In our previous study, we demonstrated that the accuracy of forearm movement deteriorates when hip joint rotation is constrained. In this study, we determined that the work table height was an important factor for hip and knee joint rotations. In condition 1, work performance was deteriorated as compared with condition 2 and condition 3. In comparing with the assembly performance (the operating time and the evaluate product quality), good cooperative movement to perform our experimental task require both wide elbow flexion angular movement and narrow shoulder flexion angular movement. However, the hip stick rotation angle was constant in all experimental conditions. Therefore, it is believed that an adequate hip rotation is conducive to efficient head and arm movement. Furthermore, good cooperative movements among the head, arm and hip produced the highest quality assembly due to limited trunk movement. Therefore, we suggest that coordination among hip rotation, head movement and knee joint movement for maintenance of an upright posture was the adaptation strategy that resulted in the highest quality assembly.

**Practitioner Summary:** In this study, we examined the effects of the restrained hip rotation controlled by the work table height. The results of our experiment suggest that hip rotation plays an important role in the quality of assembly and for reducing the physical load on the trunk. The results of our experiment suggest that the quality of low-load work, similar to our task, requires adequate hip rotation.

**Keywords:** Workload, Motion capture analysis, Electromyography

1. **Introduction**

   The rapid transition from the assembly line manufacturing system to the cellular manufacturing system is a current topic in the manufacturing industry due to an ageing society and declining birth rates in 21st century. However, several production fields require an upright posture to assemble parts or products. An upright posture during standing is a fundamental problem that results in workplace fatigue. For many years, it has been suggested that workers avoid this type of static workload. Many types of stools and chairs were suggested and developed, but none have demonstrated satisfactory usability in the workers' minds.

   In previous studies, we analysed static equilibrium to determine that restrained hip motion may be a reason that workers did not utilize assistive devices (Takahashi, 2014 a, 2014 b). These results demonstrated that maintaining the upright posture during standing requires counter movements for stable head orientation in three-dimensional space. This type of adaptive behaviour is considered to absorb redundant movements (e.g. heart beats, blood flow dynamics). Therefore, our results suggest that hip rotation plays an important role in this type of adaptive behaviour.

   In the workplace of a cellular manufacturing system, workers will be required to either adopt a standing–walking combined work style or a work style in which standing and walking are separated. If a worker has decreased muscular strength, these working postures will result in a heavy burden. If a worker with decreased muscular strength engages in this type of the manufacturing system, an assistive device will have to be developed. The purpose of this study was to examine the importance of hip rotation on restricted work postures using three-dimensional motion analysis and electromyography to obtain fundamental data for the development of assistive devices.

2. **Method**

   2.1 **Participants**

   Our experiment participants were six healthy university students (19–22 years, males = 3 and females = 3). All participants were right hand and foot dominant.
For three-dimensional motion analysis, 24 reflective markers were set to participants’ joints and landmarks. Markers were captured using a high-speed camera (EX-F1, CASIO), and three-dimensional coordinate data were calculated using dedicated analysis software (Frame DIAS IV, DKH). Twelve points of electromyography were recorded using a dedicated amplifier (PTS-137, DKH and K800, Biometrics; both used the SX-230-100 EMG amplifier). EMG data were recorded by A/D converter and analysis system (TRIAS, DKH) sampled at 100 Hz. All evaluation parameters were calculated in an off-line system.

2.3 Experimental procedures

Prior to participation, the risks and benefits of the procedure were explained to all participants, and informed consent was obtained. All participants were compensated for their participation in this experiment as defined by Hiroshima City University. All participants performed an electric thermometer assembling task in the standing posture. Twelve assembly parts were selected (including four micro-imposition parts) to ensure an operating time no longer than 120 seconds.

In the present study, the coordination between the head movement and movement of each trunk segment was examined during micro-parts assembly. Furthermore, the association among knee joint rotation, hip joint rotation and the quality of micro-parts assembly was examined using motion capture analysis and electromyography. Three experimental conditions were set using work table height to restrain trunk movement.

Condition 1: The height of work table was the participant’s elbow height – 10 cm.
Condition 2: The height of work table was the participant’s elbow height.
Condition 3: The height of work table was the participant’s elbow height + 10 cm.

The tasks in our experiment were small part assembly and packaging work. One trial required approximately 60–90 sec. In each condition, participants were required to complete 10 trials. The order of experimental conditions was randomly assigned.

2.4 Evaluation indexes

For three-dimensional analysis, the average joint angle and the velocity of each joint movement were calculated for 12 joints (right and left wrists, elbows, shoulders, hips, knees and ankles). Normalized Electromyography (EMG) was calculated for 12 muscles (right and left trapezius, erector spinae, quadriceps femoris, biceps femoris, tibialis anterior and gastrocnemius). Fundamental normalized data in each muscles were summation EMG in each trial. As hip rotation features data, the stick axis was calculated on head, shoulder, hip, knee and ankle measurement point connected. Each stick axis was normalized the ankle stick axis. Then the stick rotation angle (twist) data were recalculated based on the ankle stick axis.

3. Results and discussions

3.1 Task performance

A single-factor analysis of variance was performed for the average operating time to assemble the experimental products using the three experimental conditions as factors (Fig. 2). A significant effect was observed in the experimental conditions ($F(2,10) = 4.764, p < 0.05$). This result suggested that the condition
with the work table height = participant’s elbow height − 10 cm prolonged the time to assemble the experimental product. Then, to reveal the effect of work table height, the Wilcoxon test was performed to evaluate product quality among the three experimental conditions (Fig. 3). A significant difference was observed in condition 1 and condition 3 (z = −2.065, p < 0.05). These results demonstrate that the work table height condition 1 (the table height was participant’s elbow − 10 cm) has detrimental effects on work performance quality. It is considered that the detrimental effect to perform the experimental task was induced by increasing degree of freedom around the hip at the low work height condition (nearly equal participant’s elbow height − 10 cm).

### 3.2 Joint flexion angle

A two-factor analysis of variance was performed for the average flexion angle at the wrists, elbows (Fig. 4), shoulders (Fig. 5), hips and knees using the sides of the body (left and right) and three experimental conditions as factors. A significant main effect was observed in the experimental conditions (wrist angle; F (2,10) = 10.128, p < 0.01, elbow angle; F (2,10) = 6.802, p < 0.05, shoulder angle; F (2,10) = 124.109, p < 0.001). Figure 4 demonstrates that the condition of the work table height = participant’s elbow height resulted in larger elbow rotation compared with the other two conditions. In contrast, shoulder rotation was larger in condition 3 (work table height = elbow + 10 cm) compared with the other two conditions (Fig. 5). In comparing with the assembly performance (the operating time and the evaluate product quality), it is believed that good cooperative movement to perform our experimental task require both wide elbow flexion angular movement and narrow shoulder flexion angular movement.

Figure 2. Operating time to assemble an experimental product.

Figure 3. Evaluated rank of a product.

Figure 4. Joint flexion angle at elbows.

Figure 5. Joint flexion angle at shoulder.
3.3 Joint angular velocity
A two-factor analysis of variance was performed for the average joint angular velocity at the wrists, elbows, shoulders (Fig. 6), hips (Fig. 7) and knees using the sides of the body (left and right) and three experimental conditions as factors. A significant main effect was observed for the experimental conditions (elbow; $F(2,10) = 4.47, p < 0.05$, shoulder; $F(2,10) = 6.802, p < 0.05$, hip; $F(2,10) = 5.785, p < 0.05$, knee; $F(2,10) = 5.785, p < 0.001$), and significant main effects were observed for the sides of the body (left and right) (elbow; $F(1,5) = 13.548, p < 0.05$, shoulder; $F(1,5) = 6.701, p < 0.05$). In Figure 6, the condition of the table height = participant’s elbow height − 10 cm resulted in significantly faster shoulder joint angular velocity than the other two conditions, and the right arm velocity was significantly higher than the left arm velocity. Meanwhile, for the hip and knee, only significant main effect was observed for the experimental conditions.

3.4 EMG
A two-factor analysis of variance was performed for the normalized EMG for the trapezius (Fig. 8), erector spinae (Fig. 9), quadriceps femoris, biceps femoris, tibialis anterior, and gastrocnemius muscles using the sides of the body (left and right) and three experimental conditions as factors. Significant main effects were observed for experimental condition (trapezius; $F(2,10) = 19.027, p < 0.001$, erector spinae; $F(2,10) = 9.947, p < 0.01$). Also, a significant main effect was observed for the side of the body (left and right; biceps femoris; $F(1,5) = 24.954, p < 0.01$). In Figure 8, a significant difference (condition 1 < condition 2 < condition 3) was observed for the trapezius muscle activity measured by normalized EMG. Erector spine muscle activity (Fig. 9) was higher in condition 1 than in condition 3.
3.5 Stick rotation angle

A single-factor analysis of variance was performed for the stick angle of rotation on the head (Fig. 10), shoulders, hips and knees (Fig. 10) using the three experimental conditions as factors. Significant effects were observed for the experimental conditions (head stick; $F(2,10) = 5.775, p < 0.05$, knee stick; $F(2,10) = 9.069, p < 0.01$). In Figure 10, significant differences (head stick; condition 1 > condition 3, knee stick; condition 1 < condition 3) were observed for the angle of rotation. The head stick rotation angle shows the same tendency of assembly performance (Fig. 2 and Fig. 3) and joint angular velocity (Fig. 6 and Fig. 7). In contrast, the knee stick angle of rotation shows the same tendency of the joint flexion angle at the shoulder (Fig. 5) and the normalized EMG activity of trapezius muscles (Fig. 8). It is believed that this tendency means better coordination between head rotation and shoulder joint movement. In addition, the hip stick rotation angle was constant in all experimental conditions (approximately 2°-8°, Fig. 11). Therefore, it is supposed that the good coordination movement supported by the trapezius muscles between the head and the shoulders is based on the stable (adequate) hip rotation.

4. Conclusions

Our results suggest that the work table height is an important factor for shoulder and hip joint rotations. In addition, our results suggest that hip rotation range and direction were not influenced by experimental conditions. However, Condition 2 was associated with improvements in assembly time and quality. Therefore, it is believed that adequate hip rotation is conducive to efficient head and arm movement. Furthermore, good co-operative movements among the head, arm and hip produce the highest quality assembly due to limited movement of the body sway. Therefore, it is suggested that coordination between hip rotation and head movement for maintenance of an upright posture was the adaptation strategy that resulted in the highest quality assembly. In particular, we suggest that hip rotation plays an important role for the quality of assembly and for reducing physical loads on the trunk. The results of our experiment suggest that the quality of low-load work, similar to our task, requires adequate hip rotation.

Acknowledgements

This work was supported by MEXT Grant-in-Aid for Scientific Research (C) (25350025).

References
