Evaluation of Fatigue Reduction during Crop Harvesting Using a Power Assist Suit

Toshitake Araie, Ikeda Tomozumi, Akira Kakimoto, and Shigeki Toyama

***Abstract*—An agricultural power assist suit (PAS) was developed and researched in our laboratory. The range of movements of the joints and the physical burden in retaining the posture when wearing the PAS were evaluated. The PAS was found to provide approximately 80% of the degree of freedom of the human body, and the muscle burden on the upper arms and thighs was reduced by 42.3 and 50.2%, respectively, on average during isometric exercises. The movements during pruning and harvesting work are yet to be evaluated. An experiment was conducted to study the body movements of farmers during the harvesting of radish and cucumber to evaluate the fatigue reduction effect owing to the use of the PAS. The workload was reduced by up to 77% for radish harvesting and up to 58% for cucumber harvesting, and the muscle activity was reduced by up to 64% for radish harvesting and up to 68% for cucumber harvesting when wearing the PAS.**

***Index Terms*—Agricultural work, power assist suit, surface EMG, training impulse (TRIMP).**

I. INTRODUCTION

A questionnaire survey conducted on the farm workers of Yin Yin regarding body parts subjected to fatigue during agricultural work showed that a heavy load acts on the arms and waist during pruning and harvesting, suggesting the need for assistance in maintaining the working posture [1]. The introduction of agricultural machines has reduced the physical burden on farm workers and increased the efficiency of agricultural production. However, as these machines are large, they cannot be employed in places with many slopes and narrow areas or in small-scale farms. Moreover, pruning and harvesting are activities that need to be carefully carried out by human hands and are hence difficult to mechanize. We are therefore engaged in the development of an agricultural power assist suit (PAS) for farming that can reduce the physical burden on workers performing delicate work irrespective of the terrain.

The range of movements of the joints and the physical burden in retaining the posture when wearing the PAS have been evaluated [2]-[6]. The PAS was found to provide approximately 80% of the degree of freedom of the human body, and the muscle burden on the upper arms and thighs was reduced by 42.3 and 50.2%, respectively, on average during isometric exercises. The movements during pruning and harvesting work are yet to be evaluated.

This study aims to evaluate the physical burden on farmers during pruning and harvesting activities when wearing the PAS. We employed subjects who simulated harvesting work and measured their workload and muscle activity in cases with and without wearing the PAS. The study reports the evaluation results of the fatigue reduction effect when using the PAS.

II. OVERVIEW OF PAS FOR AGRICULTURE

The PAS developed in this study is an exoskeleton-type motorless suit, as shown in Fig. 1. The frame is made up mainly of a carbon fiber-reinforced plastic and weighs approximately 8 kg. A ratchet mechanism is mounted on the shoulder to assist in maintaining the posture of the upper arms during pruning and harvesting of crops grown on trellises. A spiral spring is mounted on the knees, and the repulsive force of the spring assists in maintaining the posture of the lower back during the rising operation.

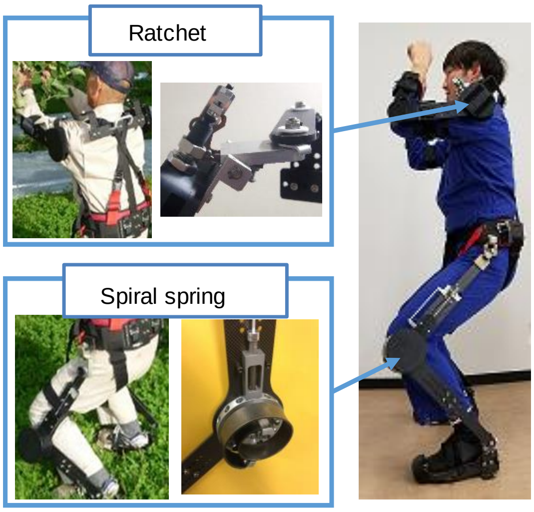


Fig. 1. Agricultural power assist suit.

The assist force provided by the ratchet mechanism for each arm corresponding to an allowable ratchet torque of 29.4 Nm and an arm length of 0.24 m from the ratchet center was 122.5 N, with the total for both arms being 245 N. In addition, a spiral spring was attached onto the knee joints. The reaction force of this spiral spring assisted the wearer in a half-sitting posture. The assist force provided by the spring mechanism corresponding to a spring constant of 0.82 Nm/deg and a maximum usage angle of 120° results in a maximum torque of 98.64 Nm. For a frame length of 0.41 m from the knee center to the knee joint, the assist force is 240.59 N, with the total force for both feet being 481.18 N.

Manuscript received April 3, 2019; revised June 12, 2019. This work was supported by JSPS KAKENHI under Grant JP18K04075.

T. Araie, T. Ikeda, and A. Kakimoto are with the Polytechnic University of Japan, 2-32-1, Ogawa-nishimachi, Kodaira-shi, Tokyo, Japan (e-mail: araie@uitec.ac.jp, ikeda@uitec.ac.jp, kakimoto@uitec.ac.jp).

S. Toyama is with the Tokyo University of Agriculture and Technology, 2-24-16, Nakacho, Koganei, Tokyo, Japan (e-mail: toyama@cc.tuat.ac.jp).

DOI: 10.7763/IJMO.2019.V9.733

The spring mechanism can be activated using a switch installed in the thigh frame, enabling the wearer to activate the assist function from any position.

Fig. 2 shows the structure of each joint of the agricultural PAS. To realize flexion and extension, abduction and adduction, and external and internal rotations of the hip joint, revolute joints are provided in the vertical direction of the sagittal, frontal, and horizontal planes. To realize dorsiflexion and plantarflexion and abduction and adduction movements of the ankle joint, a revolute joint is provided vertically with respect to the sagittal and frontal planes. As the shoulder joint has a high degree of freedom and complexity, rotational joints are provided separately for abduction and adduction and external and internal rotations. Furthermore, the frame is equipped with a sliding mechanism to correct the mismatch between the rotation centers of the human joints and the PAS joints. There is no joint on the back to support the load acting on the shoulder and elbow joints; nevertheless, there is springiness. In addition, to correct the axial distance of the joints between the human body and the PAS, adjustment mechanisms are provided on the femur, lower femur, shoulder horizontal surface, and back of the exoskeleton frame. The frame length can be adjusted in 10 mm intervals.

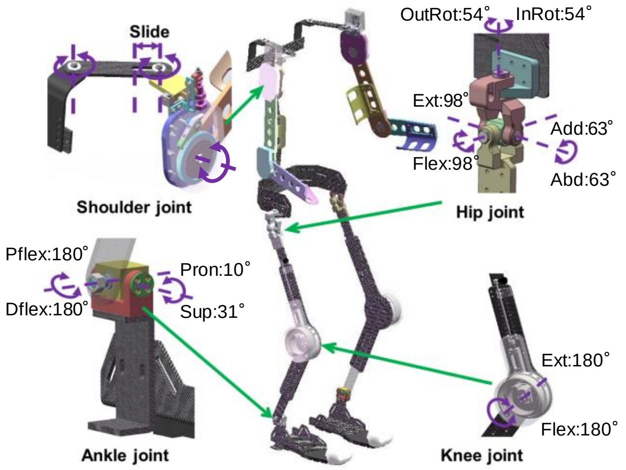


Fig. 2. Joint structure of the PAS.

Carbon fiber-reinforced plastic (CFRP) (custom-made by ACM Co., Ltd.) is used for most of the exoskeleton frame (weighing approximately 8 kg) for weight reduction. In addition, clearances are provided between the PAS frame and the human body, because the restraint position with the human body when wearing the PAS is only at three places: the foot, the waist, and the arms. The clearance between them and the PAS is 0 mm because the legs, waist, and arms are restrained using a belt. For the shoulder, back, and knees, the clearances provided are 50, 35, and 45 mm, respectively.

III. MEASURING WORKLOAD AND MUSCLE ACTIVITY

We recruited eight subjects (height: 163 to 170 cm, weight: 53 to 76 kg), including six healthy men (denoted by letters A to F) in the age group of 21 to 41 years and two elderly 73 year old men (G and H). The purpose and procedure of the experiment were explained in advance to the subjects, and their consent in participating in the experiment was obtained.

The subjects were asked to simulate the harvesting of radish and cucumber as shown below, with and without wearing the PAS.

Harvest operation of radish: Flexion and extension of knee joints; forward bending.

Harvest operation of cucumber: Flexion and extension of the knee joints while maintaining a 90° flexion position at the shoulder and elbow joints.

The operation time was 6 s, and the experiment consisted of 10 sets (1st to 10th), each set involving 3 min of work and 1 min of break. A metronome was used to ensure that the operations have identical timing.

The training impulse (TRIMP) [7], [8], which is an index used to assess training load in sports, was used as the index for the workload. From the average heart rate HR_{ex} during work, the heart rate HR_{rest} at rest, the maximum heart rate HR_{max}, and the working time T, the TRIMP for men can be determined using the following formula.

$$\mathrm{TRIMPs} = T \times \left(\frac{HR_{\mathrm{ex}} - HR_{\mathrm{rest}}}{HR_{\mathrm{max}} - HR_{\mathrm{rest}}}\right) \times 0.64e^{1.92x} \tag{1}$$

$$x = \frac{HR_{\mathrm{ex}} - HR_{\mathrm{rest}}}{HR_{\mathrm{max}} - HR_{\mathrm{rest}}} \tag{2}$$

Here, x denotes the value obtained from the Karvonen formula, and the constant term is a value that considers the difference in the load intensities between men and women (Men: $0.64\ e^{1.92x}$; women: $0.86\ e^{1.67x}$). As the subjects did not suffer from arrhythmia, the heart and pulse rates were the same. The pulse rate was measured using Epson's wristwatch-type wearable activity meter PULSENSE [9], which had very little impact on the activity.

The muscles chosen for surface myoelectric potential measurement [10] were the rectus femoris (RF), the medial latissimus dorsi (VF), and the lateral latissimus dorsi (VL). The personal-EMG (Osaka Electronic Equipment Ltd.) was used as the measuring device, and BlueSensor M (manufactured by Ambu) was used as the electrode. The myoelectric potential was obtained through a band pass filter with a sampling frequency of 3 kHz, an amplification factor of 1000, and a frequency range of 20 to 500 Hz. The analysis target was the measurements of 12 rounds including two rounds of operation of odd numbered sets as well as the 10th set. The muscle activity was determined from integrated electromyography (IEMG). A time–frequency analysis was performed using continuous wavelet transform taking the Morlet wavelet as the mother wavelet function, and the dynamics of muscle fatigue was evaluated.

The reduction rate was calculated from the following equation using the average values of the workload and muscle activity.

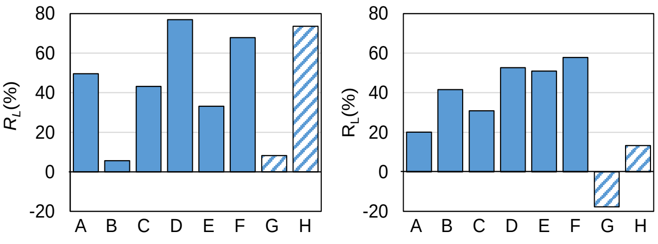
$$R_{\mathrm{L}} = \left(1 - \frac{TRIMPs_{\mathrm{with}}}{TRIMPs_{\mathrm{without}}}\right) \times 100 \tag{3}$$

$$R_{\mathrm{E}} = \left(1 - \frac{IEMG_{\mathrm{with}}}{IEMG_{\mathrm{without}}}\right) \times 100 \tag{4}$$

Here, R_L denotes the workload reduction rate, R_E denotes the muscle activity reduction rate, the subscript "with" indicates that the subjects wore the PAS, and the subscript "without" indicates that they did not wear the PAS. When the reduction rates R_L and R_E were positive, the workload and muscle activity were said to be reduced on account of wearing the PAS.

IV. EVALUATION OF FATIGUE REDUCTION IN SIMULATED HARVEST ACTIVITY

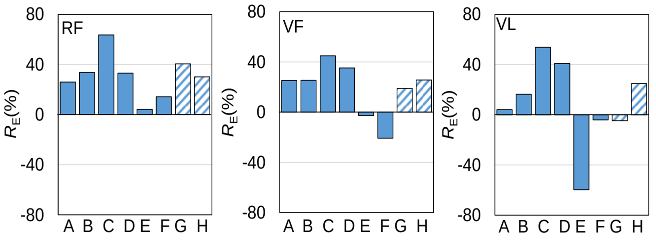
Fig. 3 shows the result of the workload reduction rate. All the subjects engaged in radish harvesting and seven subjects involved in cucumber harvesting showed positive values. The average reduction rate was 48% for radish harvesting and 31% for cucumber harvesting.



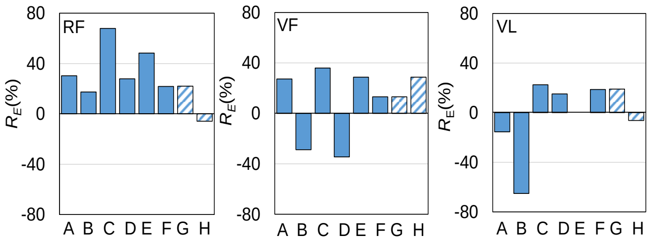
(a) Radish harvesting (b) Cucumber harvesting

Fig. 3. Workload reduction rate R_L.

Fig. 4 shows the reduction rate in the muscle activity. The workload on the VL of subject E of the cucumber harvesting group could not be measured and was therefore excluded. The reduction rates for RF of 8 subjects, VF of 6 subjects, and VL of 5 subjects in the radish harvesting group and for the RF of 7 subjects, VF of 6 subjects, and VL of 5 subjects in the cucumber harvesting group showed positive values. The average reduction rates were 31% for RF, 19% for VF, and 9% for VL in the radish harvesting work and 29% for RF, 10% for VF, and −2% for VL in the cucumber harvesting group.



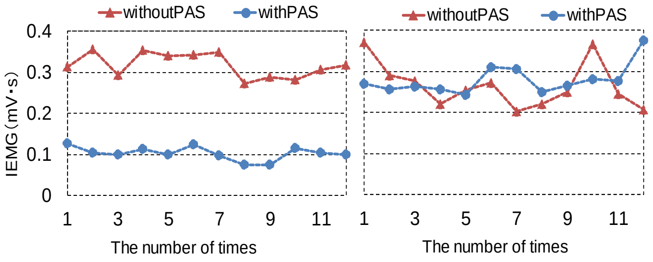
(a) Radish harvesting



(b) Cucumber harvesting

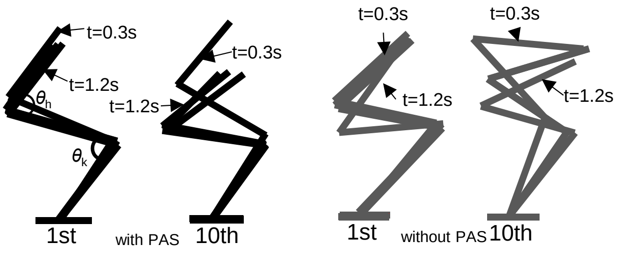
Fig. 4. Muscle activity reduction rate R_E.

Fig. 5 shows the changes in the muscle activity of subject C. The burden on the rectus femoris, which is a bi-articular muscle involved in the flexion and extension of the knee joint and flexion of the hip joint, was reduced. The figure also shows the change in the muscle activity of an elderly subject H; no reduction effect was observed for this subject. Subject C shows a low value of muscle activity when wearing the PAS, indicating reduced muscle burden. The elderly subject H did not see any difference in the muscle activity when wearing the PAS. However, the muscle activity decreased when the PAS was not used. Therefore, when wearing the PAS, it is concluded there was no change in the amount of muscle activity due to repeated work, regardless of the age of the wearer.

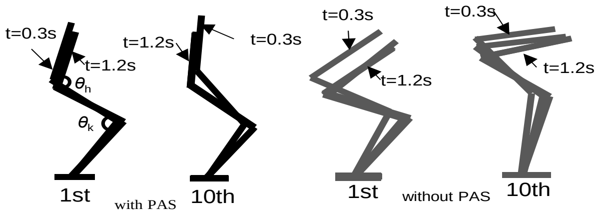


(a) Subject C (RF) (b) Subject H (RF)

Fig. 5. Change in the muscle activity during cucumber harvesting.

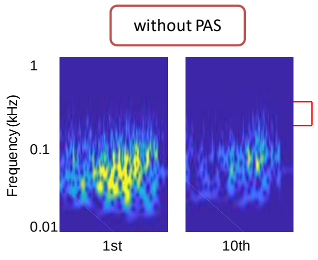


(a) Radish harvesting

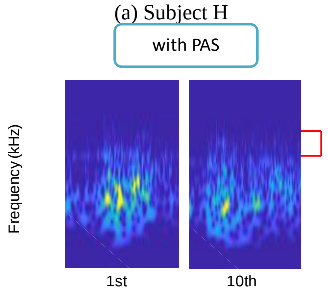


(b) Cucumber harvesting

Fig. 6. Change in posture of subject H during harvest activity.



(a) Subject H



(b) Subject H

Fig. 7. Result of wavelet analysis on RF in the case of cucumber harvesting.

The change in the bending posture of subject H with and without the PAS in the 1st and 10th sets shows a remarkable difference, as shown in Fig. 6. By comparing the minimum angles of the knee and hip joints in the 1st and 10th sets in the case of radish harvesting, we find a difference of 26° for the knee joint and 8° for the hip joint without the PAS, whereas the difference is 8° for the knee joint and 13° for the hip joint with the PAS. In cucumber harvesting, there was a difference of 13° for the knee joint and 2° for the hip joint without the PAS and 3° for the knee joint and 11° for the hip joint with the PAS. No change in the posture was observed in the PAS case. However, when the PAS was not used, the posture had changed to one of forward bending without bending the knee. In the PAS case, the result of wavelet analysis on RF shows that there is no shift to the low-frequency range from the 1st to the 10th sets, and there is no sign of fatigue, as shown in Fig. 7(a). On the other hand, in the case of subjects B, D, E, and F, who exhibited no change in the movement or reduction in the muscle activity, the results of wavelet analysis in the PAS case shows a shift to the low-frequency range with each successive set, with evident muscle fatigue, as shown in Fig. 7(b).

This shows that the workload and muscle activity can be reduced when the PAS is used in assisting agricultural activities, enabling continuous repetition of the same operation.

V. CONCLUSION

We conducted an experiment to study the body movements of farmers during the harvesting of radish and cucumber to evaluate the fatigue reduction effect owing to the use of a power assist suit. The workload was reduced by up to 77% for radish harvesting and up to 58% for cucumber harvesting, and the muscle activity was reduced by up to 64% for radish harvesting and up to 68% for cucumber harvesting when wearing the PAS. Wearing the agricultural PAS helped reduce working fatigue, thus making continuous operation possible.

In the future, we will conduct experiments on actual sloping terrains.

REFERENCES

[1] Y. Y. Nwe, S. Toyama, M. Akagawa, M. Yamada, K. Sotta, T. Tanzawa, C. Kikuchi, and I. Ogiwara, "Workload assessment with Ovako working posture analysis system (OWAS) in Japanese vineyards with focus on pruning and berry thinning operations," *J. Japan. Soc. Hort. Sci*., vol. 81, no. 4, pp. 320-326, 2012.

[2] S. Toyama and G. Yamamoto, "Development of wearable-agri-robot mechanism for agricultural work," in *Proc. International Conference on Intelligent Robots and System*, pp. 5801-5806, St. Louis, MO, 2009.

[3] S. Toyama and G. Yamamoto, "Wearable agrirobot," *J. Vibroengineering*, vol. 12, no. 3, pp. 287-291, 2010.

[4] T. Araie, T. Ikeda, U. Nishizawa, A. Kakimoto, and S. Toyama, "Mechanism evaluation of agricultural power assist suit under development," *Vibroengineering PROCEDIA*, vol. 8, pp. 328-333, 2016.

[5] T. Araie, U. Nishizawa, T. Ikeda, A. Akira, and S. Toyama, "Evaluation of labor burden reduction achieved through wearing an agricultural power assist suit," *Int. J. Modeling Optimization*, vol. 7, no. 4. pp. 202-206, 2017.

[6] T. Araie, U. Nishizawa, T. Ikeda, A. Kakimoto, and S. Toyama, "Estimation of energy consumption when wearing power assist suits," *Int. J. Modeling Optimization*, vol. 8, no. 2, pp. 95-100, 2018.

[7] W. E. Banister, R. H. Morton, and J. Fitz-Clarke, "Dose/response effects of exercise modeled from training: Physical and biochemical measures," *The Annals of Physiological Anthropology*, vol. 11, no. 3, pp. 345-356, 1992.

[8] F. H. Martini, M. J. Timmons, and M. P. McKinley, *Human Anatomy, Nishimura Co. Ltd.*, 2004, pp. 228-242.

[9] Epson, PULSENSE. [Online]. Available: https://www.epson.jp/products/myakuhaku/technology.htm

[10] D. Farina, M. Pozzo, E. Merlo, A. Bottin, and R. Merletti, "Assessment of average muscle fiber conduction velocity from surface EMG signals during fatiguing dynamic contractions," *IEEE Trans. Biomed. Eng*., vol. 51, no. 8, pp. 1383-1393, 2004.

[11] T. Moritani, M. Muro, and A. Nagata, "Intramuscular and surface electromyogram changes during muscle fatigue," *J. Appl. Physiol*., vol. 60, no. 4, pp. 1179-1185, 1986.

Toshitake Araie was born in Kaga, Japan on 19 September 1975. He received his Ph.D. degree from the Tokyo University of Agriculture and Technology in 2019. He is an assistant professor at the Faculty of Human Resources Development, the Polytechnic University. His primary research interests include the development of agricultural power assist suits, life support technology, and embodied cognitive science.

Tomozumi Ikeda was born in Matsumoto, Japan on 1 August 1971. He received his Ph.D. degree from the University of Electro-Communications in 2007. He is an associate professor at the Faculty of Human Resources Development, the Polytechnic University. His primary research interests include life support technology, embodied cognitive science, and development of multimodal interface for visually impaired people.

Akira Kakimoto was born in Hiroshima on 10 January 10 1962. He graduated from the Department of Precision Machinery Engineering, Faculty of Engineering, the University of Tokyo. He received his master's degree in 1986 and doctor's degree in 1990 from the Department of Precision Machinery Engineering, Graduate School of Engineering, University of Tokyo. He was a research associate in the Department of Rehabilitation Engineering at the Institute of Vocational Training (presently, the Polytechnic University) in 1990. In 1992, he was an assistant professor in the Department of Mechanical and Control Engineering, and since 2010, he has been a professor at the Mechanical System Engineering. His current research interests include assistive technology and machine control. Prof. Kakimoto is a member of EMBS IEEE, JSPE, JSME, LST, and JSWSAT.

Shigeki Toyama was born in Gifu, Japan, in 1954. He graduated from the University of Tokyo in the Department of Precision Machinery Engineering, Faculty of Engineering. He received the doctor's degree in 1981 in the Department of Precision Machinery Engineering, Graduate School of Engineering, University of Tokyo. He is a professor at the Faculty of Engineering, Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology. His primary research interests include robotics, actuator, and welfare technology.