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Analysis of Difference in Center-of-Pressure Positions Between Experts and Novices During Asymmetric Lifting

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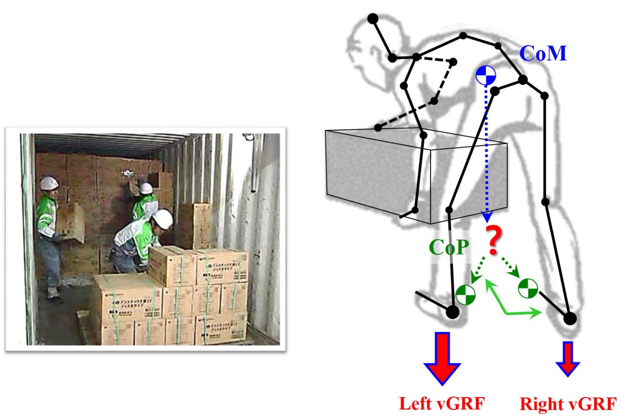
ABSTRACT Although numerous studies have analyzed the relationship between manual material handling (MMH) and the forces acting on the lumbar spine, the difference in the MMH between experts and novices through the analysis of measured data has not been well studied. The purpose of this paper was to analyze the difference in the MMH positions between ten skilled experts working at a freight transport company (Group 1) and five unskilled novices without any experience (Group 2) during asymmetric lifting. All the human subjects performed asymmetric lifting experiments with closed eyes; the experiments involved moving loads (6 and 18 kg) to the left side. Time series data of the vertical ground reaction force were measured, using a Wii Balance Board, and then, the center-of-pressure (CoP) trajectories were calculated. The balance board was used for the measurement, because it was reliable, inexpensive, and portable and provided good repeatability even on rough surfaces, and all the information pertaining to the load and worker under various conditions was captured without any omissions. Under the 18 kg load condition, the CoP positions for Group 2 were located on the same side during left asymmetric lifting; however, those for Group 1 were located on the opposite side during left asymmetric lifting ($P < 0.001$). Furthermore, under the 6 kg load condition, the load weight influenced asymmetric lifting for most subjects of Group 2 such that the CoP positions were located on the opposite side ($P < 0.001$). Based on the simulation and electromyography measurement results, we inferred that the difference in the CoP positions between the two different groups could be attributed to the difference in the hip positions. Most skilled experts position their hips in such a way that their CoP trajectories move toward the opposite side during left asymmetric lifting. Although the skillful characteristics of experts may be responsible for the lightening of the burden on the waist during asymmetric lifting, there are still two points that this paper does not clarify: the relationship between the experts' adjustment of the hip position and the load of the weight, and the influence of an imbalance of the CoP position on the forces acting on the lumbar spine.

INDEX TERMS Asymmetric lifting, center of pressure, foot pressure distribution, hip position, vertical ground reaction force.

I. INTRODUCTION

At logistics workplaces, such as freight shipping and storage companies, where workers frequently move boxes and other loads, it is important to ensure good manual material handling (MMH) during asymmetric lifting because good posture helps reduce back pain [1]–[5]. Numerous studies have analyzed the relationship between MMH and the compressive and shear forces on the lumbar spine [6]–[10]. Furthermore, some studies have indicated the importance of the effect of the stance condition on postural control during lifting [11]–[15]. Others have analyzed the relationship between work-related low back injury and muscular response [16]–[20]. Primarily, recent critical debates about the compressive and shear forces on the lumbar spine during asymmetric lifting have tended to center around the question of how much the burden on the waist has increased. Based on the analysis results of trunk angle measurements, biomechanical models, and electromyography (EMG), some researches have reported that considerable forces act on the lumbar spine during asymmetric lifting. Here, from our point of view, it is interesting to know whether there is a difference in MMH between skilled experts working at logistics workplaces and unskilled novices during asymmetric lifting under the condition of an increased burden on the waist. If such a difference exists, we should be able to determine what MMH characteristics of experts help them handle the burden more safely.



(a) Workplace inside a container. (b) Left asymmetric lifting.

FIGURE 1. (a) Logistics workplace and (b) relationship between CoM, CoP, and vGRF during asymmetric lifting.

Fig. 1 shows a logistics workplace and the relationship between the center of mass (CoM), center of pressure (CoP), and vertical ground reaction forces (vGRFs) between two feet during asymmetric lifting. Generally, one team consisting of 2–3 experts is in charge of one container. The experts inside the container rearrange all the boxes on the pallet, as shown in Fig. 1 (a), and the forklift outside the container carries the pallet to the warehouse. The frequency with which boxes should be lifted is one MMH task per 30 s, and one container should be emptied within 2–3 h regardless of the container size. The temperature inside the container rises to more than 40 °C during summer. In general, asymmetric lifting indicates the MMH task in which a load is moved to the left or right side for rearranging while twisting the trunk, as shown in Fig. 1 (b). The CoP position depends on different upper body parameters including the CoM. For example, if the upper body leans to the same side (left side) during left asymmetric lifting (Fig. 1 (b)), we can expect an imbalance in the vGRFs. In the present study, we aim to determine whether experts lean to the same side during left asymmetric lifting. However, because the direct measurement of the CoM position at a logistics workplace is difficult [21], [22], we measure the CoP position instead of the CoM position indirectly. In addition, under current conditions, the measurement or calculation of continuous changes in the CoM position in terms of the relationship among the weight of the worker, load weight, and the distance between the worker and load is difficult using conventional sensing systems [23]–[29] such as accelerometers, motion capture systems, and motion suits.

Therefore, the purpose of the present study was to present the analysis of the difference in MMH between ten skilled experts working at a logistics workplace (Group 1) and five unskilled novices without any experience (Group 2) during asymmetric lifting through the measurement of the vGRF. Time series data of the vGRF were measured under two different load conditions (light and heavy) by using the Wii Balance Board (WBB). The vGRF data were considered to be reliable because the device used for measurement was sufficiently inexpensive and portable and provided good repeatability even on rough surfaces, and all the information pertaining to the load and worker under various conditions was captured without any omission. The results indicated that the CoP positions for Group 2 were located on the same side during left asymmetric lifting; however, those for Group 1 were located on the opposite side during left asymmetric lifting ($P < 0.001$). Based on simulation and electromyography measurement results, we inferred that the difference in the CoP positions between the two groups could be attributed to the difference in the hip positions. From the results, we concluded that to lighten the burden on the waist, the skilled experts positioned their hips in such a way that the CoP positions were located on the opposite side of asymmetry.

The paper is organized into five sections. Section 2 explains the proposed method to analyze the difference in asymmetric lifting between skilled experts and unskilled novices based on the measurement of vGRFs and CoP positions. Section 3 describes the experimental results. Section 4 discusses the strategy used by the experts to modify the CoP position based on simulation and EMG results. Finally, Section 5 concludes the paper.

II. HUMAN SUBJECTS AND METHODS

A. HUMAN SUBJECTS AND EXPERIMENTAL PROCEDURE

Fifteen human subjects were employed: ten skilled experts from Konoike Transport Co., Ltd. [40] with career lengths of 10–30 years (Group 1), and five unskilled novices who were university students without any experience (Group 2). No subject from either group reported a major back or lower limb pathological condition, medication use, or a history of neurological disease that might influence standing balance. Table 1 lists the body mass index (BMI) for all the human subjects. No major difference in BMI was observed between the two groups.

The experimental procedures were performed in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Clinical Trial Center,

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TABLE 1. BMI for all human subjects.

Group	No.	Height [m]	Weight [kg]	BMI [kg/m^2]
1	1	1.69	67.5	23.6
	2	1.79	81.3	25.4
	3	1.61	66.7	25.7
	4	1.78	57	18.0
	5	1.73	73	24.4
	6	1.73	85	28.4
	7	1.71	77.5	26.5
	8	1.77	59	18.8
	9	1.7	74	25.6
	10	1.75	72	23.5
2	1	1.68	73	25.9
	2	1.73	83.5	27.9
	3	1.71	72.5	24.8
	4	1.78	77.6	24.5
	5	1.78	70	22.1

Department of Medical Innovation, Osaka University Hospital. Informed consent was obtained from all the human subjects (no. 305, August 21, 2014).

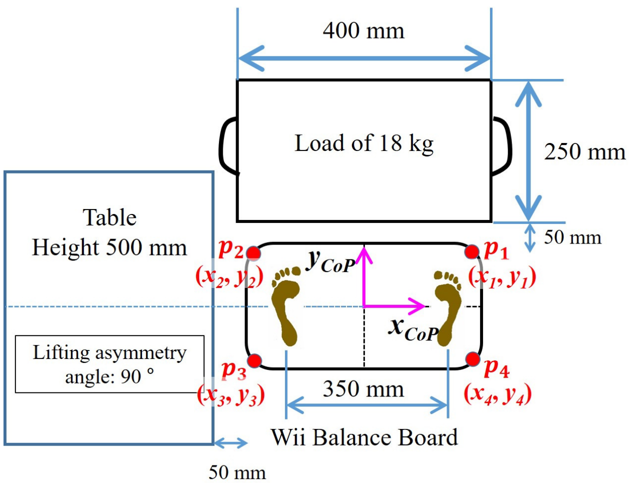

FIGURE 2. Schematic of experimental environment used to measure vGRFs between two feet and calculate CoP position during asymmetric lifting.

Fig. 2 shows the experimental condition before lifting. Because the subjects might have individual differences, we attempted to perform the experiments under the same conditions, in order to isolate and analyze the difference in MMH between the two groups. Fig. 3 shows a pictorial representation of the different phases of the experimental procedure during asymmetric lifting. Phase 1 was used for calibration (5 s). Phase 2 involved approaching the load before lifting. Phase 3 involved lifting the 6 or 18 kg load, and Phase 4 involved moving the load to the left side. For each subject, the experiment was performed three times under the same conditions. During the experiment, all the subjects were directed to close their

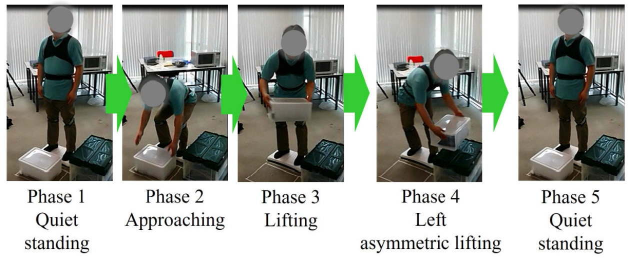

FIGURE 3. Pictorial representation of different phases of experimental procedure during asymmetric lifting.

eyes to eliminate the influence of visual feedback on postural balance, according to the results of a previous study [41], which indicated that the cerebellar vermis efferent system is involved in the active maintenance of body balance and that the visual association cortex contributes to the stability of the body possibly by monitoring the three-dimensional orientation in space while standing.

B. EXPERIMENTAL SYSTEM

In studies that quantify human posture and locomotion, two variables of key interest are the CoM of the body and the CoP of vGRFs [22]. The CoP position characterizes the whole-body position and is subject to body posture control. The CoP position is the projection of the vertical force distribution on the ground plane of the centroid. The determination of the whole-body CoM position requires knowledge of the position and mass of the body segments and the influence of the load weight on MMH. These data are rarely obtained in posture or locomotion trials, and consequently, the CoM position often cannot be directly determined [21], [22], [30], [31]. However, the CoP position for a posture can be obtained directly from force plate data [22].

Fig. 2 shows a schematic of the experimental environment used to measure the vGRF between two feet and calculate the CoP position during asymmetric lifting. The experimental system consisted of three pieces of equipment: a WBB for measuring the CoP position and vGRF, a computer for saving and analyzing data, and 6 and 18 kg loads. The WBB (23×43 cm platform), which was designed to support people weighing up to 136 kg and was probably more accurate than a typical bathroom scale [32], fed data into the computer through a Bluetooth connection. The force sensors, which consisted of a metal beam and strain gauge that acted as a uniaxial force transducer, were reported to be linear [33] with CoP noise levels of approximately ± 0.5 mm [34], [35]. The WBB was originally designed as a video game controller but has become a proven tool for assessing the CoP position and has been confirmed to be both accurate and reliable [36]. Moreover, the WBB provided a portable, inexpensive, and widely available balance assessment system. Several studies [36]–[38] have demonstrated the validity and test–retest reliability of the WBB; in these studies, the CoP position was measured, and the obtained data were compared to those from an identical study conducted using a laboratory-grade force plate. These studies found that the WBB provided reliable and consistently repeatable data. Thus, it is highly probable that the analysis of different CoP positions using the WBB is reliable, and the feasibility of using the WBB for field applications is confirmed.

C. MEASUREMENT OF vGRF AND CoP

Four pressure sensors were installed on the WBB as shown in Fig. 2, and the four pressure values p_1, p_2, p_3, and p_4 were used to determine the percentage of the human body weight on the four sensors:

$$\begin{aligned} vGRF_{p_1} &= \frac{p_1}{W_B} \times 100\,[\%] \\ vGRF_{p_2} &= \frac{p_2}{W_B} \times 100\,[\%] \\ vGRF_{p_3} &= \frac{p_3}{W_B} \times 100\,[\%] \\ vGRF_{p_4} &= \frac{p_4}{W_B} \times 100\,[\%] \end{aligned} \tag{1}$$

where W_B represents the human body weight during quiet standing. During asymmetric lifting, we measured the vGRF in each direction in terms of the percentage of the body weight. The value of W_B was measured by the WBB:

$$W_B = p_1 + p_2 + p_3 + p_4[\mathrm{kg}] \tag{2}$$

In general, the literature that the zero-moment point was equal to the CoP was proven [39]. We could calculate the CoP position because we knew the geometry information of the four pressure sensors beforehand (Fig. 2). The values for the CoP position (x_{COP}, y_{COP}) were calculated as follows [21], [22], [36], [39]:

$$\begin{aligned} x_{CoP} &= \frac{\sum_{i=1}^{4}(p_i \times x_i)}{\sum_{i=1}^{4}(p_i)}[\mathrm{mm}] \\ y_{CoP} &= \frac{\sum_{i=1}^{4}(p_i \times y_i)}{\sum_{i=1}^{4}(p_i)}[\mathrm{mm}] \end{aligned} \tag{3}$$

where (x_i, y_i) was $(215, 118.5)$, $(-215, 118.5)$, $(-215, -118.5)$, and $(215, -118.5)$ mm for $(i = 1, 2, 3, 4)$, respectively. All the measured data were stored in the computer with a sampling time of 20 ms. We denoted the CoP trajectories in the anteroposterior (AP) direction as y_{CoP} and in the mediolateral (ML) direction as x_{CoP} during asymmetric lifting. Many methods [21], [35], [39] have been developed to estimate CoM positions from CoP data. In the most elementary approach, the vertical projection of the CoM onto the floor is assumed to coincide with the CoP. Practically, this assumption is true only when the body is static, and because the body sways even during quiet standing, the assumption is generally incorrect. Thus, it is difficult to infer that the CoM is the vertical projection of the CoP during asymmetric lifting. In the present study, we assumed that the CoP was located around the vertical projection of the CoM. For example, if the measured CoP was located on the left side during left asymmetric lifting, we hypothesized that the CoM was also located on the same side.

III. RESULTS

A. RESULTS OF $vGRF_{p_i}$ ($i = 1, 2, 3, 4$)

Fig. 4 shows the experimental results obtained from the four pressure sensors during asymmetric lifting with respect to time. These data were used to determine the percentage of the human body weight, according to equations (1) and (2). The data for Groups 1 and 2 are presented in red and blue, respectively. The data for the initial 2 s in each graph indicate the data for the initial condition (the calibration time was 5 s, but data for 3 s were omitted because there was no significant difference), and the bold lines (both red and blue) indicate the measured data for Phase 4 during asymmetric lifting, as shown in Fig. 3.

The initial values (Phase 1) of $vGRF_{p_1}$, $vGRF_{p_2}$, $vGRF_{p_3}$, and $vGRF_{p_4}$ were $23.3 \pm 2.1\%$, $21.0 \pm 2.1\%$, $27.0 \pm 1.5\%$, and $28.7 \pm 3.8\%$, respectively, for Group 1 and $18.3 \pm 2.5\%$, $20.3 \pm 2.6\%$, $32.7 \pm 1.5\%$, and $28.7 \pm 4.2\%$, respectively, for Group 2. No statistical difference was found between the two different groups in the vGRF for each pressure sensor ($P > 0.05$). The measured data for Phases 2 and 3 for each vGRF also did not show any difference between Groups 1 and 2.

However, the measured data for Phase 4 were different. Because left asymmetry was considered, $vGRF_{p_2}$ and $vGRF_{p_4}$ showed some differences. $vGRF_{p_2}$ was affected by the pressure of the left forefoot, and $vGRF_{p_4}$ was affected by the pressure of the right-foot heel during left asymmetric lifting. The data for $vGRF_{p_2}$ for Group 1 increased to a maximum of 2.1 times that of Phase 1, but those for Group 2 increased to a maximum of 3.5 times that of Phase 1. The data for $vGRF_{p_4}$ for Group 1 decreased to a maximum of 30% of that of Phase 1, but those for Group 2 decreased to a maximum of 80% of that of Phase 1.

From the results, we found that one subject of Group 2 performed left asymmetric lifting with a larger increased vGRF of the left forefoot and a larger decreased vGRF of the right-foot heel.

B. RESULTS OF CoP TRAJECTORIES

Next, we aimed to understand how the difference in the vGRFs between the two different groups of subjects affected the CoP trajectories. Fig. 5 shows the results of the calculated CoP trajectories obtained from the measured vGRFs shown in Fig. 4. These CoP trajectories were calculated using equation (3). Figs. 5 (a) and (b) represent the CoP trajectories for one subject each of Groups 1 and 2, respectively. The horizontal and vertical axes represent the ML and AP displacements, respectively. To emphasize the difference in the CoP trajectories in Phase 4, colored lines are used to represent the data for the left asymmetry. Namely, the red- and blue-colored lines in Fig. 5 correspond to the red and blue-colored bold lines in Fig. 4.

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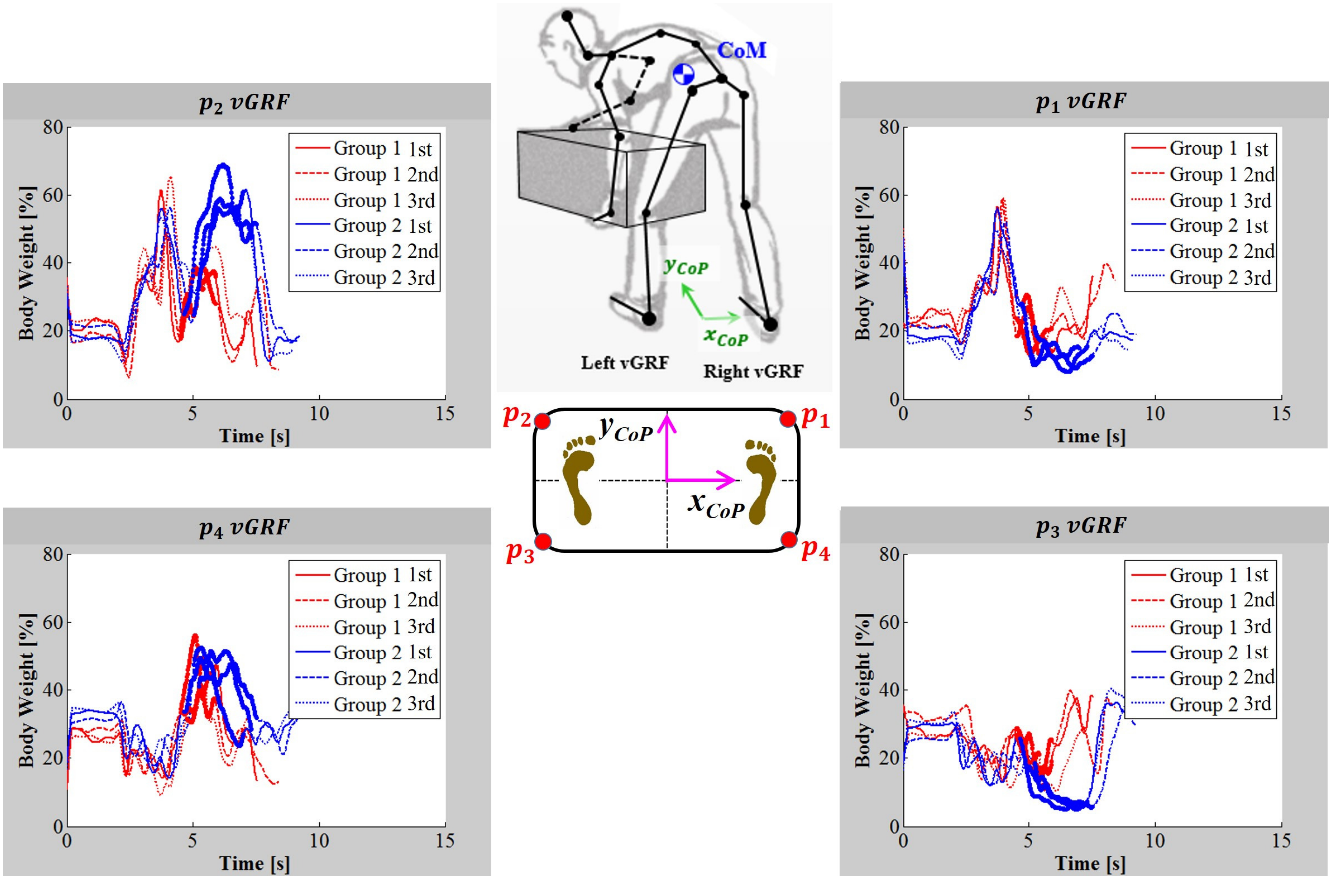


FIGURE 4. **Results obtained from four pressure sensors during asymmetric lifting under 18 kg load.**

Because black-colored lines were used for the CoP trajectories for Phases 1–3, it was difficult to identify the differences. Therefore, red- or blue-colored CoP trajectories were used for Phase 4, and it was found that the CoP trajectories for one subject of Group 1 were mainly located on the opposite side in spite of the left asymmetry; however, those for one subject of Group 2 moved from the right side to the left side and were then mainly located on the same side with the left asymmetry.

From the results, we found that the CoP trajectories along the rotation axis for one subject of Group 2 moved considerably from the right side to the left side during left asymmetric lifting, although those for one subject of Group 1 were mainly located on the opposite side and did not change considerably.

C. RESULTS OF AVERAGE CoP POSITIONS FOR ALL SUBJECTS

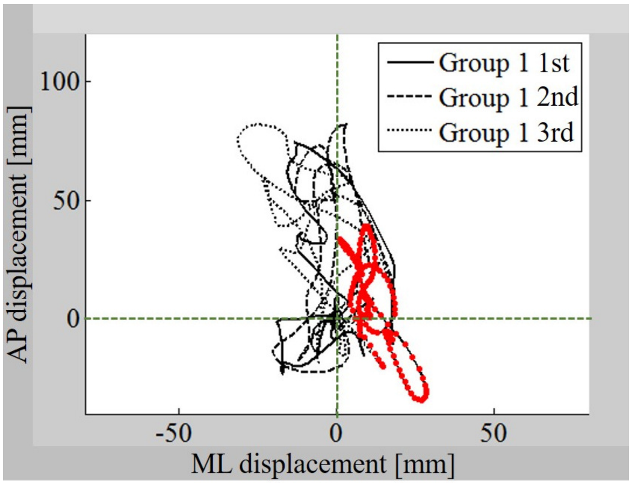
Next, we aimed to analyze the results for all the subjects. Fig. 6 shows the results of the average CoP positions during Phase 4 for all the subjects. These CoP positions represented the average CoP trajectories during asymmetric lifting shown in Fig. 5. The average CoP position was used instead of the CoP trajectory so that the difference between subjects could be explained clearly. We focused on the difference in the CoP positions for Phase 4 between the two different groups. The horizontal and vertical axes represent the ML and AP displacements, respectively. The blue and red filled circles represent the data for all the subjects of Group 1 (n = 30) and Group 2 (n = 15), respectively. The two larger blue and red open circles indicate the average values for Groups 1 and 2, respectively.

The values of y_{CoP} for Groups 1 and 2 were 7.0 ± 17.6 mm and 38.0 ± 30.4 mm, respectively. The y_{CoP} values for Group 2 were 5.4 times larger than those for Group 1 ($P < 0.001$). The values of x_{CoP} for Groups 1 and 2 were 6.4 ± 11.6 mm and −17.4 ± 23.0 mm, respectively. The x_{CoP} values for Group 2 were 3.5 times larger than those for Group 1 ($P < 0.001$). A significant statistical difference was observed in the average CoP positions between Groups 1 and 2.

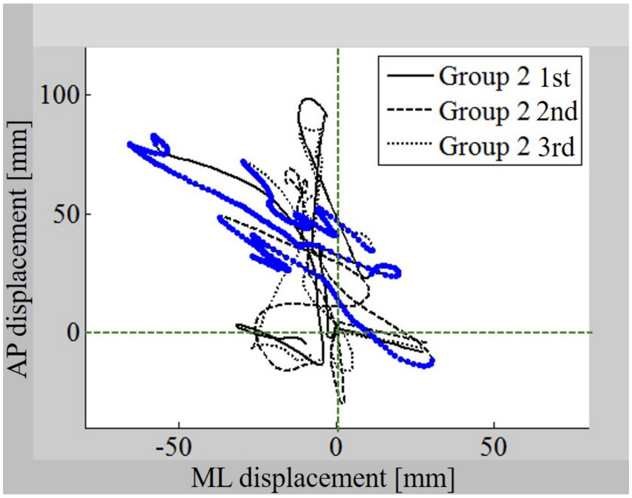
From the results, we inferred that the distribution of CoP positions for most subjects of Group 2 was on the same side during left asymmetric lifting, although that for most subjects of Group 1 was on the opposite side during left asymmetric lifting.

D. RESULTS OF INFLUENCE OF LOAD WEIGHT ON ASYMMETRY

It was necessary to confirm the reason for the difference in the distribution of CoP positions between the two different



(a) CoP trajectories for one member of Group 1.



(b) CoP trajectories for one member of Group 2.

FIGURE 5. **Results of CoP trajectories obtained from measured vGRFs under 18 kg load.**

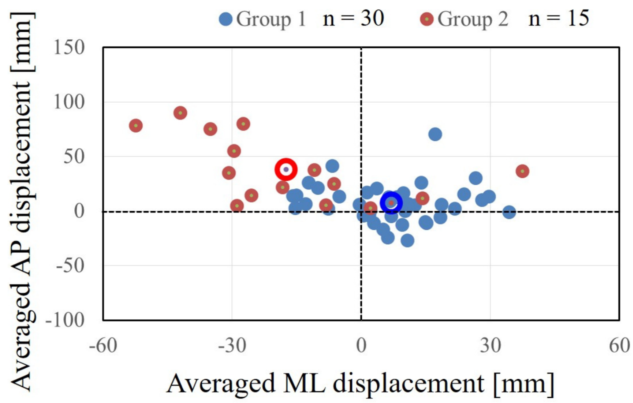


FIGURE 6. **Results of average CoP positions during left asymmetric lifting for all subjects under 18 kg load.**

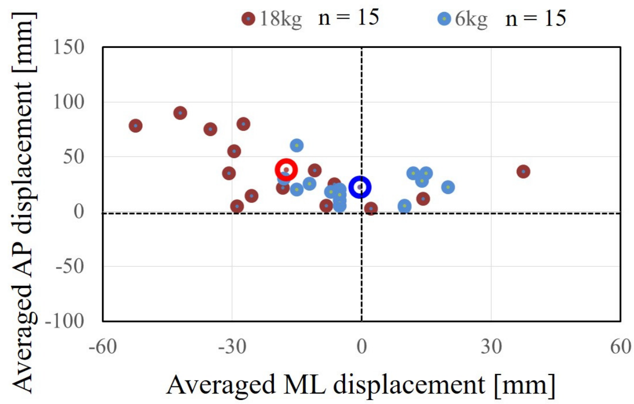


FIGURE 7. **Results of average CoP positions during left asymmetric lifting for all unskilled novices under 6 and 18 kg loads.**

groups. We considered two possible causes in the present study: the original MMH and the influence of a heavy load weight.

Fig. 7 shows the results of the average CoP positions during Phase 4 under 6 and 18 kg load weights. The subjects of Group 2 were asked to perform 6 kg asymmetric lifting under the same condition to determine the influence of the load weight on asymmetric lifting. The horizontal and vertical axes represent the ML and AP displacements, respectively. The blue and red filled circles represent the data for the 6 kg load ($n = 15$) and 18 kg load ($n = 15$). The two larger blue and red open circles indicate the average values for each load-weighted condition.

The values of y_{CoP} for the 6 and 18 kg loads were 22.1 ± 14.7 and 38.0 ± 30.4 mm, respectively. The y_{CoP} values for the 18 kg load were 1.7 times larger than those for the 6 kg load ($P < 0.001$). The values of x_{CoP} for the 6 and 18 kg loads were -0.4 ± 12.6 and -17.4 ± 23.0 mm, respectively. The x_{CoP} values for the 18 kg load were 43.5 ($= 17.4/0.4$) times larger than those for the 6 kg load ($P < 0.001$). A significant statistical difference was observed in the average CoP positions between the two different load-weighted conditions.

From the results, we found that the different distributions of CoP positions for most subjects of Group 2 showed similar tendencies to those for most subjects of Group 1 during left asymmetric lifting under the 6 kg load weight. These findings indicated the influence of the load weight on asymmetric lifting. Thus, we could attribute the opposite distribution of the CoP positions for most subjects of Group 1 during asymmetric lifting to the MMH characteristics of experts based on their extensive experience, which might have helped them to lighten the increased burden. In the case of unskilled novices, the load weight influenced asymmetric lifting.

IV. DISCUSSION

The purpose of the present study was to analyze the difference in MMH between skilled experts working at a logistics workplace (Group 1) and unskilled novices (Group 2) during asymmetric lifting based on measured CoP positions. From the experimental results, we found that most of the experts performed asymmetric lifting with the CoP ML positions distributed on the opposite side during left asymmetric lifting. To the best of our knowledge, no study has so far focused on the analysis of the difference in MMH between experts and novices during asymmetric lifting based on measured CoP positions. Thus, we discuss the possible reasons why experts lift differently, and explore, through simulation and EMG measurement, how skilled experts are able to achieve better lifting results.

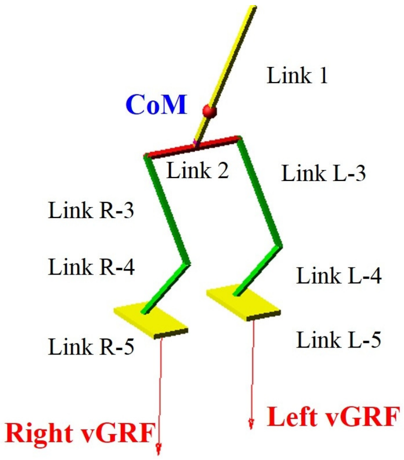


FIGURE 8. Inverted pendulum biomechanical model used to confirm hip strategy.

A. SIMULATION

Computer simulations of AP and ML control can be performed using simple biomechanical models such as the one shown in Fig. 8. In the AP model, the CoM of the lower limbs was located on the ankle and hip joints, which acted as possible control sites. Similarly, in the ML model, the CoM was located on the two hip and two ankle joints, which acted as potential control sites. This model was created using ADAMS [42]. As the world's most widely used multibody dynamics software, ADAMS helps engineers to study the dynamics of moving parts and how loads and forces are distributed throughout mechanical systems. Table 2 lists the weight and link lengths used for the simulation model. These data were derived from young Russian athletes by Plagenhoef *et al.* [43] and de Leva [44].

TABLE 2. Weight and link lengths used in simulation model.

Link Name		Segment	Length [mm]	Weight [kg]
Link 1		Upper body	805	39.8
Link 2		Hip	400	18.3
Link L-3	Link R-3	Thigh	416	10.5
Link L-4	Link R-4	Shank	436	3.3
Link L-5	Link R-5	Foot	270	1.0

By using the inverted pendulum biomechanical model, we could confirm why and how experts performed better. Previous research results [45]–[48] have demonstrated that subjects could synthesize a continuum of different postural movements by combining two distinct strategies of the ankle and hip in different magnitudes and temporal relations. It is known that the combination of strategies used in a particular instance is influenced not only by the current support-surface conditions but also by the subject's recent experiences [45]. In the present study, we focused on a hip strategy that helps maintain the posture balance. The simulation results indicated how the vGRFs between the two feet and the ML positions were affected by the modification of the hip position.

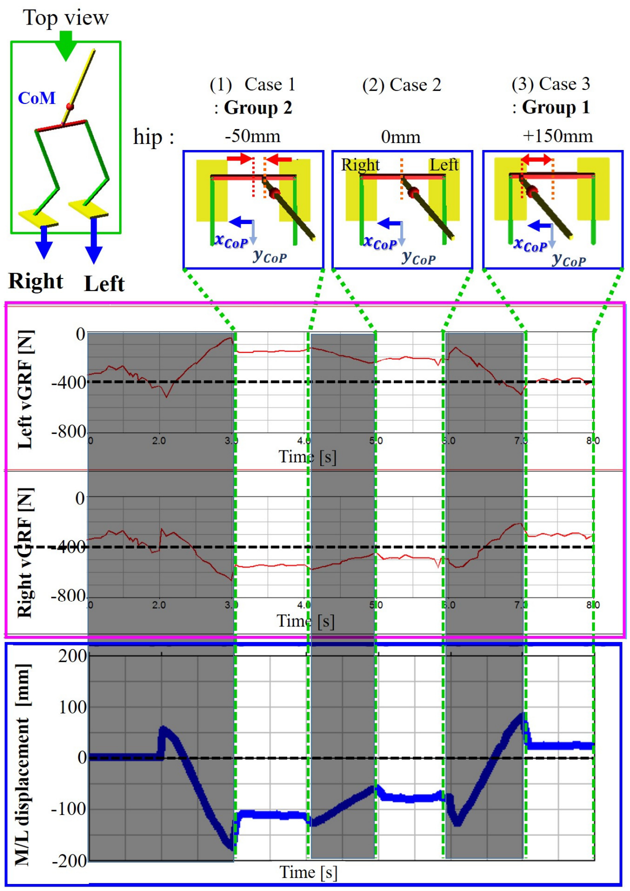


FIGURE 9. Simulation results of CoP ML trajectories during asymmetric lifting through modification of hip position.

Fig. 9 shows the simulation results of the CoP ML trajectories during asymmetric lifting based on the hip strategy. In Case 1, the hip was moved to the same side (−50 mm) during left asymmetric lifting (Case 1 represented Group 2). In Case 2, the hip was positioned in the center of the trunk (0 mm), and in Case 3, the hip was moved to the opposite side (+150 mm) during left asymmetric lifting (Case 3 represented Group 1), as shown in Fig. 9 (top).

The values of the right vGRF ($vGRF_{p_1} + vGRF_{p_4}$), left vGRF ($vGRF_{p_2} + vGRF_{p_3}$), and ML displacement (x_{CoP}) for Case 1 are shown in the three graphs in Fig. 9 and were approximately −150 N, −550 N, and −100 mm, respectively.

The values of these parameters for Case 2 were approximately −200 N, −500 N, and −75 mm, respectively. Two cases (Cases 1 and 2) showed a big difference between the left and right vGRFs and the one-sided CoP ML position. However, the values of these parameters for Case 3 were approximately −400 N, − N, and 15 mm, respectively. No big difference was observed in the vGRFs between the two feet and the one-sided CoP ML position. According to the hip strategy, we could see that the difference in the vGRFs between the two feet decreased and that x_{CoP} moved to the zero position.

From the simulation results, we found that Cases 1 and 2, in which the hip moved to the same and center sides during left asymmetric lifting, were similar to Group 2, and Case 3, in which the hip moved to the opposite side, was similar to Group 1, according to the results shown in Fig. 5 and 6. Thus, the MMH characteristic of experts was the hip strategy, which involved maintaining the balance of the vGRFs between the two feet. In the present study, the definition of balance was decided by the CoP ML position, as shown in Fig. 9 (bottom). When the CoP ML position was near the zero position, that the balance of the vGRFs was maintained was proven. Through the simulation results, it was found that the balance between the two feet was regulated by the modification of the hip position. We could evaluate the balance between the two feet by using the CoP ML position.

B. ELECTROMYOGRAPHY MEASUREMENT

Next, verification experiments were performed to confirm the simulation results pertaining to the effect of the modification of the hip position on asymmetric lifting. The verification experiments focused on the relationship between the CoP positions and EMG measurement during asymmetric lifting. Figs. 10 (a-1), (b-1), (c-1), and (d-1) represent the cases in which the CoP position was located on the same side during left asymmetric lifting, and Figs. 10 (a-2), (b-2), (c-2), and (d-2) represent the case in which the CoP position was located on the opposite side during left asymmetric lifting. The data for the CoP positions were displayed on the top right side of a monitor in real time. Three EMG measurement points were chosen: biceps brachii for the upper limbs (arm), rectus femoris for the lower limbs (thigh), and erector spinae from L1 to L5 (lumbar spine/waist).

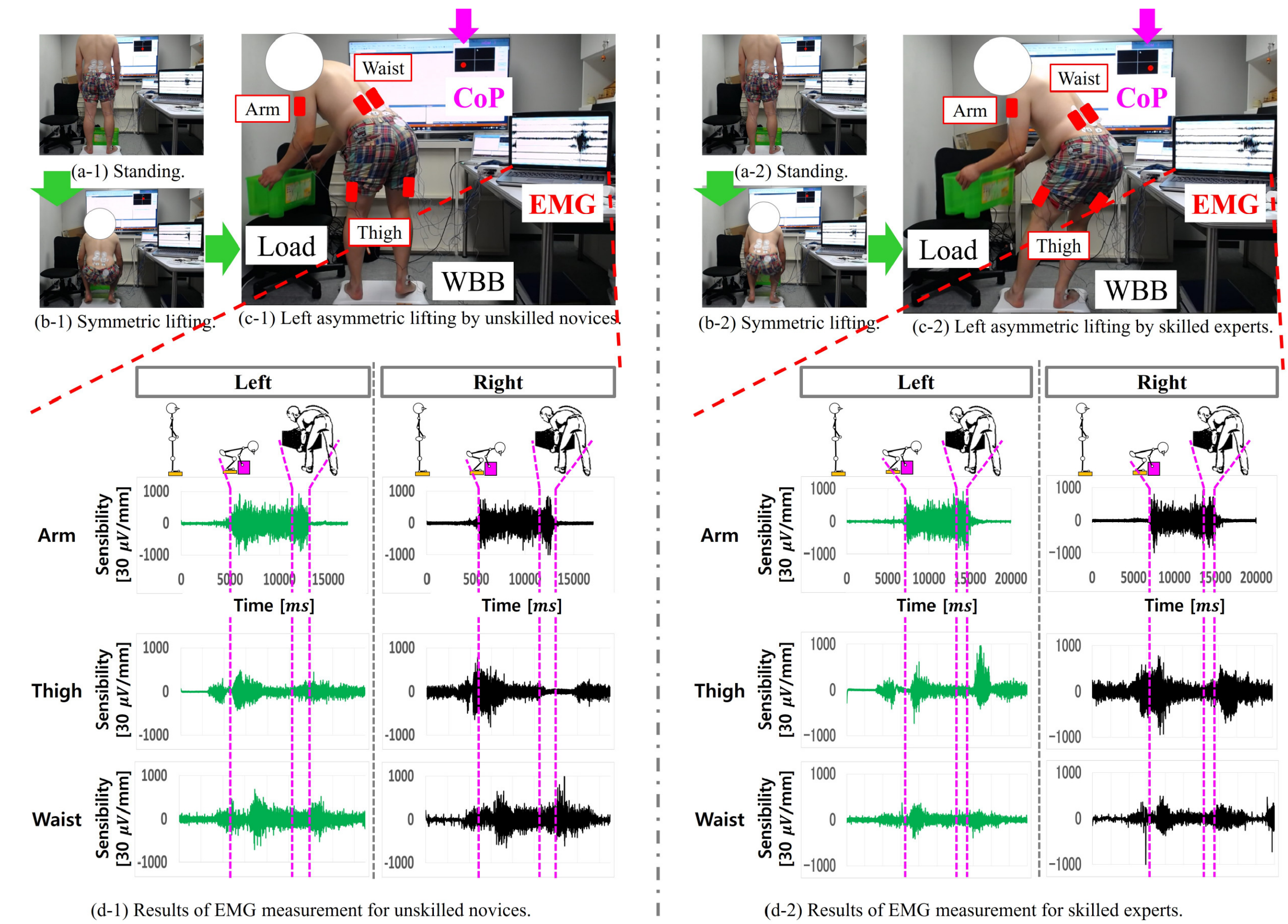


FIGURE 10. Relationship between EMG measurement and CoP position during left asymmetric lifting (posture of unskilled novices: (a-1), (b-1), (c-1), and (d-1), and posture of skilled experts: (a-2), (b-2), (c-2), and (d-2)).

The device Polymate II (AP216) made by Miyuki Giken Co., Ltd. was used for the EMG measurement with a sampling time of 1 kHz [56]. All the participants could perform the verification experiment while observing their own CoP position in real time, as shown in Figs. 10 (c-1) and (c-2).

Figs. 10 (d-1) and (d-2) show the results of the EMG measurement under two different conditions of the CoP position. The EMG measurement results shown in the upper two plots for the activation of the biceps brachii (arm) indicated the moment at which the participants lifted the load. It was observed that the maximum peak values for the two arms suddenly increased during left asymmetric lifting when the CoP position was located on the same side, but it seemed that there was no sudden increase in the peak value when the CoP position was located on the opposite side. The results for the thigh shown in the middle two plots indicated the activation of the rectus femoris during left asymmetric lifting. It was observed that the measured EMG values for the left thigh increased, although those of the right thigh decreased when the CoP position and direction of asymmetry were the same. This implied that the posture exhibited a leaning toward the left side. However, it was inferred that the EMG results for the two thighs were balanced when the CoP position and direction of asymmetry were opposite. The results for the lumbar spine (waist) shown in the bottom two plots indicated the activation of the erector spinae during left asymmetric lifting. The EMG values for the lumbar spine showed a slight tendency to increase when the CoP position and direction of asymmetry were the same ($n = 10$) [6]–[20]. As a result, it was found that the imbalance of the CoP position resulted in an imbalance in the EMG measurement of the thigh, including an increase in the EMG values for the arm and waist. This tendency was similar to the simulation results shown in Fig. 9.

It is well known that the torque is the tendency of a force to rotate an object about an axis, fulcrum, or pivot [57]. The torque on a particle can be defined as the following cross product:

$$\tau = r \times F \tag{4}$$

where r is the particle's position vector relative to the fulcrum and F is the force acting on the particle. We conclude that the modification of the hip position for balancing the CoP position in the present study was related to a reduction in the value of r, which was the length from the rotating axis to the load point. Thus, it could be inferred that the balance of the CoP position was related to a reduction in the burden on the waist, as shown in Fig. 10 (d-1) and (d-2). Many studies have been conducted on the effects of different foot positions and pressure distributions on the hip position, spinal posture, and low back pain [49]–[55].

Therefore, we can conclude that the difference in the distribution of the CoP positions for Group 1 during asymmetric lifting may be one type of strategy to lighten the burden on the human body based on measured results while maintaining the balance of the vGRFs between the two feet. We can also conclude, based on simulation and measurement results, that the main feature of the MMH of experts is the hip strategy that moves CoP positions to the opposite side of asymmetry.

V. CONCLUSIONS

This study attempted to determine the main characteristic of the MMH of experts during asymmetric lifting. Our findings showed that most of the skilled experts moved the CoP MP positions to the opposite side during left asymmetric lifting through modification of the hip position. We inferred that this characteristic of the experts may be involved in lightening the burden on the waist during asymmetric lifting; however, there are still two points that the present study do not clarify:

(1) The relationship between the degree of modification of the hip position and the weight of the load: Although the modification of the hip position was limited by the heavier load weight, it was difficult to clarify exactly how most of the skilled experts determined the hip position for different load weights.

(2) The influence of imbalance of the CoP ML position on the forces acting on the lumbar spine: Although the MMH characteristics of experts could be involved in lightening the burden on the waist during asymmetric lifting, it was difficult to calculate how much force was acting directly on the lumbar spine.

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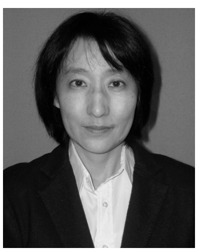

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