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Communications

THE EFFECTS OF THE LOAD MASS AND LOAD POSITION ON BODY SWAY IN SUPPORTING A LOAD ON THE BACK

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We examined the effects of a load's mass and position on body sway during standing with a load on the back. Three healthy male subjects participated in this experiment. The subjects supported loads of 23kg, 33kg, and 43kg on their backs using a carrier frame. They were asked to stand for 75s on a force platform with their eyes open while being as quiet as possible. Time series data of center-of-pressure (COP) were collected at a sampling rate of 50Hz during the last 60s of the 75s standing period. The COP was measured under three conditions in terms of the load position on the frame: lower (close to the hip), middle, and upper (close to the shoulder). All subjects showed that the lower the position of the load, the more anteriorly the mean COP coordinate was located in the anteroposterior (AP) direction, and the smaller the total distance of the COP trajectories became. Regarding carrying the heavier loads, each subject showed a specific tendency in the mean AP coordinate. The three subjects had different physical characteristics in terms of body height and experience at carrying heavy loads. These results suggest that the examintion of the COP in a static posture can help our understanding of individual information on the posture supporting loads and the general positioning of the body.
Key Words: center-of-pressure; force platform; upright posture; carrier frame

INTRODUCTION

Humans have carried heavy items from place to place since time immemorial. Carrying heavy loads on the back has been one traditional manner of hauling. In order to establish the optimal carrying technique to minimize energy consumption, the centroid of the load on the back has been studied over time. The energy consumption during carrying a load decreased as the load was located closer to the trunk (Soule and Goldman, 1969). Moreover, it has been reported that carrying a load on the sacrum is more efficient than carrying it on the lumbar vertebrae (Kawahara et al., 1998). These studies have been undertaken from the viewpoint of energy consumption during walking.

When one begins walking, the action of the first step involves effectively losing one's balance from a static upright posture. The standing posture is inherently unstable, and an additional load on the back certainly increases instability during upright standing. Although carrying a load on the back is a dynamic task, it is also necessary to consider a load-carrying posture in its static aspect. Generally, the trunk tends to lean forward by supporting a load on the back as a compensatory response against falling backward. Variations in the mass of a load and/or the load's position on the back may induce different postural changes and consequently influence properties of the body sway. It is, however, still unclear how the load's mass and position influence postural stability during stand-

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ing with a load on the back.

This study investigated the relationship between the load's mass and position on the back and the wobbliness of the trunk. This investigation was anticipated to provide information on how humans stabilize the body during quiet standing with a heavy load on the back. Body sways in quiet standing with loads were evaluated using a force platform that measured the center-of-pressure (COP) under the subject's feet.

METHODS

Subjects consisted of three male adults, all in good health condition. Age, body height, and body weight for each subject were as follows: subject A, 35 years old, 171 cm, 82 kg; subject B, 35 years old, 160 cm, 64 kg; and subject C, 39 years old, 182 cm, 72 kg. None of the three subjects had taken part in regular physical exercise for the past few years. Subject A used to do hill and mountain climbing during his student days. He had quite a bit of experience in supporting loads of over 10 kg as compared to the other two subjects.

Each of the subjects supported a load on his back using a specially constructed aluminum carrier frame (for detailed design of the carrier frame, see Kawahara et al. 1998). The net mass of the carrier frame was 8 kg. Loads employed in the experiment consisted of iron weights and attachments. The total masses of the combined frame and loads were 23, 33, and 43 kg. The loads were attached at three different respective positions on the frame. These positions were located approximately at the buttocks (lower), the center of the back (middle), and the shoulders (upper). The three positions and the three different masses of the loads provided nine different experimental conditions. Further, a no-load condition (i.e., normal standing without the carrier frame) was carried out. Two trials were performed for each of these 10 conditions.

Postural sways during standing with and without the loads were evaluated using a force platform (KYOWA, ECG-S-1 KNSA1). Before the experiments, the carrier frame was fitted to each subject's body, and each subject's stance on the force platform was standardized. Each subject adjusted the length of the shoulder straps so that the frame was carried with the brunt of the load on the sacrum. In the standardized stance, the subject's ankles were separated mediolaterally by a distance of 3 cm and each of the feet was abducted 5 degrees.

The subjects shouldered the loaded frame and then stood on the force platform in the respective standardized stance. They were asked to maintain a standing posture for 75 seconds as quietly as possible and with their eyes open. While supporting the load on their backs, the subjects were asked to focus on a fixation mark placed on the wall in front of them. The height of the respective fixation mark was determined by the corresponding subject's preference. They were allowed to position their hands and arms in whatever position felt natural and comfortable, but were instructed not to move them voluntarily during the experimental trials.

Time series data of the COP from the force platform were collected at a sampling rate of 50Hz. The mean COP coordinates (MEAN), the standard deviation of COP coordinates (SD), the total distance of COP trajectories (DISTANCE), and the average velocity of COP (VELOCITY) were calculated from the time series data for the last 60 seconds of the test period. In preliminary analyses, the MEAN in the medial-lateral direction showed no outstanding difference between the experimental conditions. Therefore, the MEAN and the SD in the anterior-posterior (AP) direction were used for later analyses. All measurements were averaged for the two trials under each condition. The MEAN and SD values were normalized by the subject's foot length.

RESULTS

Figure 1 shows the MEAN and the SD for each subject. For each of the three mass conditions, the lower the position of the load, the larger the MEAN values; that is, the mean COP coordinates shifted toward the toes. This tendency was consistently found across the subjects.

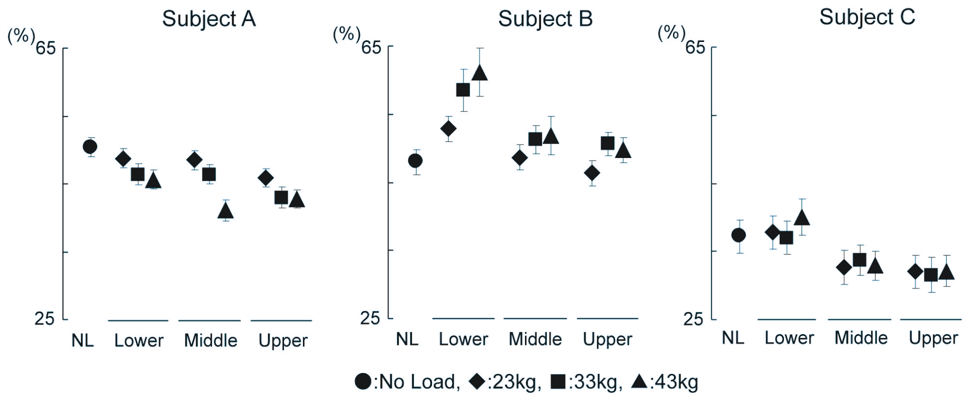

Fig.1. The MEAN and SD for the mass and installation position of the loads. Values on the vertical axes are expressed as a ratio of the subject's foot length (%). Larger values indicate that the mean COP coordinates shift toward the toes.

The MEAN for subject A was around 50% under the no-load condition. The heavier the load, the more posteriorly the COP coordinates shifted. This tendency was consistent regardless of the installation position of the loads. The MEAN for subject B was around 48% under the no-load condition. Subject B showed changes opposite those of subject A in terms of the COP shifts. As the load mass increased, the COPs for subject B moved in the anterior direction. This tendency was consistent regardless of the installation position. The MEAN for subject C was around 37% under the no-load condition. In contrast to subjects A and B, for subject C there were small differences in the MEAN values within each condition of load positioning. This indicates that the increased load mass induced no major shifts of the COP. In a comparison of the overall tendencies among the subjects, the MEANs for subject C were smaller than those for the other subjects, and those for subject B were largest. The values for subject A were in the middle. In terms of body height, subject B was 11 cm shorter than subject A and 22 cm shorter than subject C. These results suggest that relative magnitudes of forward shifts of the COP may depend on body height. Regarding the SD, subject A had values under all experimental conditions considerably smaller than those of the other two subjects. In particular, values of subject A were quite small under the heaviest load conditions. Because the SD can represent averaged extent of body sway, this result implies that subject A could stabilize his standing posture very well, even when supporting a relatively heavy load.

Table 1 shows the DISTANCE for each subject. The three subjects showed a similar trend in terms of the effects of the load mass and load position. The DISTANCEs were the largest under the no-load condition. When the heavier loads were applied, the DISTANCEs became smaller. Additionally, when the installation position became lower, the DISTANCEs decreased except for the load of 33kg. That is, DISTANCE values for all subjects were smallest when the load of 43kg was applied at the lowest position (i.e., at the buttocks). A two-way ANOVA revealed that the main effects of the load mass and the load position were statistically significant ($F=28.62$, $p<0.01$ and $F=3.61$, $p<0.05$, respectively). There was no significant interaction ($F=2.14$, $p=0.12$).

Table 1. Total distance of COP trajectories (mm) for all subjects. Integral values for COP movement data collected over 60 seconds.

	Subject A			Subject B			Subject C		
	Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper
23kg	478.2	497.1	520.7	556.6	586.2	600.6	520.3	521.4	537.7
33kg	429.1	440.5	434.9	520.5	515.9	503.8	462.0	458.6	450.0
43kg	294.1	387.0	405.2	361.3	452.8	473.9	322.9	421.0	441.9
No load		625.4			783.7			685.8	

The results of the VELOCITY were consistent with those of the DISTANCE mentioned above. The VELOCITY decreased as the mass of the loads increased. The smallest values of VELOCITY were obtained when the subjects supported the load of 43kg at the lowest position on the carrier frame. A two-way ANOVA indicated that the main effect of the load mass was significant (F=19.33, p<0.01). The main effect of the load position and the interaction were not significant (F=1.94, p=0.17 and F=1.58, p=0.22, respectively).

DISCUSSION

Countless studies have been carried out focusing on COP characteristics when subjects maintained an upright posture without any load placed on their back. It has been reported that the possible range of the mean COP coordinates in the AP direction was, on the whole, from 30 to 60% of a subject's foot length away from the heel (e.g., Fujiwara et al., 1984; Kilby et al., 1987). In the present experiment, the MEANs were almost in this range in spite of the load mass and load installation position.

With regard to the effect of the load mass on postural sway, consistent results were found across the subjects. The heavier the mass conditions, the smaller the DISTANCEs became. The largest DISTANCE was obtained under the no-load condition. Hellebrandt et al. (1944) reported that postural sway was suppressed by carrying a backpack. In contrast, Watanabe et al. (1987) showed that the total distance of the COP trajectories increased with the mass of loads. In both studies, however, no statistically significant effects of load mass on the total distance of the COP trajectories were found. This seems to reflect the fact that their subjects supported relatively small mass loads (i.e., about 10kg). The present experiment, in which the subjects supported loads up to 43kg, revealed significant differences in the DISTANCE among the mass conditions. Supporting a load on the back results in an increase in the moment of inertia of the body. According to the law of inertia, because a static (or dynamic) state will continue persistently, the increased mass results in further stabilizing a static posture. This is the reason why the DISTANCE decreased when the load mass increased. It should be noted that the heavier load leads to a more stable posture in static tasks such as standing, while it leads to larger sways in dynamic tasks such as walking. Furthermore, joints such as the hip, knee, and ankle might be locked by muscles in order to prevent lower limbs from buckling under heavy loads. The locked joints can work as a unified stiff structure and thus reduce noise or fluctuation of joint movements as compared to noise and fluctuation of unlocked joints. This seems to be another possible explanation for the result that the total distance of the COP trajectories became smaller under the condition of supporting the heavier load.

Remarkable results on the effect of the installation position of the load on postural sway were also found. The lower the position, the smaller the DISTANCEs became. A higher position of the load on the back leads to a great loss of physical performance in some mobility tasks (Holewijn and Lotens, 1992). It also causes levels of muscle activity significantly higher than those at a lower position (Bobet and Norman, 1984). Bobet and Norman suggested that these results are due to differences in the torque arising from the angular acceleration of the load. Increased angular acceleration around the hip joints can cause wobbling of the trunk and consequently produce additional body sway. Carrying a load at a higher position on the back reinforces this influence, because the distance from the center-of-gravity of the load to the hip joints is longer. From this viewpoint, it may be the case that the lowest position resulted in the smallest degree of body sway, resulting in the smallest DISTANCE.

Finally, this study presented very important findings in terms of the postural responses to the load position and load mass. The change of the MEAN was dependent on the load position. The installation position being lower moved the mean COP coordinates toward the toes. Bloom and Woodhull-McNeal (1987) reported that the body leaned more forward when a backpack with a lower center-of-volume was worn than when one with a higher center-of-volume was worn. In the present study, an estimated position of the center-of-mass of the loads including the carrier frame was about 10 cm posterior to the surface of a subject's back. In this setup, the loads produced the force to extend the trunk around the hip joints. This force, which pulls the trunk back and downward, strongly worked in the case of the lowest position of the load. In order to resist falling backward, it was necessary for the subjects to lean their trunks more forward. As a consequence of the forward leaning, the mean of the COP coordinates might shift more toward the toes.

On the other hand, the change in the MEAN with increase of the load mass was unique to each subject. There was a specific tendency in terms of the direction of the shifts of the mean COP coordinates. This result may indicate that each subject unconsciously selected distinct strategies to support the load as its mass increased. The three subjects had different physical characteristics in terms of body height and experience in carrying heavy loads. Subject A, when he was a student, engaged in hill and mountain climbing and had a wealth of experience in carrying heavy loads. The difference in these physical factors might affect the posture and the general positioning of the body when supporting loads.

In conclusion, we detected unique and common postural responses respective to the load's mass and position in supporting a load on the back, based on COP measurements. Further examination of the relationship between the COP values and other individual physical characteristics will be able to provide important information on how humans perform the work of carrying heavy items.

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