Evaluation of Postural Stability during Forward Reaching on a Stepladder for Occupational Fall Prevention

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ABSTRACT

This study aims to evaluate the standing stability during forward reaching tasks on a stepladder in 10 male subjects for prevention of occupational falls. The postural stability was evaluated by measuring the horizontal displacement of the center of pressure (COP) on a stepladder. The experimental conditions comprised four different standing positions on a stepladder: on the platform, stepping over the platform, at one step below the platform, and at two steps below the platform. The results show that the horizontal displacement of the COP in the front direction at two steps below the platform was larger than that on the platform or at one step below it, while it in the horizontal directions were not significantly different between the standing positions. These results suggest that the posture stability could be improved at two steps below the platform for forward reaching tasks on a stepladder.

KEYWORDS

Stepladder, Postural stability, Ergonomics, Occupational safety

1 INTRODUCTION

Stepladders are one of the most common types of tool for moving to or working at an elevated location. According to a previous survey, occupational accidents caused by the use of stepladders in Japan led to nearly 4,000 injuries requiring a leave of absence of four or more days and to 20 fatalities [1]. This makes up 2.9% of all reported Japanese occupational accidents in a year.

The fall accidents from stepladders often result in severe or multiple injuries [2, 3]. Moreover, in Japan, a legal provision for fall prevention apparatus for high-place work is only applicable to work at heights of more than 2 m. Therefore, protective equipment is not mandatory for such work with stepladder at lower heights. This involves a possibility that could lead to serious accidents.

The stability of the body posture in quiet standing has been evaluated with the inverted pendulum model that explains the relationship between the center of mass (COM) and COP [4-6]. A wider range of the theoretical area of COP (BOS) in a standing position is preferable to a narrower one [7]. Regarding the stepladder tasks, COM and COP movements have also been investigated in previous studies [8, 9], while the functional BOS on the stepladder has not been examined experimentally.

In this study, we compared the COP positions in the horizontal plane during static reaching tasks to compare the effects of different standing positions on human body balance.

2 METHODS

2.1 Subjects

Ten young (21–25 years old) male subjects participated in the study. The mean values of their body height and weight were 170.6 ± 6.3 cm and 70.2 ± 14.8 kg (mean ± standard deviation), respectively. The vertical distances from the standing surface to the acromion and the mid-patella were 138.5 ± 5.7 cm and 46.6 ±

1.4 cm, respectively. The upper limb length (distance from the acromion to the fingertip) was 71.8 ± 2.7 cm.

2.2 Equipment

In this study, a three-step folding standing stepladder [10] with a platform (the platform itself is considered as the top step), as shown in Figure 1, was used for the experiment.

Two force plates with built-in amplifiers (Kistler Instrument Corp., 9286B A) were mounted under the stepladder to estimate the COP position in the horizontal plane.

To prevent any fall accidents during the experiments, each subject wore a full-body safety harness, a hard hat, elbow and knee protectors, and a waist-protection belt.

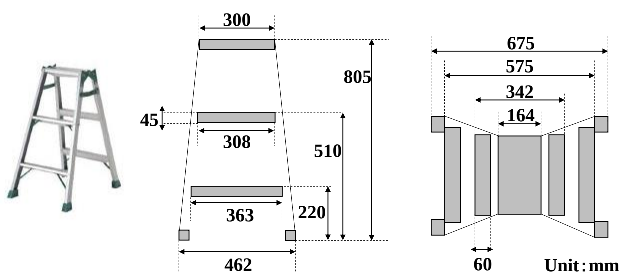

Figure 1. Dimensions of the stepladder used in this experiment. A photo, the side view, and the top view.

2.3 Protocol

Each subject stood on the stepladder as instructed. He then slowly elevated his right arm to shoulder height. The subject was then instructed to lean his body and reach in the indicated direction as far as he could (Figure 2), holding that body posture for 5 s.

Prior to each experiment, the risks were explained to the subject of falling from a stepladder if excessive force was applied to the frame because the stepladder was not fixed to the floor. The subject then practiced reaching several times until he achieved adequate posture control.

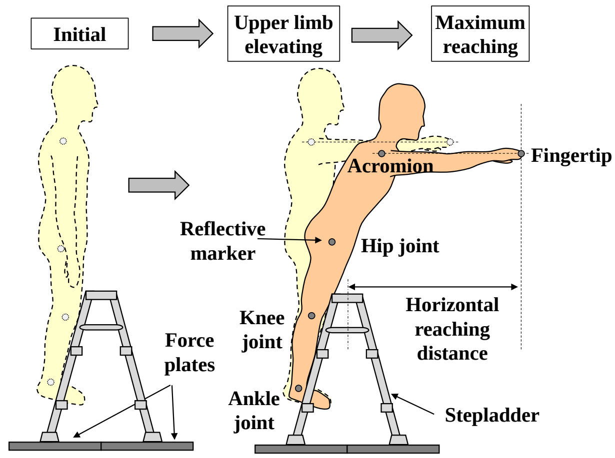

Figure 2. Experimental protocol.

2.4 Experimental Conditions

Combinations of four stepladder standing positions and five reaching directions were tested, as shown in Figure 3. The standing positions were (i) on the platform (platform), (ii) stepping over the platform (stepping over), (iii) one step below the platform (1 step below), and (iv) two steps below the platform (2 steps below). For positions (iii) and (iv), each subject stood on the same side of the ascendable plane. For position (ii), the forward direction for each subject was parallel with the long axis of the platform; for all others, it was parallel with the short axis.

The reaching direction was classified based on directions in the horizontal plane with reference to the acromion of the dominant arm: in front of

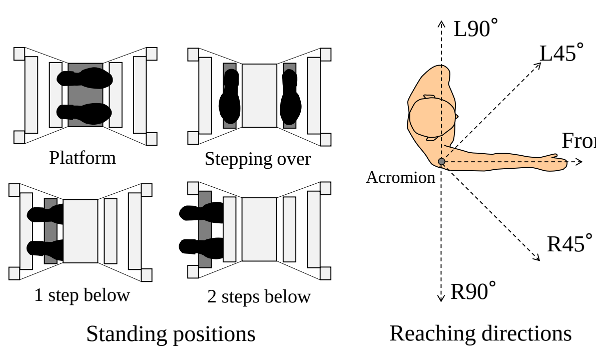

Figure 3. Experimental conditions.

the acromion (0°), 45° to the right (R45°), 90° to the right (R90°), 45° to the left (L45°), and 90° to the left (L90°). Each subject elevated and kept their dominant arm at the height of their acromion while leaning their body.
The experimental conditions were completely randomized and two trials were measured for each condition.

2.5 Measurement and Analysis

The functional BOS on the stepladder has to be examined experimentally based on the COP positions in the horizontal plane during static reaching tasks in this study. The resultant COP from the two force plates was calculated as follows:

$$CP_x = (LCP_x \cdot LF_{vertical} + RCP_x \cdot RF_{vertical}) / (LF_{vertical} + RF_{vertical}), \quad (1)$$

$$CP_y = (LCP_y \cdot LF_{vertical} + RCP_y \cdot RF_{vertical}) / (LF_{vertical} + RF_{vertical}), \quad (2)$$

where *CPx* and *CPy* are the *x* and *y* components of the resultant COP of the body and the stepladder in the global reference system, *LCPx* and *RCPx* are the COPs of the first and second force plates, and *LFvertical* and *RFvertical* are the vertical components of the ground reaction forces on the first and second force plates, respectively. The vertical and horizontal loads were offset after setting the stepladder on the force plates. These signals were recorded at 100 Hz through an analogue-to-digital data recording system (PH-703, DKH Co. Ltd, Japan). The measured signals were low-pass filtered using a second-order Butterworth filter (2-Hz cut-off frequency).
Statistical analyses were performed to determine the effects of standing positions and reaching directions on the evaluation indices. A randomized block design was used in which subjects experienced all combinations of the four standing positions and five reaching directions. The experiment was blocked on the four standing positions. Tukey's honestly significant difference test was used to group the standing positions and reaching directions. A 0.05 significance level was applied throughout the analyses.

3 RESULTS

Figure 4 shows the horizontal movement distance of COP between that of initial standing and maximum reaching. The COP movement distance was affected by standing positions ($F(3,361) = 201.39$, $p < 0.001$), reaching directions ($F(4,361) = 25.99$, $p < 0.001$), and the interactions ($F(12,361) = 83.43$, $p < 0.001$).
For all reaching directions, the COP movement distances at 2 steps below, in the 15 cm to 20 cm range, were longer than those of the other standing positions. The shortest COP movement distances, ranged from 5 cm to 10 cm, were observed in the platform condition. Moreover, there were no significant differences between platform and stepping-over or 2 steps below conditions at the forward and R45° directions.
Figure 5 shows the mean horizontal coordinates of COP during maximum reaching on the stepladder. The origin of the axes indicates the center of the platform. The forward reaching direction for each subject is to the right of the figure for the platform, 1 step below, and 2 steps below conditions, whereas it is to the bottom for the stepping-over condition.
The initial COP positions while standing were located on the opposite side of the dominant hand. One dot per each standing condition was plotted as initial COP positions because there were no significant differences between the reaching directions.
COP positions while reaching forward on the platform were located behind the center of the platform. For the 1 step below condition, COP did not exceed the front edge of the footstep, while it did so significantly for the 2 steps below condition.
In reaching to the right and left, COP movements were longer than those for the forward directions. In particular, COP positions were located close to the left edge of the footstep in

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the L90° direction and to the left edge of the supporting leg.

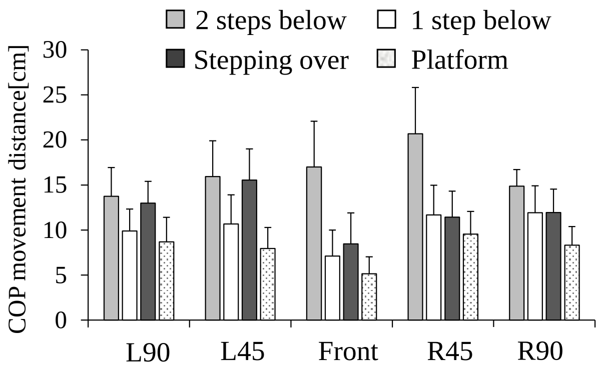

Figure 4. Horizontal movement distance of COP between initial and maximum reach postures.

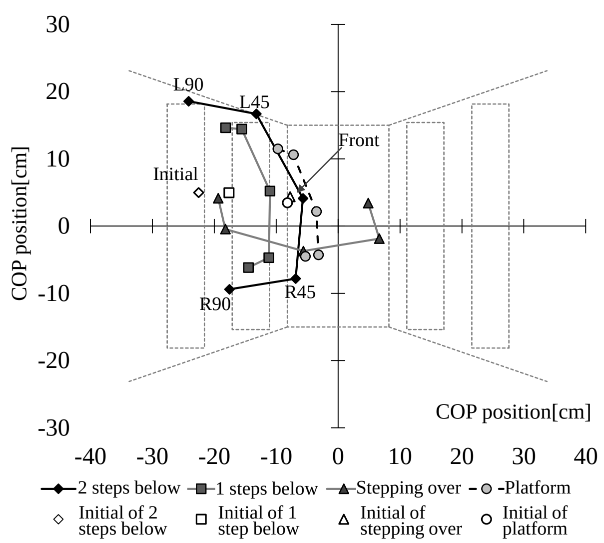

Figure 5. Horizontal coordinates of COP during initial posture and maximum reach. Colorless markers express values during maximum reach. Colored markers are connected in order as follows: Left-90°, Left-45°, Forward, Right-45°, Right-90°. Dotted lines express the outer shape of the stepladder.

4 DISCUSSION

Regarding the other standing positions, COP moved under the platform in the 2 steps below condition and under the front edge of the standing step at 1 step below. This indicates that users feel the need to make contact between their lower limbs (i.e., outside the thighs) and the rungs to improve standing posture stability during reaching forward. Therefore, choosing a sufficiently high stepladder and not standing higher than its upper two steps is a preferable way to work safely. In occupational sites, workers often tend to prefer a lower stepladder for the ease of carrying and to stand on its platform. This behavior is considered to increase the risk of losing balance. However, workers should not adopt a posture that involves leaning on the stepladder from above because the vertical load due to the lower limbs decreases the ground reaction force to the their feet and reduces the maximum friction force [11]. In the stepping-over condition, forward COP displacement was less than that to the right or left. These results indicate that standing while stepping over the platform is preferable for minimizing body sway in the horizontal direction, but undesirable in terms of body sway in the anteroposterior direction and for tasks involving a reaction or an impulsive force.

5 CONCLUSIONS

The aim of this study was to evaluate the effect of standing positions and reaching directions on the horizontal displacement of COP on a stepladder. The results revealed that standing on the platform restricts the displacement of COP to a narrower range than the platform itself and increases the risk of losing balance. Therefore, standing two steps below the platform and leaning against the stepladder frame extends the range of COP displacements and contributes to the stability of body posture.

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