Occupational Hazards

Portable Ladders

Understanding and preventing slips at their bases

By Wen-Ruey Chang and Chien-Chi Chang

LADDER ACCIDENTS are a major safety problem despite standards and regulations designed to protect workers. Based on data published in 1982, 1985 and 1987, Häkkinen, et al (1) and Axelsson and Carter (250) estimated that ladders are involved in one to two percent of all occupational accidents in industrialized countries, and that roughly one of 2,000 workers has a ladder accident each year. Nearly 40 percent of individuals involved in ladder accidents were absent from work for more than one month, and half of injured individuals experienced continuing—possibly permanent—disability (Axelsson and Carter 250). Björnstig and Johnson (9) found that almost half of ladder accidents resulted in moderate or serious injuries.

Straight ladders were involved in most of these ladder accidents (Häkkinen, et al 1; Björnstig and Johnson 9; Axelsson and Carter 250). The ladder slipping at its base is one of the most common causes of accidents involving portable straight ladders (Dewar 67; Häkkinen, et al 1; Björnstig and Johnson 9; Axelsson and Carter 250).

Activities on the ladder when the accidents occurred included standing or working (39 percent), ascending (35 percent) and descending (23 percent) (Häkkinen, et al 1). Among the sliding incidents, accidents occurred because of contaminants on the floor surfaces such as ice, snow and water, or because of an inappropriate ladder angle (Björnstig and Johnson 9). The angle of inclination (measured between the ladder and ground) was less than 65 degrees in 49 percent of the straight ladder accidents (Axelsson and Carter 250).

One of the most common initiating events in straight-ladder accidents is slipping at the base. Björnstig and Johnson (9) found that ladders involved in 59 percent of sliding accidents were equipped with plastic or rubber antislip pads that did not prevent the incident. Partridge, et al (31) reported that 45 percent of the ladder accidents studied occurred because of incorrect ladder placement. Tsipouras, et al (516) indicated that 23 percent of accidents were because the ladder slid from its position, which did not include sideways tilting.

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Coefficient of Friction

The coefficient of friction (COF) between two contacting bodies is defined as a dimensionless quantity obtained by dividing the tangential component of the contact force at the interface by the corresponding normal component perpendicular to the contact interface (Rabinowicz 56). Required COF represents the minimum friction needed at the ladder bottom to prevent a slip while supporting human activities on the ladder; available COF represents the maximum friction that can be supported at the ladder shoe and floor interface without a slip.

Required COF can be obtained by measuring the contact force between the ladder shoe and floor surfaces during human climbing. Available COF is a measure of the resistance to initiate a motion at the ladder shoe and floor interface. A slip is most likely to occur when the required COF exceeds the available COF (Pesonen and Häkkinen 6). A higher required friction could increase the potential of a slip at the base of the ladder.

Although manufacturers are required to list relevant warnings on labels attached to portable ladders, these warnings can leave the users wondering which is most important. This article summarizes the current understanding (based on results published in the literature) of several important factors that could potentially be used to reduce incidents of slips at the bases of portable straight ladders. These studies deal with straight ladder use on hard, level surfaces as opposed to unleveled floors or outdoor use on soft ground.

Required COF

Several studies have investigated friction requirements between ladder shoes and floor surface in order to support human climbing on the ladders (e.g., Häkkinen, et al 1; Pesonen and Häkkinen 6; and Chang, et al 791). To collect their data, these researchers often use a force plate at the base of the straight ladder to measure contact forces between the ladder shoes and floor surface. Figure 1 illustrates a typical setup.

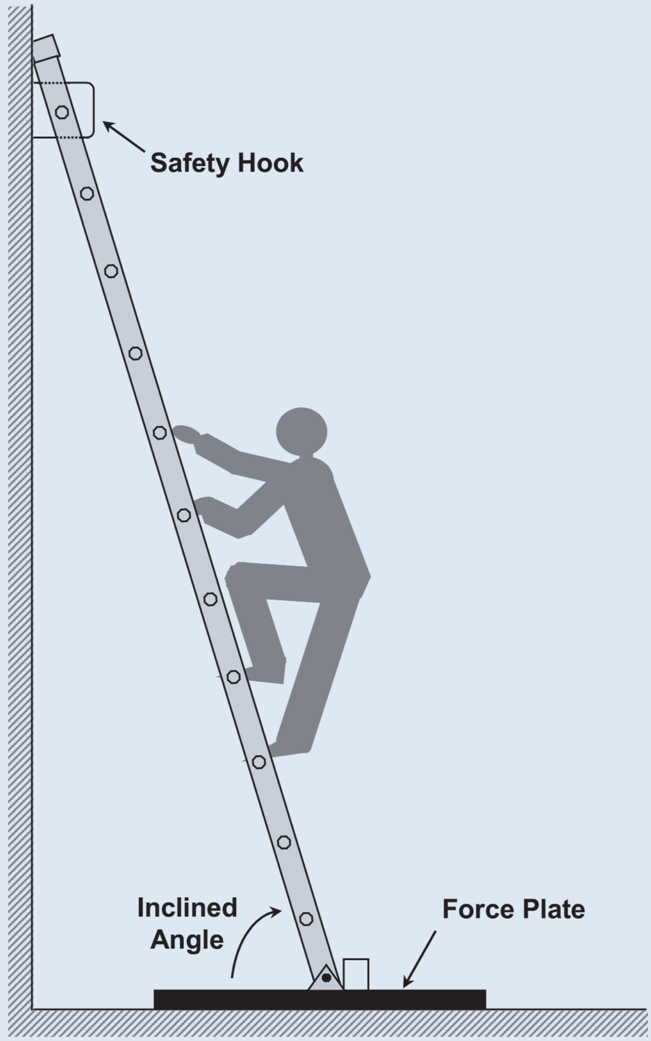
The output measures of the force plate were the normal and shear forces at the ladder bottom and floor interface. The normal force is the component of the total force at the ladder shoe and floor interface perpendicular to the interface, while the shear force is the corresponding component tangent to the interface. An instantaneous friction coefficient for the required COF measurement was then calculated by dividing the shear force by the normal force at the same instant.

In one study, six male subjects were asked to climb a straight ladder using different climbing manners under different ladder angles (Häkkinen, et al 1). The maximum local values of normal and shear forces at the bottom of the ladder were reached when stepping off a rung. In the ascending task, the maximum values of normal force were 1.5 to 2.4 times the subject's weight due to the dynamic climbing on the ladder. As the ladder angle was increased, the dynamic normal and shear forces at the interface decreased. Individual climbing manners seemed to affect the forces, but the researchers did not measure body motions of these subjects. Based on the results from a subject climbing on a straight ladder with the ladder angle of 68 degrees, Pesonen and Häkkinen (6) concluded that the required COF was 0.17 to 0.28 for climbing up to the eighth rung.

A more recent study reported the effects of climbing speed, body weight category, ladder type, ladder angle and type of support at the top of the ladder on the friction requirements between ladder bottom and floor surface during ladder ascending (Chang, et al 791). Seventeen subjects, representing light (less than 75 kg or 165 pounds), intermediate (between 75 and 95 kg or 165 and 209 pounds) and heavy (more than 95 kg or 209 pounds) weight categories, participated. There were two levels for each additional independent variable. Climbing speeds were 55 and 75 steps/minute for slow and fast, respectively. Ladder inclined angles were 65 and 75 degrees. Commercially available aluminum and fiberglass ladders were the ladder types used. Different supports at the top of the ladder included normal and reduced friction using rollers.

Figure 1

Experimental Apparatus for the Required Friction Measurements



Source: Chang et al, 791.

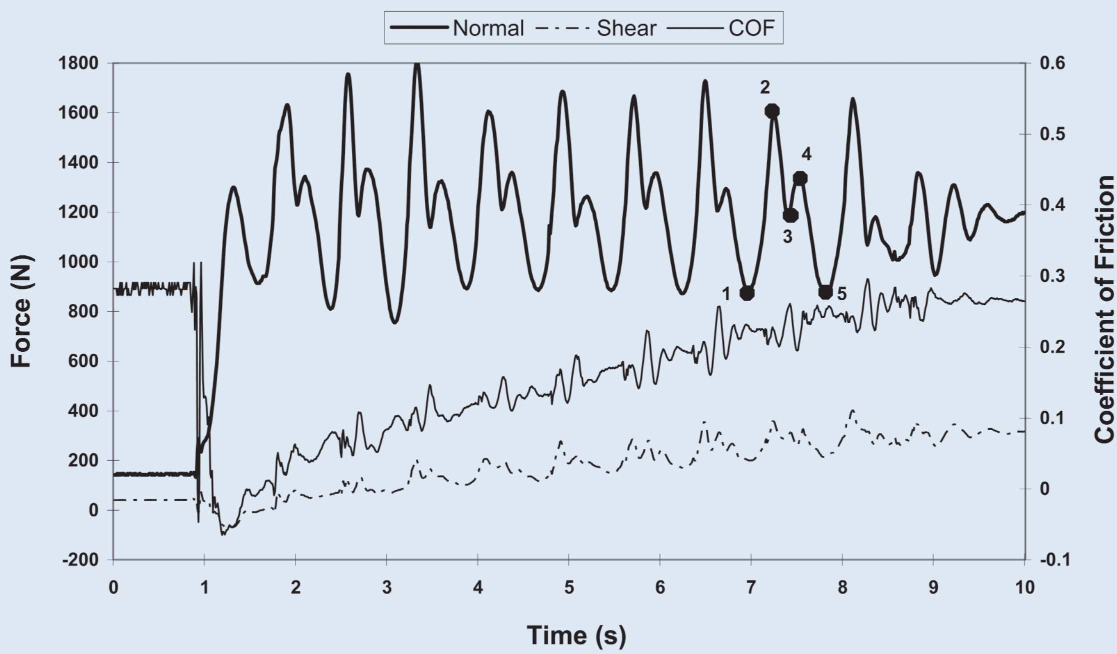
Abstract: *The slipping of the bases of portable ladders away from the wall is a major cause of injuries. This article summarizes causes and potential interventions. These include developing practical guidelines on proper ladder setup and reminders not to rush on a ladder. In addition, users should know to avoid setting up ladders over contaminated areas, as well as to always use antislip ladder shoes.*

The results shown in Figure 2 illustrate a typical example of the normal and shear forces and the calculated COF measured with a force plate during ladder ascending for the required COF measurement. These data were generated with one test subject who had a body weight of 108.9 kg (240 pounds) and climbed at a fast speed on an aluminum ladder inclined at 65 degrees with the reduced friction on the top support.

As shown from point 1 to 5 in Figure 2, a step was defined as the duration from the moment a foot stepped on a rung until the moment the other foot stepped on the next rung. The normal force reached a minimum (point 1) right before a foot stepped onto a new rung. As soon as the subject stepped on a new rung, the normal force increased rapidly and reached the first peak (point 2). The normal force decreased after the first peak, then increased again before reaching the second peak (point 4), which is usually lower than the first peak. The shear force at

Figure 2

Typical Results of Force Plate Measurements During Ladder Ascending



Source: Chang et al, 791.

Table 1

Required COF for Different Climbing Conditions

		Average	Min.	Max.
Body Weight	Light	0.213	0.119	0.337
	Intermediate	0.211	0.122	0.313
	Heavy	0.197	0.107	0.294
Inclined Angle	65 degrees	0.264	0.223	0.337
	75 degrees	0.149	0.107	0.215
Ladder Type	Aluminum	0.207	0.107	0.337
	Fiberglass	0.206	0.113	0.319
Climbing Speed	Fast	0.213	0.120	0.337
	Slow	0.200	0.107	0.314
Top Support	Reduced Friction	0.209	0.114	0.321
	Normal Friction	0.205	0.107	0.337

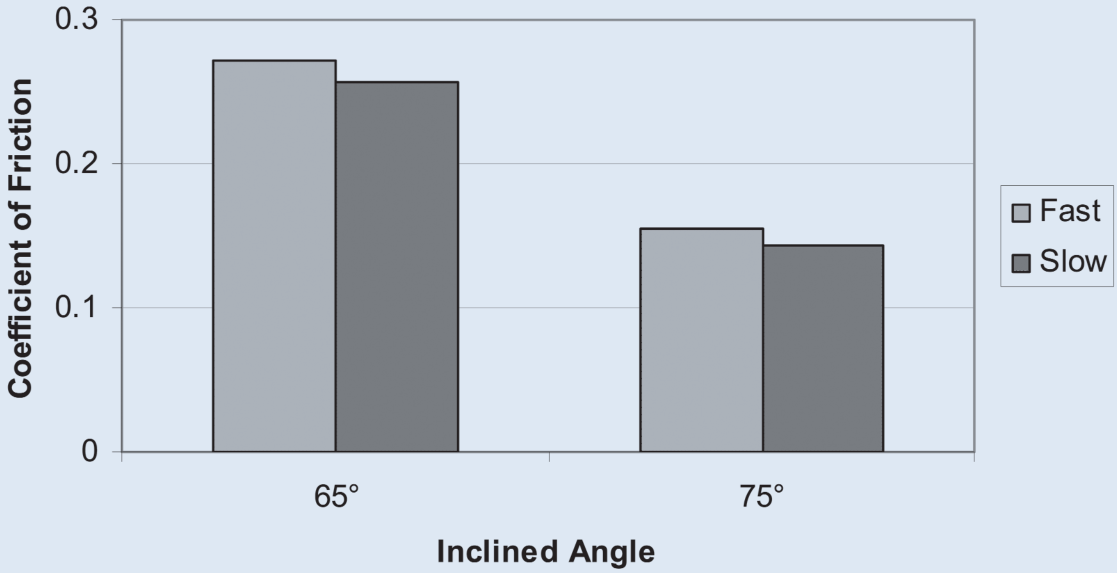
the interface usually reached one of the peaks during a step when the normal force reached a minimum (point 3) between the first and second peaks (points 2 and 4). The COF for the required COF measurement usually reached the maximum due to a lower normal force and a higher shear force at this instant. A step ended at point 5.

Since COF increased as subjects climbed higher on the ladders, the average of the maximum COF of the top three full steps measured with the force plate for each climb was obtained to represent the friction requirement for this climb. Results of the required COF for different levels of each factor evaluated by Chang, et al (791) are shown in Table 1. As a comparison with human locomotion, the required COF is approximately between 0.15 and 0.3 for level walking, and approximately between 0.4 and 0.6 for walking on inclined surfaces (Grönqvist, et al 1167).

The ladder inclined angle appeared to be the most significant factor contributing to differences in the required COF, and the body weight category and climbing speed were the next most influential factors with much less impact when compared with the inclined angle from Table 1. The effects of the inclined angle and climbing speeds on the required COF are graphically illustrated in Figure 3. The required COF at a 65-degree inclined angle was on average 77 percent higher than that at 75 degrees as shown in Table 1. The fast climbing speed used in this experiment led to approximately a 6.5-percent increase in the required COF when compared with the slow climbing speed. The results in Table 1 also indicated that the required COF for subjects in the heavy weight category was less than that for those in the light and intermediate weight categories.

Figure 3

Effects of Inclined Angle & Climbing Speed on COF



The effects of the factors evaluated by Chang, et al (791) on the required COF are not completely independent of each other. Significant interactions between them are shown in Figures 4 and 5.

Available COF

Häkkinen, et al (1) reported the available COF between common ladder shoes and floor surfaces. A static weight of 29 pounds was hung on a ladder to generate the normal force at the interface for measuring the available COF between the ladder base and floor surface. They measured the resistance at the ladder shoe and floor interface with a force plate when the bottom of the ladder was forced to move under the normal force generated with the weights of 29 pounds and ladder.

For safety against a slip, Häkkinen, et al (1) and Pesonen and Häkkinen (6) classified conditions with an available COF greater than 0.7 as good, 0.5 to 0.7 as satisfactory, 0.3 to 0.5 as marginal and less than 0.3 as dangerous. These researchers reported that the rubber antislip shoes had a higher available friction than both the plastic antislip shoe and no-shoe conditions evaluated; however, these types might not be sufficient to support the ladder when oil was present on the floor surfaces. Contaminants on the surfaces, especially oil, could significantly reduce the available friction.

As noted, the available COF obtained by Häkkinen, et al (1) was measured with a static weight of 29 pounds. Häkkinen, et al (1) also reported that the typical normal force at the ladder shoe and floor interface during the required COF measurements was approximately 1.5 to 2.4 times the subject's body weight. By comparison, the weight of 29 pounds was well below typical normal forces generated under normal use of the ladder. Since the normal force can affect the value of the available friction, the available COF reported by Häkkinen, et al (1) should be used with caution.

Discussion

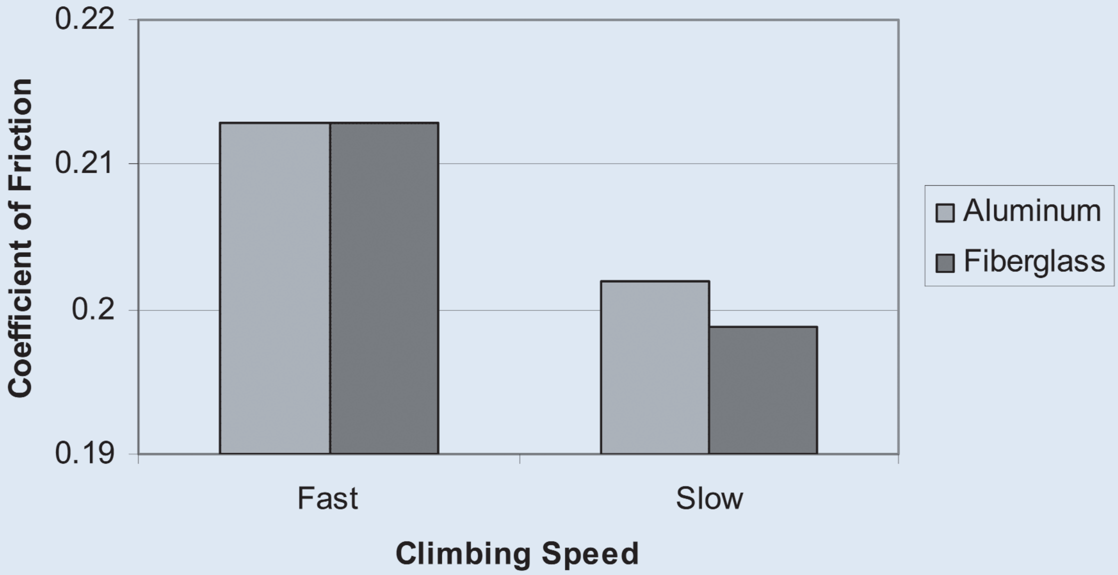
Among the factors evaluated, a ladder's inclined angle appears to have the most significant effect on the required friction at the bottom of a ladder. The data shown in Table 1 indicate that the required COF at a 65-degree inclined angle is on average 77 percent higher than that at 75 degrees. In their study, Young and Wogalter (111) investigated the accuracy of human perception in the ladder inclined angle setup. Sixty-eight lay subjects were asked to set up a ladder at a 75.5-degree inclined angle without using any physical measurement device. The actual angle set up by subjects had a mean of 71.8 degrees and a standard deviation of 4.38 degrees. These results imply that human judgment in the ladder's inclined angle could result in a considerable variation.

Ergonomists and SH&E professionals often recommend a "4:1 ratio" method to set up a straight ladder. This method requires that the working length of the ladder be four times the distance from the ladder base to the wall (Young and Wogalter 111; Bloswick and Crookston 1015). The working length of the ladder is the distance from the bottom of the ladder to the point where it contacts the vertical wall. If done properly, this ratio results in 75.5 degrees of inclined angle as recommended in ANSI A14-1 and A14-2 [ALI(a); (b)].

However, human judgment of distances, especially when subjectively comparing distances in different directions, could lead to a significant variation in the

Figure 4

Interaction Between Climbing Speed & Ladder Type on COF



Source: Chang et al, 791.

Most ladder users are not aware that a small change in the ladder inclined angle could result in a significant difference in the required COF at the base of the ladder.

inclined angle. Young and Wogalter (111) reported the ladder angle with a mean of 73.4 degrees and a standard deviation of 5.67 degrees when subjects were asked to set up the ladder using the 4:1 ratio method. This variation may seem small; however, in considering the 77-percent increase of the required COF when this angle was reduced from 75 to 65 degrees, these potential variations could easily lead to a significant increase in the required COF, and, therefore, increase the potential for ladder accidents.

Additional results reported by Young and Wogalter (111) showed that without instruction subjects generally prefer a shallower inclined angle as compared to recommended inclined angle of 75.5 degrees [ALI(a); (b)]. In this experiment, subjects were told (with no further instruction) to set up the ladder as they would if they were going to climb to the top. Results showed that the ladder inclined angle setup by the subjects had a mean value of 66.9 degrees and a standard deviation of 6.1 degrees.

Unfortunately, it may not be common practice for most ladder users to measure the inclined angle with a proper tool, although such devices could be available. Some ladder manufacturers have affixed an "L" symbol on the side of their ladders to help users. The long arm of the "L" is supposed to stay vertical and the short arm is supposed to be level with the ground. However, it is difficult to align these two arms with no reference.

In addition, environmental factors, such as improper ladder lengths or obstacles on the ground, can prevent proper setup—even if users are aware of the recommended inclined angle. One way to reduce ladder accidents is to raise users' awareness of the potential problems and to develop practical guidelines for proper ladder setup. Objective measurements of the ladder angle using a bubble level (Young and Wogalter 111), a plum-bob device (Bloswick and Crookston 1015), or perhaps either mechanical or electronic angle measurement devices could improve ladder setup as well.

Climbing speed appears to be another important factor in the required COF as the results in Table 1 show. A faster climbing speed resulted in an increase in the required COF, which, therefore, increases the potential for a slip at the base of the ladder. It is critical that the user not rush on the ladder. The data in Table 1 also indicated that the reduced friction condition at the top of the ladder could result in a higher required COF than the normal contact condition. The use of high-friction materials, such as antislip rubber caps, at the top of the ladder can slightly reduce the required COF at the ladder bottoms.

According to the results shown in Figure 5, a slower climbing speed can lead to slightly greater reduction in the required COF due to different top supports than a faster speed. In addition, the fiberglass ladder seems to result in a slightly lower required COF at the bottom of the ladder than the aluminum ladder. The slight difference in the required COF due to different ladder types could result from the higher stiffness of a fiberglass ladder. However, the benefit of using a fiberglass ladder in reducing the required COF was almost eliminated when climbing at a fast speed (Figure 4).

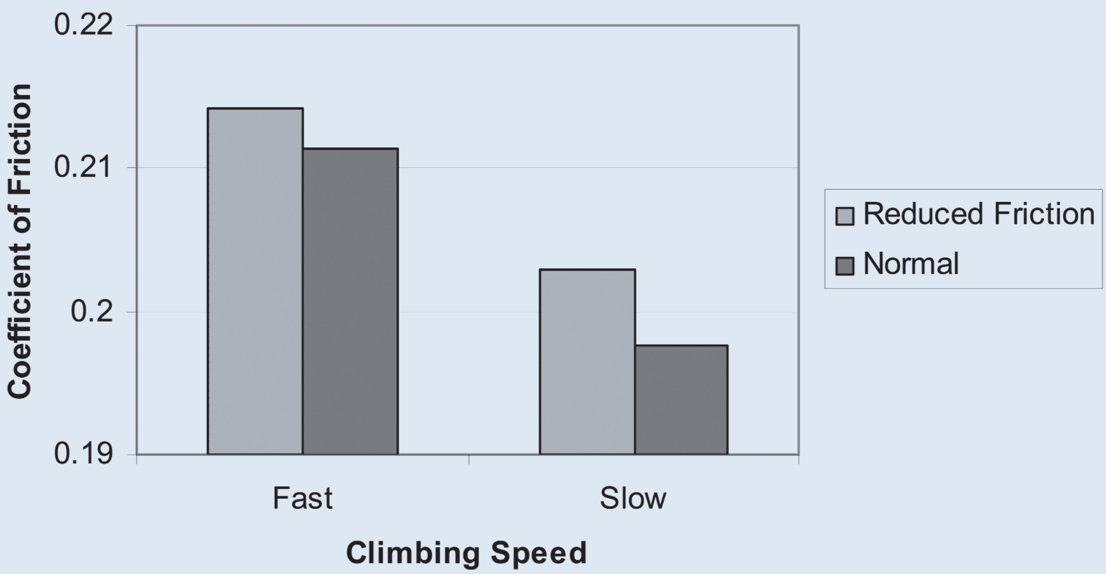
Required COF increased as subjects climbed higher on the ladder (Figure 2). The required COF reported in the literature depends on how high subjects climbed in the experiment. Pesonen and Häkkinen (6) asked subjects to climb to the eighth rung; Chang, et al (791) asked subjects to climb to the tenth rung. The required COF reported was used for relative comparisons among the factors evaluated. It will exceed those values reported by Pesonen and Häkkinen (6) and Chang, et al (791) if the subjects need to climb higher on the ladders.

In general, a ladder will likely slip at its base when the required friction exceeds the available friction. To increase the available friction, antislip ladder shoes should always be used, maintained and replaced as needed. However, Björnstig and Johnson (9) reported that ladders involved in 59 percent of sliding accidents were equipped with plastic or rubber antislip pads that did not completely prevent the sliding. In addition, users should avoid setting up ladders over contaminated areas.

Interventions to reduce the required COF could include a proper inclined angle and a slower climbing speed. Additional interventions include use of antislip materials at the top of the ladder and the use of fiberglass ladders instead of aluminum, although their contributions are more minor when compared with the contributions of the inclined angle and climbing speed.

Figure 5

Interaction Between Climbing Speed & Top Support on COF



Source: Chang et al, 791.

Conclusion

Ladder inclined angle appears to be a critical parameter for friction requirements at the bottom of a ladder. However, most ladder users are not aware that a small change in this angle could result in a significant difference in the required COF at the base of the ladder.

To prevent ladder slips at their bases, practical guidelines are needed to help users properly set up ladders. In addition, users must know not to rush on the ladder and should know to always use antislip ladder shoes. Placing antislip rubber at the top of the ladder or using fiberglass rather than aluminum ladders could also help reduce the required COF at the base of the ladder. ■

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