Evaluation of Standing Stability and Reaching Postures on a Stepladder for Occupational Fall Prevention

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Abstract. This study aims to evaluate the standing stability and body postures during forward reaching tasks on a stepladder for prevention of occupational falls. In this research, the stability of reaching tasks was evaluated in 10 male subjects by measuring the horizontal displacement of the center of pressure (COP) of the body weight 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 at two steps below the platform was more than that on the platform or at one step below it. 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, Occupational safety, Fall, Standing stability, Ergonomics

1. INTRODUCTION

A stepladder is a tool for moving to or working at an elevated location, which is used at various situations. According to a previous survey, occupational accidents caused by the use of stepladders (stepladder accidents) in Japan led to nearly 4,000 injuries requiring a leave of absence of four or more days and to 20 fatalities (Sugama and Ohnishi, 2015). 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 (Muir and Kanwar, 1993; Navarro and Clift, 2005). 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 most frequent occurrence of a stepladder accident is when a worker is standing on one (Cohen and Lin, 1991; Axelsson and Carter, 1995; Faergemann and Larsen, 2001; Sugama and Ohnishi, 2015). The major factors contributing to stepladder falls are the loss of human balance and the collapse of the stepladder by itself or because of human movement such as reaching too far sideways while standing on the stepladder (Faergemann and Larsen, 2001). Although the human body balance (Clift and Navarro, 2002) and stepladder stability (Yang and Ashton-Miller, 1995) have been examined in previous studies based on the analysis of the center of mass (COM) or the center of pressure (COP), the stability of postures assumed in an actual stepladder use has not been examined sufficiently. Verification of body posture stability on a stepladder is required in order to understand how to use stepladders safely and to establish the associated safety rules.

In this study, we compared the effects of different standing positions on human body balance. In addition, we focused on forward-reaching tasks in situations where a user loses balance due to excessive reaching movements.

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.

Each subject provided informed consent to the potential risks associated with their participation. This experiment was conducted with permission from the ethics committee of the National Institute of Occupational Safety and Health, Japan.

2.2 Equipment

In this study, a three-step folding standing stepladder (Japanese Standards Association, 2013) with a platform (the platform itself is considered as the top step), as shown in Figure 1, was used for the experiment. This is typical of the stepladders that are used in various occupational situations in Japan. The stepladder was two-legged, self-supporting, and bilaterally ascendable. Its vertical height was 810 mm, and the size of the platform was 300 × 164 mm. The length of step treads from front to back was 60 mm; the inner dimension of the width of step treads was 310 mm at one step below the platform and 360 mm at two steps below it.

A motion capture system (NaturalPoint Inc., OptiTrack) with 10 optical cameras was used to measure body postures. The three-dimensional (3D) coordinates of 19 reflective markers placed on the subject's skin were sampled at 100 Hz. The X-axis of the world coordinate system was set parallel to the anterior, the Y-axis was to the left, and the Z-axis was to the upper direction for the subject who was facing the lifting plane of the stepladder. In this study, coordinate data of markers on the acromion and the fingertip of the right-hand index finger as well as similar data from the bilateral hip, knee, and ankle joints were used to analyze the body-joint angles.

Two force plates with built-in amplifiers (Kistler Instrument Corp., 9286BA) 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. The lanyard of the safety belt was connected to a beam in the ceiling. Each subject wore a hard hat, elbow and knee protectors, and a waist-protection belt. In addition, safety mats were set around all four directions of the stepladder in anticipation of a fall accident.

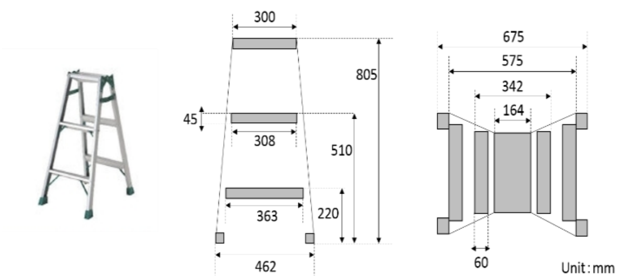

Figure 1: Dimensions of the stepladder used in this experiment. A photo, the side view, and the top view.

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.

After each trial, the subject answered a questionnaire about his subjective evaluation (see section 2.5.3).

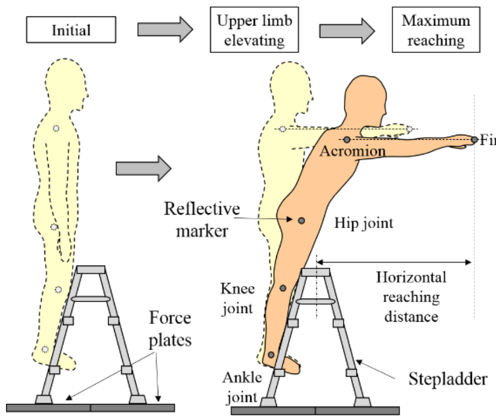

Figure 2: Experimental protocol.

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 (see Figure 3).

The reaching direction was classified based on directions in the horizontal plane with reference to the acromion of the dominant arm: in front of 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. Each subject was instructed to stand with his feet in a comfortable position on the steps. He was instructed to raise only his heels and to keep both feet on the step surface. His lower limbs could make contact with the outer frame while reaching on the stepladder.

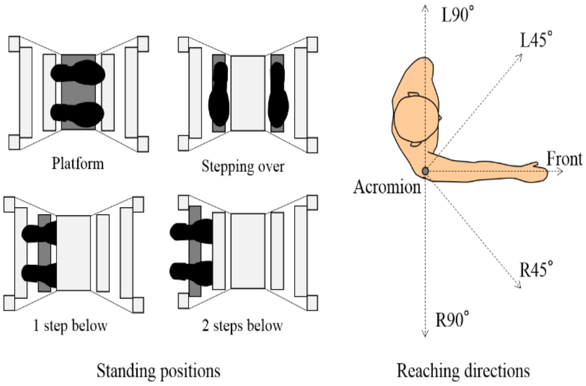

Figure 3: Experimental conditions.

2.5. Measurement and analysis

2.5.1 Joint angles and Reaching Distance

Body posture was evaluated by the hip joint flexion, the hip joint lateral flexion, and the hip and upper body rotation angles, as shown in Figure 4. The hip joint flexion is defined as the angle between the body trunk and the thigh. The hip joint lateral flexion is defined as the angle between the body trunk and the pelvis. The hip rotation angle is defined as the angle between the pelvis and the line that connects the right and left ankle joints in the horizontal plane. The upper body rotation angle is defined as the angle between the pelvis and the line that connects the right and left acromia in the horizontal plane.

Reaching distance was measured by the linear distance in the horizontal plane between the center of the stepladder and the fingertip of the dominant hand.

These angles were measured for 5 s while reaching on the stepladder, and average values were calculated for a median time of 1 s.

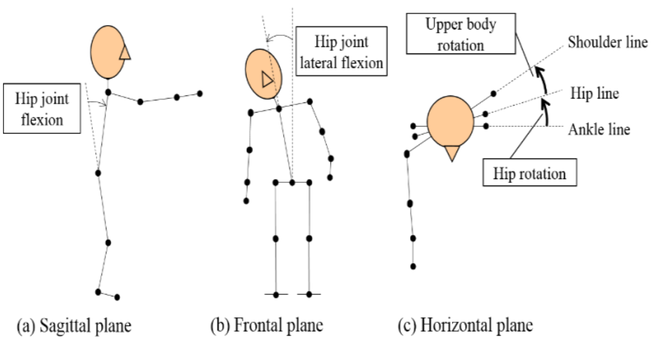

Figure 4: Definition of joint angles.

2.5.2 Postural Stability

The stability of the body posture in quiet standing has been evaluated with the inverted pendulum model that explains the relationship between COM and COP (Winter et al., 1996; 1998; Gage and Winter, 2004). COP movement precedes the movement of COM, and the theoretical area of COP is defined as the base of support (BOS). A wider range of BOS in a standing position is preferable to a narrower one (Winter, 2009). However, the functional stability region, defined as the area within which the body's COM can be controlled, may be smaller than the theoretical one (Holbein, 1997). This is typically the area beyond which an individual will not place their COM.

Regarding the stepladder tasks, COM and COP movements have also been investigated in previous studies (Otten, 1999; Yang and Ashton-Miller, 2005). With no contact between the subject's lower limbs and the stepladder frame, the theoretical BOS is equal to the area of the standing rungs and the platform. With contact, however, the theoretical BOS becomes the same as the square zone formed by the feet of the four supporting legs of the stepladder. Then, the functional BOS on a stepladder may be smaller than this theoretical one because of the lower limbs making contact with the stepladder frame. 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 CP_x and CP_y are the x and y components of the resultant COP of the body and the stepladder in the global reference system, LCP_x and RCP_x are the COPs of the first and second force plates, and $LF_{vertical}$ and $RF_{vertical}$ 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 synchronized with the motion capture system at 100 Hz and recorded through an analogue-to-digital data recording system (PH-703, DKH Co. Ltd, Japan). The spatial gap between the force plates and the motion capture system was corrected by measuring the setting positions of the stepladder with the motion capture system. The measured signals were low-pass filtered using a second-order Butterworth filter (2-Hz cut-off frequency).

2.5.3 Subjective Evaluation

After each measurement, each subject evaluated his subjective sense about the instability of his body postures on a five-point scale: 1 = nothing wrong, 2 = slightly unstable, 3 = moderately unstable, 4 = quite unstable, and 5 = very unstable. Then, to investigate the relationship between the subjective difficulty of reaching tasks and other quantitative indices, the mean value of 10 subjects and correlation coefficients with other indices were calculated.

2.5.4 Data Analysis

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

3.1. Joint Angles and Reaching Distance

Figure 5 shows the results of the hip joint flexion angle. The bar charts show the means and the error bars show the standard deviations. ANOVA analysis showed that the standing positions, the reaching directions, and the interactions (standing position × reach direction) were significant for all measures ($p < 0.001$). Hip joint angles at 2 steps below were ~10°–20° smaller than those at the other conditions, indicating that subjects adopted the extended trunk posture at 2 steps below.

Figure 6 shows the horizontal distance from the center of the stepladder to the fingertip. ANOVA analysis showed that the standing positions, the reaching directions, and the interactions were significant for all measures ($p < 0.001$). The reaching distance at 1 step below was significantly shorter than that of the other standing positions. There was no significant difference between Platform and 2 steps below. The longest horizontal reaching distances to the forward direction was for the stepping-over condition (110 cm) and the shortest was at 1 step below (90 cm). Furthermore, the ratio of reaching distances to upper limb length was varied from 1.28 to 1.54 for the forward direction.

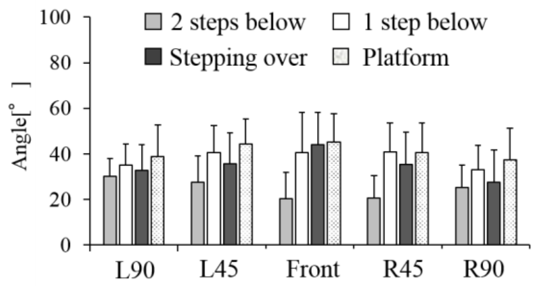

Figure 5: Hip joint flexion angle. Positive values indicate joint flexion. Error bars express standard deviations.

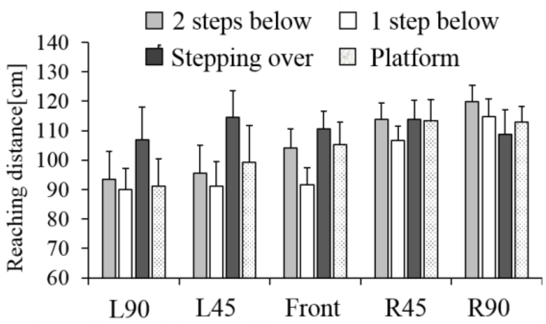

Figure 6: Horizontal reach distance from the center of the stepladder to the fingertip.

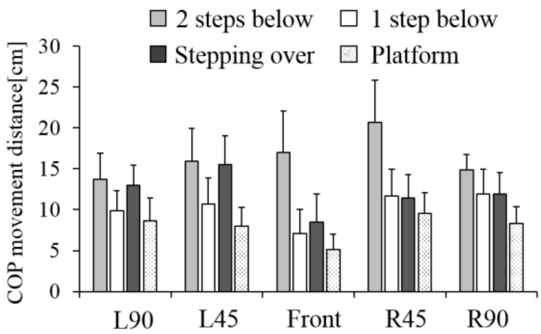

Figure 7: Horizontal movement distance of COP between initial and maximum reach postures.

3.2 Postural Stability

Figure 7 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 (15–20 cm) were longer than those of the other standing positions. The shortest COP movement distances were observed in the platform condition (5–10 cm). Moreover, there were no significant differences between platform and stepping-over or 2 steps below conditions at the forward and R45° directions.

Figure 8 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 the L90° direction and to the left edge of the supporting leg.

Table 1 shows the movement directions of COP and the angular differences from the instructed directions. While the angular difference in the forward direction was relatively small, the largest difference observed for L45° was ~25°. In addition, the >90° value observed in the L90° direction indicates that the subjects moved their COP backward from its initial position.

3.4 Subjective Evaluation

Figure 9 shows the results of subjective body posture instability. There were significant differences between standing positions ($F(3,361) = 78.24, p < 0.001$), but relatively

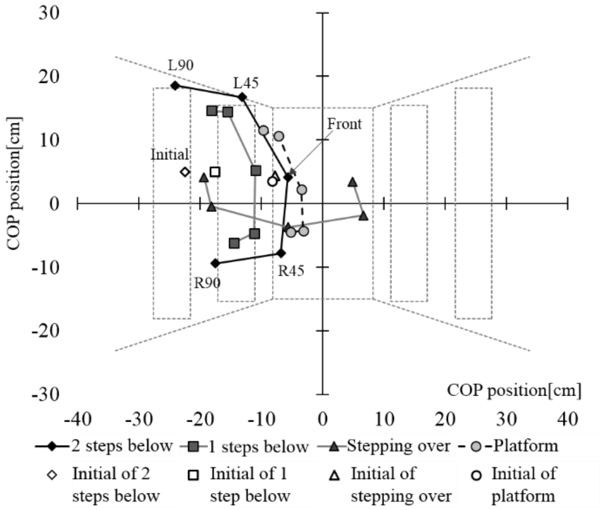

Figure 8: Horizontal coordinates of COP during initial posture and maximum reach. Colorless markers express values during maximum reach. Colored markers are connected in order as follows: Left-90°, Left-45°, Forward, Right-45°, Right-90°. Dotted lines express the outer shape of the stepladder.

little difference between reaching directions. These results show that subjective instability was significantly higher on the platform and lower 2 steps below. There was no significant difference between stepping over and 1 step below.

Table 2 shows the correlation coefficients between subjective instability and the other evaluation indices. The vector length representing the displacement of the horizontal COP position (from the initial posture to the maximum reaching) was described as the COP movement distance, and the inner product of COP vector and the unit vector to each reaching direction was the COP inner product.

These results show that the highest correlation coefficient for subjective instability was observed in the COP movement distance (−0.869), which was slightly lower in the COP inner product (−0.864).

Table 1: COP movement directions and angular differences from instructed directions in the horizontal plane. Directions are calculated on the basis of the COP location of initial postures. Positive values indicate left directions and negative values indicate right directions.

Reaching directions	Standing positions				Mean difference with reaching direction
	2 steps below	1 step below	Stepping over	Platform	
L90°	97.0	93.3	85.7	100.9	4.20
L45°	51.6	77.7	66.7	82.2	24.54
Front	−2.9	2.0	14.9	−15.5	−0.35
R45°	−39.3	−56.3	−65.3	−57.1	−9.50
R90°	−71.0	−74.3	−88.9	−70.0	13.94

Table 2: Correlation coefficients between subjective instability and evaluation indices.

	Hip flexion	Hip lateral flexion	Body rotation	COP movement distance	COP inner product	Reaching distance
Subjective instability	−0.628	0.011	−0.006	−0.869	−0.863	−0.252

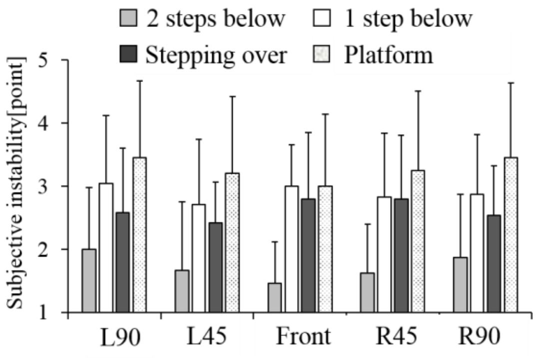

Figure 9: Subjective instability of maximum reach posture.

4. DISCUSSION

4.1. Standing Posture and Reaching Distance

The effect of standing position was investigated mainly in terms of the hip joint flexion angle. This was attributed to the fact that the static body balance on the stepladder is controlled by the adjustment of this angle. The COM should be positioned over the BOS while maintaining static stability on the stepladder. Therefore, in the platform, stepping-over and 1 step below conditions, hip joint flexion is a way to move the hip backward to maintain COM position during horizontal reaching. As the characteristic trends, at 1 step below, subjects flexed their hip joint for reaching although they made contact their thigh with rungs. This is considered that contact their thigh and the rungs does not contribute to increase the contact force that contributes to support their body. In addition, the lower-limb pain caused by contact with the rung was another reason why subjects did not lean over the stepladder in the 1 step below condition. However, 2 steps below, the hip joint was extended and subjects leaned over their lower body on the stepladder. This is because the horizontal reaction force received from contact with the stepladder rungs produces the rotational moment that rotates the body backward.

The results of reaching distance show that there was no significant difference in the horizontal reaching distance between the platform and 2 steps below conditions, even though a difference had previously been expected. The reason for this is thought to be as mentioned above, i.e., it is due to the difference in reaching posture that compensated for the horizontal displacement difference of ~20 cm between the two standing positions. The shortest reaching distance was observed in the 1 step below condition, this being 15 cm shorter than that at 2 steps below. This is thought to be caused by standing behind the center of the stepladder and by the difficulty of leaning forward. On the other hand, in the stepping-over condition, the horizontal reaching distance was 20 cm longer than that at 1 step below. We consider that contact between the lower limbs and the rungs contributed to supporting the reaching posture.

4.2. COP and Subjective Evaluation

The theoretical BOS for a person standing on a platform is defined as the convex hull encompassing the contact area of the feet with the platform (Winter, 2009). The anteroposterior width of the theoretical BOS in the platform condition is equal to the short axis width of the platform. Therefore, it was expected that COP would move to the front edge of the platform during reaching forward. However, the results showed that COP did not even pass the center of the platform. The reason for this was that a sufficient safety margin for COP displacement was allowed in order to avoid the loss of balance to the front due to psychological response. Moreover, because COP of the initial posture was displaced toward the posterior edge of the platform, we consider that COM was displaced backward in advance for reaching forward.

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 (Jin, 2011). 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.

As the results for subjective instability showed a clear inverse correlation with COP movement distance, we consider that users tend to feel subjectively stable in the direction in which they are able to move their COM. However, the subjective instability while reaching to the left showed no significant difference with that to the right while COP moved under the left edge of the supporting leg during reaching to the left. This characteristic implies that the COP position relative to the frame of the stepladder is barely perceptible by the user standing on it and that the risk of a fall is not adequately evaluated by subjective instability alone. Particularly, in tasks involving twisting of the upper body, it is necessary to be careful about both the potential of stepladder collapse and the loss of body balance.

4.3. Limitations

The limitations of this study are the sample size and the effects of sex and age factors. Studies of larger samples and female participants may more accurately evaluate the range and variability of reaching distance and joint angles. Moreover, as elderly participants may secure a large safety margin to avoid the loss of balance, the horizontal movement distance of COP in them may also decrease than in young male participants (Yang and Ashton-Miller, 2006). However, the effects of standing position and reaching direction seem to be relatively similar among the groups.

Although this study used a common type of stepladder and targeted at the reaching task, experiments using other types of stepladders and the evaluation of other tasks should be cautiously undertaken. In particular, the effect of external force applied from the reaction of hand tools, such as a hammer and an electrical nail gun, should be examined and announce a suitable way of stepladder works.

5. CONCLUSIONS

The aim of this study was to evaluate the effect of standing positions and reaching directions on working postures, the maximum reaching distance, and the displacement of COP in order to reduce fall accidents from stepladders due to balance issues. In line with the stated objectives, four main conclusions are drawn from the results.

1) The hip joints extend and the lower limbs make contact with the stepladder frame while reaching forward from two steps below the platform. The hip joints flex when standing either on the platform or on one step below it.
2) Standing two steps below the platform allows the body to lean forward so that the forward reaching distance is as long as it is when standing on the platform. However, the reaching distance from one step below the platform was shorter than that from two steps below.
3) Standing on the platform restricts the displacement of COP to a narrower range than the platform itself and increases the risk of losing balance. 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.
4) Considering the maximum reaching distance and the posture stability, standing two steps below the platform is preferable for forward-reaching tasks on a stepladder.

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