary movement support by following motor intention of the wearers. Estimation of the motor intention is important for the voluntary movement support. In this study, we adopt a bioelectrical signal (BES) as the method for estimating the motor intention [11]-[16]. The BES contains nerve command signals and myoelectrical signals. The BES is detected on the surface of the human skin covering the muscle when the human is going to move their muscle. The BES is effective for voluntary movement support because this electrical signal reflects muscle activity and the motor intention directly. A movement support algorithm for the ULSS based on the BES is required to achieve voluntary movement support.

In previous research, we have developed a static movement support algorithm for the holding movement such as the cement chipping work, and dynamic movement support algorithm for the vertical movement such as the pipe cutting work [17][18]. These algorithm supports simple static or dynamic movement. In the simple work such as the chipping work or cutting work, the workers treat tools and materials by their both hand. However, the workers perform compound movement of the static holding movement and dynamic vertical movement in the actual work sites. The installation of ceiling boards is compound movement. This work is one of the most demanding types of the work in terms of the weight of the tools and materials. The workers move a nailing machine vertically with one arm while holding the heavy ceiling board with another arm. During this work, required support power changes according to the movement of each arm. Thus, it is necessary to develop a new compound movement support algorithm for the upward high load works such as the installation of ceiling boards.

The purpose of this study is to develop a new compound movement support algorithm for the ULSS based on a BES to achieve continuous upward high load works. In addition, we confirm the effectiveness of the ULSS with the algorithm through evaluation experiments. In the evaluation experiments, we assess the voluntariness of the ULSS, and the effectiveness of the ULSS for the compound movement.

2 Material and Method

2.1 Upper Limb Support System (ULSS)

Figure. 1 shows an overview of the ULSS. The ULSS is a powered exoskeleton. Basic points of the movement of the arms are shoulder joints. When the workers raise their arms, the clavicles and the scapulas of the wearers which hold the humeruses tilt to upward [19]. In addition, the spine moves three-dimensionally. Consequently, the positions of the shoulder joints move significantly. The ULSS has the middle joins, and this joint is redundant with respect to the structure of the wearer in the sagittal plane. The wearers of the ULSS can move smoothly through the middle joints. Moreover, Japanese adult males, who have dimensions of the human body between 5%tile to 95%tile, can wear the ULSS by the shoulder width adjusting mechanism.

A total of six power units are installed on the arms of the ULSS. The ULSS supports the wearer's upper limb movement by moving independently on the left side power units and the right side power units. The shoulder joints and middle joints are connected by the parallel link mechanism to reduce the required support force [20]. The ULSS is attached to the wearer by belts. There are cuffs that transmit support forces to the wearer. Each joint has a mechanical angle limiter. The lumber load support unit transmits the reaction force of the support force to the iliac horns of the wearer. The total weight of the ULSS is 8.3 kg. The minimum safety factor for the breaking strength is over 2.0 in a state of maximum load. In order to ensure safety, the wearers only handle tools and materials that they can handle without the support of the ULSS. In addition, the wearers have enough training and explanation before the evaluation experiments.

Figure. 2 shows a system configuration of the ULSS and the method for measurement of the BES. Power units in each joint have angle sensors and actuators. There is a control unit in the back part of the ULSS that consists of a main-computer, BES sensing unit, A/D converters, absolute angle sensor, and motor drivers. The reset switch is within reach of the jaw of the wearer. There is a battery unit in the lumbar load support unit, and the battery unit supplies electricity to the power units and each unit circuit. The BES sensing unit

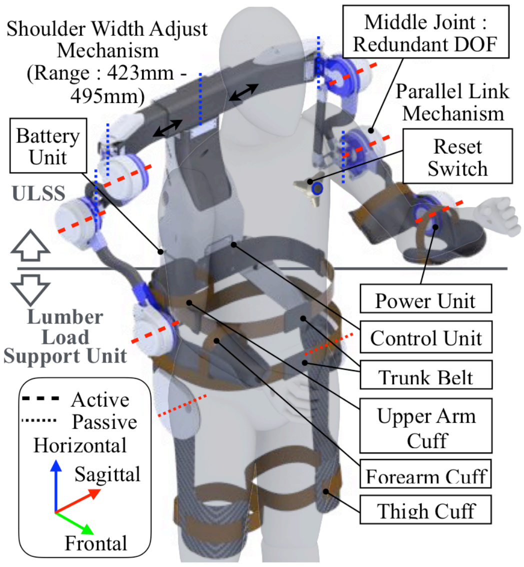


Figure 1. Overview of the ULSS. The ULSS is a powered exoskeleton and has redundant DOF for smooth movement of the wearer.

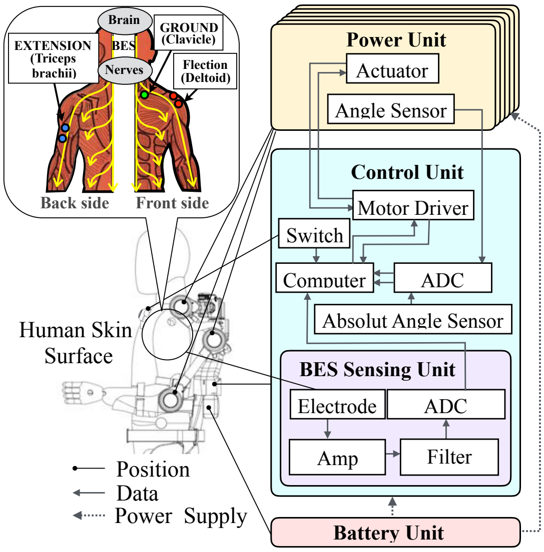


Figure 2. System configuration of the ULSS and the method for measurement of the BES.

measures the BES for the estimation of the motor intention by the wet type electrodes. The BES contains nerve command signals and myoelectrical signals and reflects muscle activity and the motor intention directly. The BES is detected on the surface of the human skin covering the muscle when the human is going to move their muscle [11]-[16]. The electrodes are attached on the deltoid, the triceps brachia, and the roots of the clavicle. The ULSS performs calibration process of the BES before the movement support.

2.2 Compound Movement Support

During the upward high load works, required support power changes according to the movement of each arm of the wearer. The ULSS supports the wearer by the compensation of gravity and viscosity according to the control phase. The developed algorithm achieves the compound movement support by shifting control phases. The support torque in each drive joint is

$$\tau = MgL + \tau_S + \tau_W + \tau_V \tag{1}$$

The M is the assumed weight which is held by the wearer in wearer's hand. We treat M as the known value because the weight of tools and materials will not change particularly in one upward high load work. It is considered that the method can support the actual works by inputting the weight value of the tools and materials. The ULSS achieves the compound movement support by changing the M according to the control phase. The g is the acceleration of gravity. The L is a moment arm of the position of M and each drive joint. The τ_S is the self-weight compensation torque around each joint, and the τ_W is the wearer's arm weight compensation torque around each joint, The τ_V is the viscosity compensation torque around each joint. It's possible to reduce the required gravity compensation torque around the shoulder joint by the parallel linkage [20].

The algorithm is compatible with the compound movement such as the installation of the ceiling boards. The workers move a tool vertically with one arm while holding the heavy material with another arm in such the work. The algorithm distinguishes between whether the movement of the wearer is the holding movement or the vertical movement based on the BES.

Figure. 3 shows a state transition diagram of the control phase. The control phase decides support power. This diagram illustrates the control phase of a single arm of the ULSS. The symbols in parentheses are equivalent to the M of the equation (1). The MH simulates the weight handled in holding movement, and the MV simulates the weight handled in vertical movement. In most cases, the MH is heavy than the MV in the compound movement such as the installation of ceiling boards. After the calibration, the control phase shifts to the NO-LOAD phase. When the reset switch was pressed, the control phase shifts to the WAIT phase. After that, the control phase shifts voluntarily based on the BES. The flection side BES is the fl, and the extension side BES is the ex. The control phase does not shift, when the co-innervation of the flexor muscle and extensor muscle occurs. The decision condition is

$$THR_{CO} < |fl - ex| \tag{2}$$

The THR_{CO} is the threshold value of the decision condition.

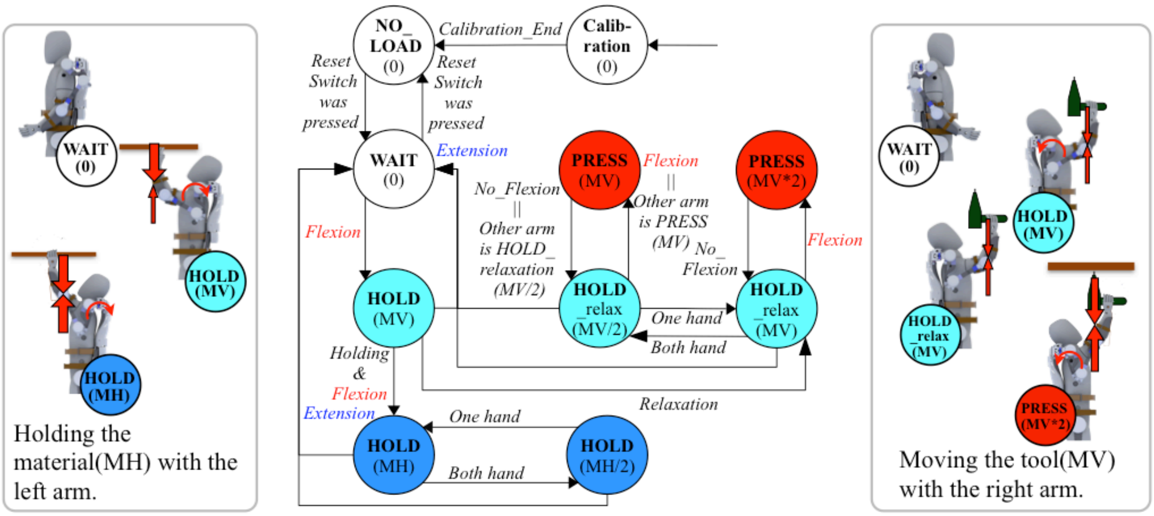


Figure 3. State transition diagram of the control phase for one arm part of the ULSS. When the reset switch was pressed, the control phase shifts to the WAIT phase.

The shift of the control phase in the vertical movement is shown below. The Flection indicates that the fl exceeds the threshold value THR_{FH} . The Extension indicates that the ex exceeds the threshold value THR_{RE}, and fl goes below the threshold value THR_{FL}. The THR_{FH} is larger than THR_{FL}. When the wearer holds the MV with his one arm, the state of the BES changes to the Flection. In addition, the WAIT phase shifts to the HOLD(MV) phase. At this time, the arm of the wearer can relax by the support of the ULSS. The decision condition of the relaxation is

$$(fl < (fl_{max} - THR_{FR}))\ \&\ (fl - THR_{FL}) \qquad (3)$$

The fl_{max} is the maximum value of the fl, and the THR_{FR} is a threshold value of the relaxation. After the relaxation, the control phase shifts to the HOLD_relaxation(MV). When the wearer presses the MV upward, the state of the BES shifts to the Flextion, and the control phase shifts to the PRESS(MV*2). When the state of the BES shifts to the No_Flextion, the control phase shifts to the HOLD(MV). The No_Flextion indicates that the fl goes below the threshold value THR_{FL}. When the wearer pulls down his arm, the state of the BES shifts to the Extension, and the HOLD phase shifts to the WAIT phase.

The shift of the control phase in the holding movement is shown below. When the wearer holds the MH with one arm, the state of the BES changes to the Flection, and the WAIT phase shifts to the HOLD(MV) phase. At this time, the gravity compensation for the weight in the wearer's hand is less than the support required for the MH. Thus, the BES keeps the Flection. At this time, the joint angular velocity shifts the Holding state and goes below the threshold value. For this reason, the control phase shifts to the HOLD(MH). When the control phases of both arms are the HOLD(MH) or the HOLD_relaxation(MV), the ULSS estimates that the wearer handles the heavy load by both arms. In this case, the control phases of both arms synchronize, and the assumed weight of the single arm becomes a half. Thus, the compound movement algorithm can support the holding movement and vertical movement voluntarily.

3 Experiment

3.1 Outline

Evaluation experiments were conducted to confirm the effectiveness of the system with the developed algorithm. The experiments were a random instruction experiment and a movement support experiment conforming to the installation of ceiling boards. Figure. 4 shows the pattern diagram of the experiments. A weight of 15 kg simulated the ceiling board, and a weight of 5kg simulated the nailing machine. Another weight of 5 kg simulated the reaction force, and this heavy load was passively moved vertically. The volunteers were five healthy adult Japanese males who had heights below the 95%tile value. The volunteers moved the two heavy loads of 5kg vertically with the dominant hand while holding the heavy load of 15kg with the non-dominant hand in synchronization with an instruction. The instruction was performed by a beep sound. The volunteers wore protectors.

3.2 Random Instruction Experiment

The random instruction experiment was conducted in order to confirm that the control phase changes by following the motor intention. The volunteers wore the ULSS and moved the heavy loads vertically. At first, the volunteers waited 5 s. Next, the volunteers gripped both of the below head height heavy loads at random intervals of 1 - 4 s. Next, the volunteers moved the upper heavy load vertically 3 times with dominant hand while holding the heavy load with the non-dominant hand. At this time, the rise of the two heavy loads of 5kg was performed for random intervals of 1 - 4 s, the descent of the heavy loads was performed for 1 s, and each vertical movement was performed after random intervals of 1 - 4 s. Next, the volunteers put the heavy loads on the pedestal after random intervals of 1 - 4 s, and pressed the heavy loads down. Finally, the volunteers waited 5 s. We measured the timing of the instructions, the movement of the wearers, and the shifts of the control phases.

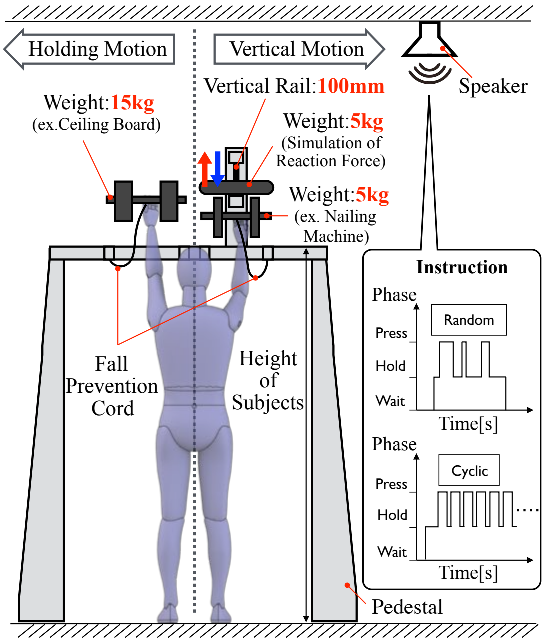


Figure 4. Pattern diagram of the experiments.

3.3 Movement Support Experiment

The movement support experiment was conducted in order to confirm that the ULSS with the developed algorithm had a supportive effect for the compound movement. The volunteers performed the compound movement in synchronization with cyclic instructions. The volunteers continued the movement to the limit of the physical strength without and with the ULSS. At first, the volunteers waited 5 s. Next, the volunteers gripped both of the below head height heavy loads for 5 s. Next, the volunteers moved the upper heavy load vertically with the dominant hand while holding the heavy load with the non-dominant hand. At this time, the rise of the two heavy loads of 5kg was performed for 4 s, and the descent of the heavy loads was performed for 1 s. When the volunteer could not continue this compound movement, they put the heavy loads on the pedestal and pressed the heavy loads down. Finally, the volunteers waited 5 s. We measured the number of the compound movements. Moreover, we conducted a dependent t-test to compare the number of compound movements without and with the ULSS, and the level of significance was 5 %. The volunteers took a rest between both of experiments to recover.

4 Result

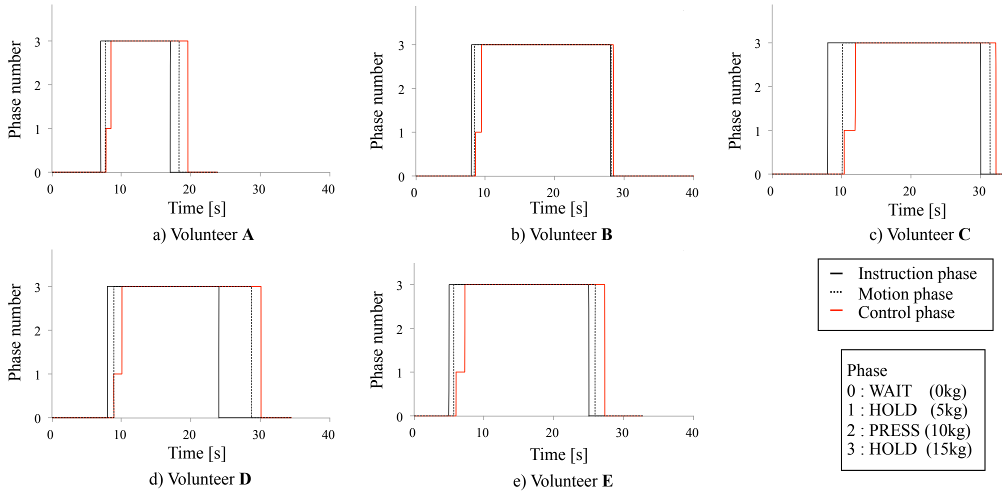
Figure. 5 shows results of the holding movement in the random instruction experiment. The control phase of all volunteers followed the instruction with a delay. In addition, the control phase shifted in the order of the WAIT(0kg), the HOLD(5kg), and the HOLD(15kg).

Figure. 6 shows the results of the vertical movement in the random instruction experiment. The control phase of the volunteer A, B, and E followed the instruction with a delay. As for the volunteer C, the HOLD(5kg) shifted to the PRESS(10kg) 2.25 s faster than the instruction. As for the volunteer E, the number of phase shift is smaller than the number of vertical movement instruction. In addition, when the instruction phase shifted from the PRESS(10kg) to the HOLD(5kg), the control phase didn’t shift from the PRESS(10kg) to the HOLD(5kg) once in a while. As for the control phase of all volunteers, the control phase shifted in the order of the WAIT(0kg), the HOLD(5kg), and the HOLD(10kg).

Figure. 8 shows the state of the movement support experiment. Figure. 9 shows the results of the movement support experiments. In the experiment without the ULSS, the average number of the compound movement repetitions was 9.4 sets, and the 95%CI was 11.7 - 7.1 sets. In the experiment with the ULSS, the average number is was 19.0 set, and the 95%CI was 23.4 - 14.6 sets. The number of all the volunteers increased with the ULSS. The average number of the compound movement repetitions with the ULSS was 2.0 times higher than without the ULSS. The result of the t-test was that the number of compound movement repetitions with the ULSS was significantly large higher.

5 Discussion

The volunteers performed holding movement and the vertical movement in the random instruction experiment. The results of the holding movement showed that the control phase of all volunteers followed the instruction with a delay. From this result, the volunteers performed the holding movement as per the instruction, and the developed algorithm voluntarily shifted the control phases by following motor intention of the wearers who perform the holding movement. In addition, the control phase shifted in the order of the WAIT(0kg), the HOLD(5kg), and the HOLD(15kg).



a) Volunteer **A** b) Volunteer **B** c) Volunteer **C** d) Volunteer **D** e) Volunteer **E**

Figure 5. Results of the random instruction experiment (holing movement).

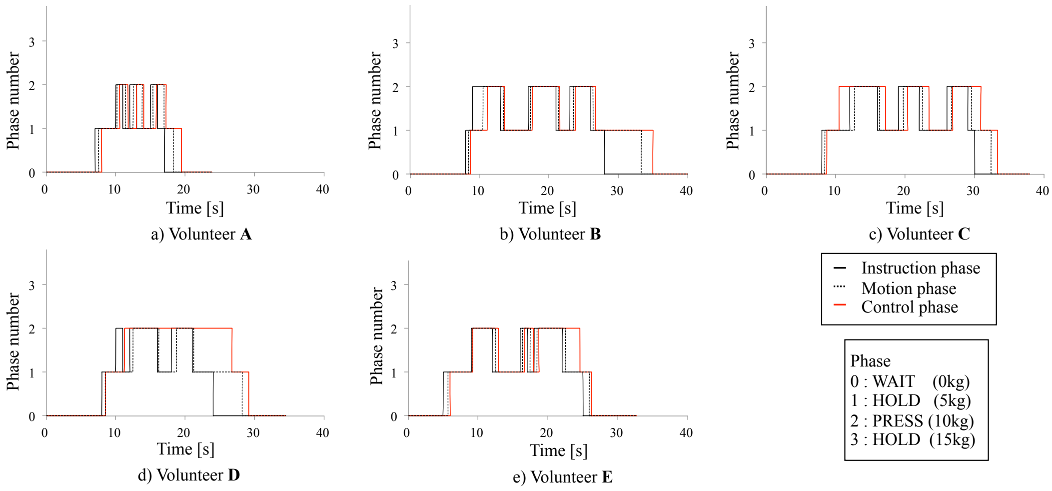
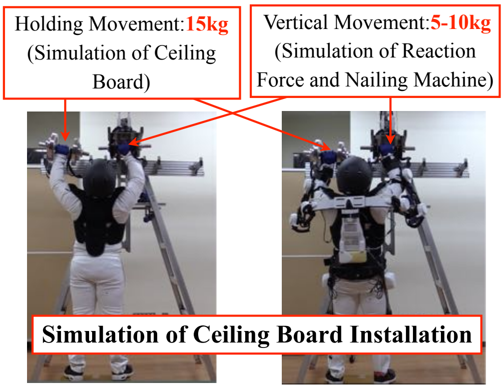


Figure 6. Results of the random instruction experiment (vertical movement).



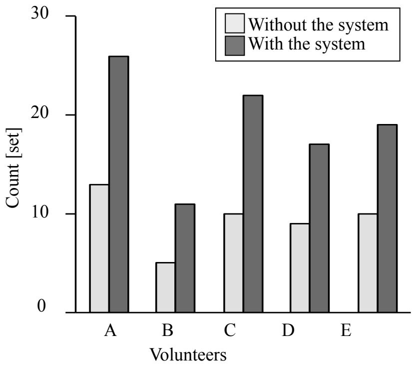
a) Without the system b) With the system

Figure 7. State of the compound movement experiment.

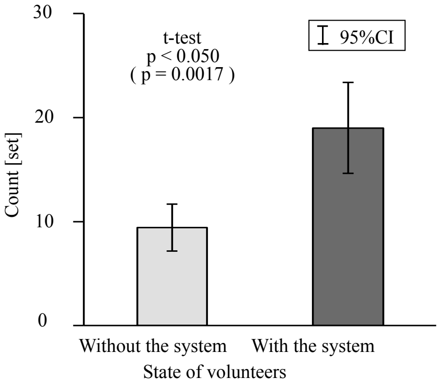
Thus, the developed algorithm detected the lack of the support power based on the BES, and switched the control phase adequately.

The results of the vertical movement showed that the control phase of the volunteer A, B, and E followed the instruction with a delay. From the result of the vertical movement, the volunteers A, B, and E performed the movement as per the instruction. As for the volunteer C, the HOLD(5kg) shifted to the PRESS(10kg) 2.25 s faster than the instruction. When the control phase of the vertical movement side shifted to the PRESS(10kg) from the HOLD(5kg) for the first time, the control phase of the holding movement shifted to the HOLD(5kg) from the WAIT. For this reason, we could assume that he moved both of his arms as per the instruction for his one arm.

As for the volunteer E, the number of phase shift is one smaller than the number of vertical movement instruction. We could assume that he couldn't react to the first instruction for the PRESS(10kg) because the instruction was performed for a short time. In addition, when the instruction phase shifted from the



a) Number of the compound motion



b) Average number of the vertical motion

Figure 8. Results of the movement support experiments. The number of compound movement repetitions with the ULSS is significantly greater.

PRESS(10kg) to the HOLD(5kg), the control phase didn't shift from the PRESS(10kg) to the HOLD(5kg) once in a while. We could assume that the volunteer E supported the heavy loads while performing the descent of the heavy loads. For these reasons, the developed algorithm voluntarily shifted the control phases by following motor intention of the wearers who perform the vertical movement having a large personal deviation. Thus, the control phase changes by following motor intention of the wearers who perform the compound movement.

The volunteers performed cyclic compound movement in the movement support experiment. The number of the compound movement repetitions of all the volunteers increased with the ULSS. The average number of the compound movement repetitions with the ULSS was 2.0 times significantly-higher than without the ULSS. From the result, the ULSS with the developed algorithm had a supportive effect for the compound movement consist of the static holding movement and the active vertical movement. We could assume that the support torque of the ULSS reduced the joint torque of the volunteers for the compound movement. For this reason, the volunteer could perform the more continuous compound movement.

The developed algorithm changed the control phases by following the motor intention of the wearers, and the ULSS had the effect of support for basic compound movement. Because of that, the ULSS with the algorithm was effective for the continuation of compound movement. When the control phase shifted by following the wearer's movement, the delays of the phase shift were large in the random instruction experiment. The volunteers performed the movement without a problem and had the effect of the support, but there is room for improvement for the delay of the phase shift. It is necessary for the algorithm to develop a function adjusting the threshold values automatically. In the evaluation experiment, the basic compound movement conforming to the installation of ceiling boards was performed. This movement is the one of the most demanding types task in terms of the weight of tools for heavy overhead task. For this reason, we can apply the ULSS with the developed algorithm to other construction sites using lighter tools and materials.

6 Conclusion

In this study, we developed a novel compound movement support algorithm for the ULSS based on the BES to achieve the continuous upward high load works. The developed algorithm achieves the compound movement support by voluntary shifting of the control phase in response to a change of the BES. In the random instruction experiment, the algorithm voluntarily shifted the control phases of the ULSS by following the motor intention of the wearer. In addition, the algorithm had the effect of the support for the basic compound movements, conforming to the actual work. Therefore, we could confirm that the ULSS with the algorithm had effectiveness for the compound movement. In our future work, we will improve the delay of the phase shift. We can expect that the ULSS with the algorithm increases the work efficiency, and improves environment of the actual work sites.

7 Acknowledgment

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