The Kinematic Evaluation of Shoulder and Elbow Joints for Different Walking Speeds

Jae Ho Kim, Jaejin Hwang, Myung-Chul Jung, and Seung-Min Mo

***Abstract*—The objective of this study was to evaluate the effect of different walking speed on the range of motion, angular velocity, and angular acceleration of the shoulder and elbow during walking. An optical motion capture system was used to capture the walking motion on the treadmill system. The independent variable of this study was set as four levels of walking speeds including 3.6, 5.4, 7.2 km/h, and preferred walking speed. Seven dependent variables were analysed as follows: maximum joint angle, minimum joint angle, range of motion (ROM), maximum joint angular velocity, minimum joint angular velocity, maximum joint angular acceleration and minimum joint angular acceleration. The subject walked according to the randomized walking speed during 90 seconds on the treadmill. Twenty gait cycles of motion capture data from each experiment condition of each subject were extracted. In the shoulder joint, the mean of ROM and the mean of maximum angular acceleration were the highest at 5.4 km/h walking speed. It can be considered that the arm swing was sufficiently performed to maintain the walking stability. At the walking speed 7.4 km/h, the gait pattern of one cycle was too short due to fast walking. It indicated that the time of motion for sufficiently swinging the arm was short. At the walking speed 7.2 km/h, the ROM and angular velocity of the shoulder joint decreased but those of the elbow joint were increased. It could be related to maintain the walking balance by swinging the elbow to compensate the reduction of the shoulder movement during a fast walking. We suggest that the ergonomic threshold walking speed of the wearable robot is limited to 5.4 km/h. In addition, the fast walking speed can cause biomechanical load and discomfort in the arm movement.**

***Index Terms*—Shoulder, elbow, kinematic, wearable robot, human-robot interaction, walking speed.**

I. Introduction

Wearable robots have been designed and developed to improve humans' strength, speed, and endurance. They have been applied to various tasks such as walking, running, lifting, lowering, pushing, and pulling.

Despite of the rapidly grown technology, wearable robots still face several challenges. Previous studies still have focused on improving the mechanical performance of a wearable robots [1]-[3]. Users could experience the resistance of their movement while walking and feel discomfort on their body regions if the joints of the wearable robots are not properly aligned [4]. In addition, adding extra mass to the human body could increase the metabolic expenditure and lead to the early fatigue during walking [5].

In order to overcome these limitations of the wearable robot, understanding natural biomechanics of walking could be essential. Natural rhythm of movements in the upper extremity while walking could be useful to determine the functional limit (e.g., joint torque and range of motion) of the wearable robot to promote the safety level and comfort of users.

Thus, the objective of this study was to evaluate the effect of different walking speed on the range of motion, angular velocity, and angular acceleration of the shoulder and elbow during walking.

II. Method

A. Subjects

A total of three male subjects participated in this study. Subjects had no experience with musculoskeletal disorders during the last 6 months and were controlled by a normal weight subject with an average BMI of 23.2 (±0.2) for similar walking movements. Table I shows the anthropometric data of the subjects.

TABLE I: The Basic Information (Mean ± Standard Deviation) of Participants

Age (year)	Height (mm)	Weight (kg)	BMI
25.3(±0.5)	1717.7(±14.0)	68.6(±1.4)	23.2(±0.2)

B. Apparatus

A treadmill system was used to measure the joint angle, angular velocity and angular acceleration of the shoulder and elbow joint relative to walking speed. An optical motion capture system (Natural Point, Inc. Optitrack, USA) was used to capture the walking motion, and eight 1.3-megapixel Flex 13 cameras were used (Figure 1). The marker set for calculating the kinematics values of the human body during walking was Plugin Gait Full Body Model and 39 markers were attached to the entire body of the subject.

C. Experimental Design

The independent variable of this study was set as four levels of walking speeds including 3.6, 5.4, 7.2 km/h, and preferred walking speed (PWS). The level of walking speed

Manuscript received October 12, 2018; revised Janary 14, 2019. This study was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1D1A3B03035407).

Jae ho Kim and Myung-Chul Jung are with the Department of Industrial Engineering, Ajou University, Suwon, Republic of Korea (e-mail: jaeho82@ajou.ac.kr, mcjung@ajou.ac.kr).

Jaejin Hwang is with the Department of Industrial and Systems Engineering, Northern Illinois University, DeKalb, IL, USA (e-mail: jhwang3@niu.edu).

Seung-Min Mo is with the Department of Industrial and Chemical Engineering, Suncheon Jeil College, Suncheon, Republic of Korea (e-mail: smmo@suncheon.ac.kr).

DOI: 10.7763/IJET.2019.V11.1141

was referenced criteria to slow, normal and fast from previous studies [6]-[8]. In this study, PWS defined as subjectively comfortable walking speed for each subject. As shown in Fig. 2, this study considered dependent variables as follows: maximum joint angle [deg], minimum joint angle [deg], range of motion (ROM) [deg], maximum joint angular velocity [deg/sec], minimum joint angular velocity [deg/sec], maximum joint angular acceleration [deg/sec^2] and minimum joint angular acceleration [deg/sec^2].

A within-subject design with repeated measures on the cycles was used. All experiment conditions were randomized across subjects.

Fig. 1. The optical camera(L) and treadmill(R) for experiment

D. Protocol

Before performing the experiment, 39 retro-reflective skin markers were placed on the head, arms, torso, legs, and feet of subject. Each subject exercised three walking speeds on the treadmill. Then, PWS was measured while walking with a normal gait along treadmill at a selected speed. The mean and standard deviation of PWS was 3.87 (±0.09) km/h.

The subject walked according to the randomized walking speed during 90 seconds on the treadmill. To minimize fatigue, subjects were given at least 5 minutes between experimental conditions.

E. Signal Processing

The period for the walking was analysed based on one gait cycle. One gait cycle was defined as the period from the time when the heel reached the floor to the time when the heel reached the floor again [9]. Because each gait cycle time was different, the operating time was normalized to 100% and compared.

Twenty gait cycles of motion capture data from each experiment condition of each subject were extracted. Then, these data were post-processed using MOTIVE version 2.0.3 (Natural Point, Inc. Optitrack, USA), and the joint angle, angular velocity and angular acceleration of the shoulder and elbow joint were calculated using the Visual 3D v6 (C-Motion, Inc., USA).

The obtained motion capture data was filtered using a lowpass filter at a cut off frequency of 6 Hz.

The joint angle, angular velocity and angular acceleration of the shoulder and elbow joints of right side were calculated, and only the sagittal plane (flexion–extension movement) of the 3D plane motion were used for analysis.

F. Statistics

Data was analysed by one-way repeated measures analysis of variance (ANOVA) with Tukey's test. A significance level of 0.05 was used all statistical analysis which were performed using SAS software 9.4 (SAS Institute, USA).

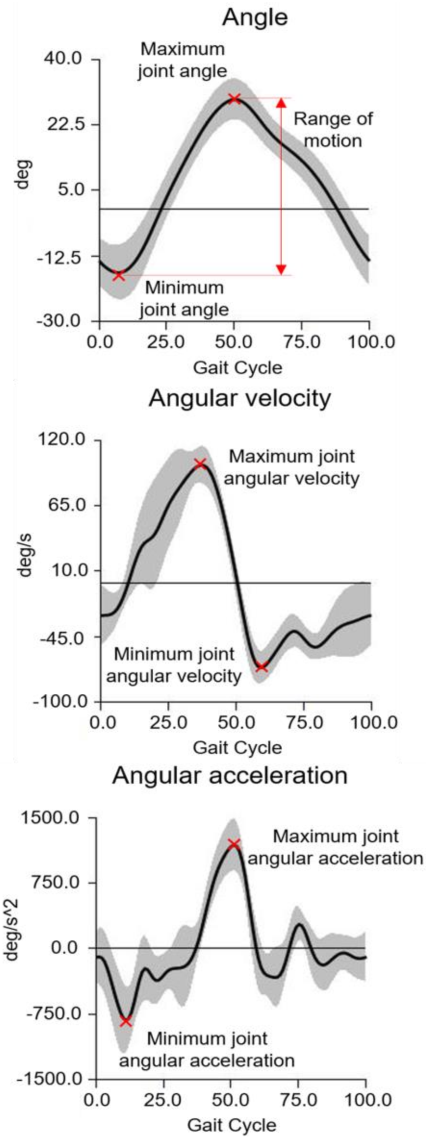


Fig. 2. Plot showing the dependent variables were extracted kinematic data

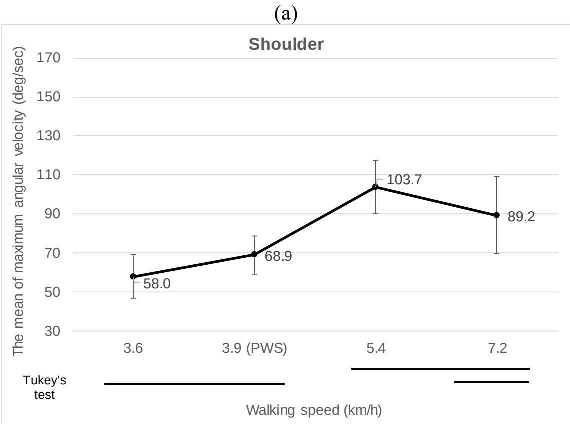
III. Result

A. Shoulder

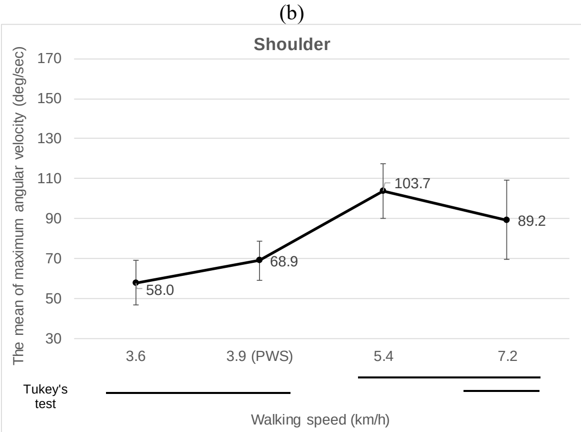
As a result of ANOVA, there were significant differences were found for minimum joint angle (F=19.52 p<0.0017), mean of range of motion (F=7.83 p<0.0017), maximum joint angular velocity (F=8.76 p<0.0130), minimum joint angular velocity (F=4.79 p<0.0493), maximum joint angular acceleration (F=9.20 p<0.0116) and minimum joint angular acceleration (F=17.68 p<0.0022). There was no significant difference was found dependent variable for maximum joint angle.

As shown in Fig. 3-4, the mean of range of motion for 5.4 km/h was higher than other walking speeds. There was an increasing trend until walking speed of 5.4 km/h, and then it decreased to 7.2 km/h. The mean of maximum angular velocity also showed a similar result. The mean of maximum angular acceleration increased toward walking speed of 7.2 km/h.

(a)

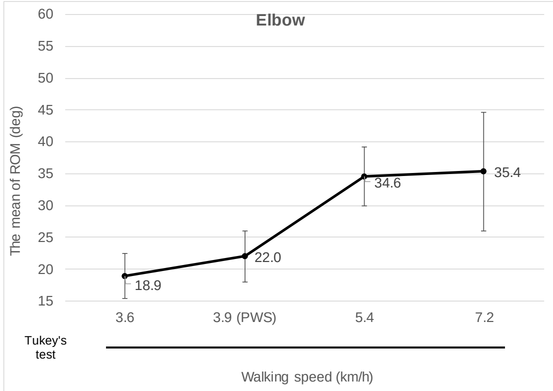


(b)

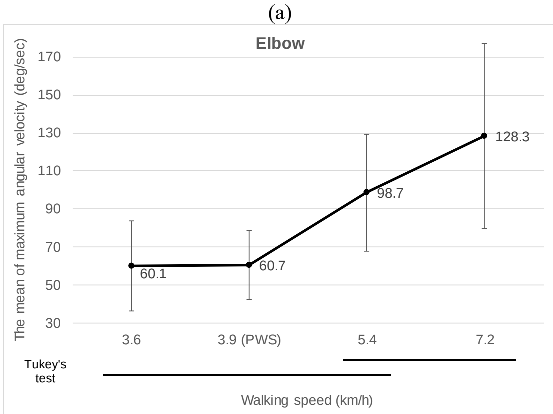


(c)

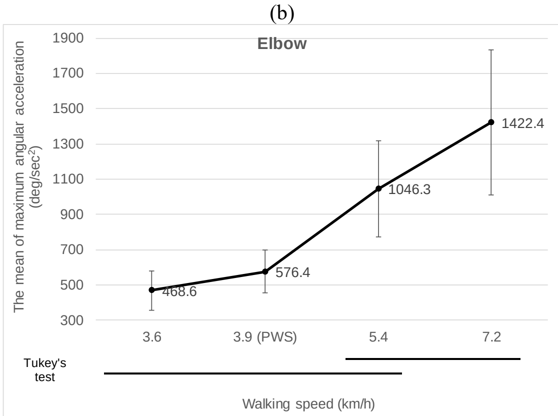
Fig. 3. The mean and standard deviation of kinematic data of shoulder joint for the different walking speeds, (a) ROM, (b) maximum angular velocity and (c) maximum angular acceleration.



(a)



(b)



(c)

Fig. 4. The mean and standard deviation of kinematic data of elbow joint for the different walking speeds, (a) ROM, (b) maximum angular velocity and (c) maximum angular acceleration.

B. Elbow

As a result of ANOVA, there were significant differences for maximum joint angle (F=6.20 p<0.0287), range of motion angle (F=5.87 p<0.0323), maximum joint angular velocity (F=9.38 p<0.0111), maximum joint angular acceleration (F=13.61 p<0.0044) and minimum joint angular acceleration (F=22.65 p<0.0011). There was no significant difference for minimum joint angle and angular velocity.

As shown in Fig. 5-7, the mean of ROM was increased toward walking speed of 7.2 km/h. Although the mean of ROM was varied significantly, there was no difference between the walking speed levels according to the result of Tukey's test. The mean of maximum angular velocity and acceleration also showed similar results.

IV. Discussion

This study analysed the tendency of kinematic variables of the shoulder and elbow joints by different walking speeds in the repetitive gait pattern.

In the shoulder joint, the mean ROM and the mean maximum angular acceleration were the highest at 5.4 km/h walking speed. In this study, the normal walking speed was set as the 5.4 km/h. Therefore, it can be considered that the arm swing is sufficiently performed to maintain the walking stability [10]-[12].

However, the 7.2 km/h was set as the fastest speed in this study. At this speed, the gait pattern of one cycle was too short due to the fast walking. Accordingly, it was considered that the time of motion for sufficiently swinging the arm was short. The mean maximum angular velocity also showed a similar trend.

The maximum angular acceleration increased as the walking speed increased, which meant the instantaneous velocity of the shoulder joint increased. It indicated that the load of the shoulder joint increased with the increase of the walking speed. Based on the results of this study, it is possible to cause biomechanical load and discomfort in the shoulder joint during a walking speed of 7.2 km/h. Hence, this study suggests that the ergonomic threshold for walking speed of the wearable robot is limited to 5.4 km/h.

In the elbow joint, most of the dependent variables showed an increasing trend as the walking speed increased. These results could be explained that the arm reacted as passive mass dampers which reduced torso and head rotation [13]. And also, upper body movement was primarily activated by lower body movement. At the walking speed of 7.2 km/h, the ROM and angular velocity of the shoulder joint decreased but those of the elbow joint were increased. To maintain the walking balance, the elbow joint swung to compensate the restricted movement of the shoulder during fast walking.

V. Conclusion

This study evaluated the kinematic data of shoulder and elbow joints during different walking speeds for suggesting design parameters of natural walking while wearing wearable robot. We suggest that the ergonomic threshold of the walking speed in the wearable robot could be limited to 5.4 km/h. In addition, the fast walking speed could cause biomechanical load and discomfort in the arm movement. The limitation of this study was the small size of the sample, resulting in the fact that no general conclusions could be drawn. Further study should be considered to validate these results, including more samples.

The findings of this study may provide the fundamental understanding for the ergonomically designing powered exoskeleton in the wearable robot industry, prosthetics and rehabilitation. Also, it could improve the safety and usability of human wearing a wearable robot.

Acknowledgment

This study was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1D1A3B03035407).

References

[1] A. Riani, T. Madani, A. Benallegue, and K. Djouani, "Adaptive integral terminal sliding mode control for upper-limb rehabilitation exoskeleton," *Control Eng Pract*, vol. 75, pp. 108-117, June 2018.

[2] M. Bergamasco, F. Salsedo, S. Marcheschi, and N. Lucchesi, "A novel actuator for wearable robots with improved torque density and mechanical efficiency," *Adv Robot*, vol. 24, pp. 2019-2041, April 2012.

[3] D. Copaci, E. Cano, L. Moreno, and D. Blanco, "New design of a soft robotics wearable elbow exoskeleton based on shape memory alloy wire actuators," *Appl Bionics Biomech*, 2017.

[4] A. T. Asbeck, S. M. De Rossi, I. Galiana, Y. Ding, and C. J. Walsh, "Stronger, smarter, softer: Next-generation wearable robots," *IEEE Robot Autom Mag*, vol. 21, pp. 22-33, December 2014.

[5] R. C. Browning, J. R. Modica, R. Kram, and A. Goswami, "The effects of adding mass to the legs on the energetics and biomechanics of walking," *Med Sci Sports Exerc*, vol. 39, pp. 515-525, March 2007.

[6] B. Bilney, M. Morris, and K. Webster, "Concurrent related validity of the GAITRite® walkway system for quantification of the spatial and temporal parameters of gait," *Gait Posture*, vol. 17, pp. 68-74, February 2003.

[7] H. G. Kang and J. B. Dingwell, "Separating the effects of age and walking speed on gait variability," *Gait Posture*, vol. 27, pp. 572-577, May 2008.

[8] N. Lythgo, C. Wilson, and M. Galea, "Basic gait and symmetry measures for primary school-aged children and young adults. II: Walking at slow, free and fast speed," *Gait Posture*, vol. 33, pp. 29-35, January 2011.

[9] J. A. Zeni, J. G. Richards, and J. S. Higginson, "Two simple methods for determining gait events during treadmill and overground walking using kinematic data," *Gait Posture*, vol. 27, pp. 710-714, May 2008.

[10] J. D. Ortega, L. A. Fehlman, and C. T. Farley, "Effects of aging and arm swing on the metabolic cost of stability in human walking," *J Biomech*, vol. 41, pp. 3303-3308, December 2008.

[11] B. R. Umberger, "Effects of suppressing arm swing on kinematics, kinetics, and energetics of human walking," *J Biomech*, vol. 41, pp. 2575-2580, August 2008.

[12] S. M. Bruijn, E. G. Meijer, P. J. Beek, and J. H. V. Dieën, "The effects of arm swing on human gait stability," *J Exp Biol*, vol. 213, pp. 3945-3952, December 2010.

[13] H. Pontzer, J. H. Holloway, D. A. Raichlen, and D. E. Lieberman, "Control and function of arm swing in human walking and running," *J Exp Biol*, vol. 212, pp. 523-534, February 2009.

Jae Ho Kim was born in South Korea. He received his Ph.D. in the Industrial Engineering from Ajou University, Suwon, South Korea in 2019, and the M.S. in the Automotive Engineering from Kookmin University, Seoul, South Korea in 2009.

He is a researcher in the Department of Industrial Engineering at Ajou University, Suwon, South Korea. His research area includes the development of rehabilitation devices, upper extremity biomechanics and ergonomic PUI (physical user interface) design.

Dr. Kim is a member of Ergonomics Society of Korea and Korean Institute of Industrial Engineers.

Jaejin Hwang was born in South Korea. He received his Ph.D. in industrial and systems engineering from the Ohio State University, Columbus, OH, USA in 2016, and the M.S. in industrial and information systems engineering from Ajou University, Suwon, South Korea in 2011.

He is an assistant professor in the Department of Industrial and Systems Engineering at Northern Illinois University, DeKalb, IL, USA. His research area includes the spine and upper extremity biomechanics and neuroergonomics.

Dr. Hwang is a member of Human Factors and Ergonomics Society and Korean Institute of Industrial Engineers.

Myung-Chul Jung received a B.A. in industrial engineering from Hanyang University in South Korea (1996), a M.S. in industrial engineering from the University of Nebraska in US (2000), and a Ph.D. in industrial engineering from the Pennsylvania State University in US (2004).

He is currently a professor in the Department of Industrial Engineering at Ajou University in South Korea where he directs the ErgoDynamics Laboratory (ED Lab). His research interests lie in work design, ergonomics, product development, and biomechanics.

Seung-Min Mo was born in Republic of Korea. He received the B.A. in safety engineering from Hankyong University in Republic of Korea (2008), and the M.S. (2010) and the Ph.D. (2015) in Industrial Engineering from Ajou University in Republic of Korea.

He is currently an assistant professor in the Department of Industrial and Chemical Engineering at Suncheon Jeil College in Republic of Korea. His research interests lie in ergonomics, human-robot interaction, biomechanics, work design and electromyography.

Dr. Mo is a member of Ergonomics Society of Korea and the Korean Society of Safety.