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# Development of Design Interventions for Preventing Falls from Fixed Ladders


Thomas J. Armstrong, Ph.D.
James Ashton-Miller, Ph.D.
Charles Woolley
Janet Kemp
Justin Young
Hogene Kim

The Center for Ergonomics
The Biochemical Research Laboratory
The University of Michigan



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8484 Georgia Avenue
Suite 1000
Silver Spring, MD 20910

PHONE: 301.578.8500
FAX: 301.578.8572

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# Preventing Falls from Fixed Ladders

## Key Findings and Recommendations

Falls are the leading cause of death among construction workers. Dr. Tom Armstrong and researchers at the University of Michigan Center for Ergonomics studied the hand and foot forces while climbing on fixed ladders. The investigators reported that:

1) Most of the bodyweight is supported by the feet (peak foot force ranges from 94 to 100% of body weight).
2) The hands are necessary to stabilize the body and to prevent falling from vertical or near vertical ladders (peak hand forces ranges from 28 to 39% of body weight)
3) Laterally tilted (sideways) ladders are more difficult to climb and require more time than vertical ladders.
4) Maximum reaches to the side of the ladder required sustained lateral hand forces of 34% of body weight. Exertion of force with free hand would significantly increase the force required to hold onto the ladder.
5) Sliding the hands along the rails is less demanding than climbing from rung to rung.
6) Significantly more force can be exerted to support body weight with a round horizontal rung than a round vertical rail; more force can be exerted to support the body weight with a round vertical rail than a rectangular vertical rail.

<u>Based on these findings, the investigators offered the following recommendations to help prevent falls:</u>

1) Footwear should be selected that prevents the feet from slipping from a rung
2) Mud or snow should be removed from the feet before climbing
3) Designing rungs with tread plate may increase foot traction, but it will reduce hand traction. If other than round rungs are used, then round vertical rails should be provided
4) Round vertical rails provide maximum hand traction when reaching to the side of the ladder.
5) Workers should avoid hurrying and pay attention to foot placement while climbing
6) Workers should not use their hands to carry tools or equipment while climbing
7) Gloves that interfere with grip because they are stiff or slippery should not be used while climbing.
8) Where possible, vehicles should be parked on level surfaces. Special care should be exercised when climbing on tilted vehicles.
9) Ladders should be tilted forward so that workers do not lose their balance and fall backwards if hand contact is lost. Workers should test their balance before climbing past the first rung.
10) Workers should avoid prolonged lateral reaching and exertion of force to prevent fatigue of the hand holding onto the ladder. They also should sudden exertions that could cause them to lose their grip on the ladder.
11) Workers should not perform tasks from a vertical ladder without a safety harness.

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# 1 Summary:

An adjustable ladder was constructed with the side rails and first, second, seventh, and eighth rungs instrumented in order to record the hand and foot forces while climbing. An experiment was conducted to examine postures and forces that might be encountered by persons operating ready mix trucks. Experimental treatments included 1) rung versus rail climbing, 2) ladder pitch (vertical and 10º forward), 3) ladder bank (vertical and 5º right), 4) carrying a toolbox and 5) reaching to the left side of the ladder. Subjects included twelve college-aged subjects ranging from a 5% tile female stature to a 95% tile male stature. Findings and Recommendations:

- Subjects were allowed to choose their own climbing style. As a result there were great inter-subject variations in climbing style. These variations merit further study.
- The average peak resultant foot forces (the vector sum of the forces acting in the vertical, horizontal and lateral direction) for 12 subjects ascending or descending the ladder are (94-100% of bodyweight) were consistently greater than average peak resultant hand forces (28-39% of body weight). Further analysis of data of a subset of data from six subjects showed that the major foot forces were vertical.
- The major hand forces shifted between vertical and horizontal during the climbing cycle. The contact time between the body and the ladder was greater for the hands than for the feet and the subjects did not pick up a foot unless both hands were on the ladder. It appears that subjects tend to instinctively use "three-point climbing." It also appears that the most of the work to lift the body is performed with the feet. The hands help to lift the body, but more importantly stabilize the body so that the worker does not fall over backwards.
- Peak resultant hand forces are significantly less for rail climbing than rung climbing. It appears that rail climbing is less strenuous on the upper body than rung climbing.
- Hand and foot force profiles exhibit two distinct peaks near the beginning and end of the loading period. These peaks follow placement of the foot or hand on the ladder and the release. The mechanism may involve cyclical changes in body inertia in the climbing cycle. They are important because the feet and hands are at greatest risk of slipping during these peak forces.
- An initial force plateau that corresponds to contact between the foot and the rung precedes the initial force peak. It appears that the ankle dorsiflexion at initial contact with the rung signals the climber that the foot is on a rung before committing full force ramp-up. Rung design and training should be explored as possible interventions for prevent applying force before there is adequate contact between the feet and rungs to support the body. Further studies are required to determine the best rung and rail design for the hands and feet. It is unlikely that the best rung design for the feet is the best design for the hands.
- It appears that climbing a ladder tilted sideways is more difficulty than climbing a vertical ladder. Hand cycle times were the longest for the laterally tilted ladders. Foot cycle times were also increased, which indicates subjects climbed more slowly on the laterally tilted ladder than on the vertical ladder. The effects of ladder tilt are a particular concern for ladders mounted on mobile equipment. Further studies should be performed to determine if training workers to take extra time would help reduce fall risk for tilted

ladders. Further studies of ladder tilt should consider the effects of rung spacing, anthropometry and climbing styles.

- Climbing with the toolbox yields the greatest overall peak forces on the hands. This was also reflected in the subject's opinions and indicates that this is a very difficult task. Subjects indicated that climbing with a toolbox was easiest when the ladder was pitched forward 10°. This orientation allows the subject to balance the weight of the body over the ladder rung, which greatly reduces the force required to hold onto the ladder. Tilting ladders forward is a potential intervention for situations – especially if the climber is expected to carry equipment up the ladder.
- The average hand force exerted while reaching laterally off a ladder is between 23-30% of bodyweight, with peak values as high as 34% of bodyweight. These are similar to the forces exerted during climbing. Although these hand forces are well within the climber's capability, they may need to be sustained for a period of time while the climber performs a secondary task. A prolonged exertion at these force levels will lead to fatigue and diminished hand strength.
- Hand forces peak at the beginning and end of the reach. Tilting the ladder forward appears to reduce hand force and should be explored as a possible intervention – especially if the climber is expected to perform a secondary task while on the ladder.
- These results show that some strong subjects can support their full bodyweight with one hand on a 1" fixed steel rung. Most people should be able to support their full body weight with two hands using a 1" steel rung. Few if any people can support their full body weight with one hand using either a 1" diameter rod or a 1" x ¼" bar type rail. Most people should be able to at least briefly support their full bodyweight with two hands using either a rod or bar rail. These results also show that traditional grip strength measures do not predict peoples' ability to hang by their hands well. Further studies should be performed to develop models that can predict the effects of hand strength, rails shape, size and orientation and friction climbers ability support their body with their hands.

## 2 **Investigators (support) contributions:**

Armstrong, Thomas (no cost): Overall project management, coordination and reporting

Ashton-Miller, James (no cost): Assistance with project management, experimental design, data collection and data analysis

Young, Justin (CPWR Pilot Grant Support – NIOSH support): Data collection, analysis and reporting

Kim, Hogene (CPWR Pilot Grant Support): Assistance with data collection, analysis of whole body posture data.

Kemp, Janet (CPWR Pilot Grant Support): coordinate subject recruitment and IRB compliance

Woolley, Charles (CPWR Pilot Grant Support): Design and construction of equipment and software

Sackllah, Michael (UROP): Assistance with data collection and analysis.

J. Nigel Ellis, Ph.D., (Ellis Fall Systems): Advise regarding ladder design specifications and experimental design.

# 3 Introduction

## 3.1 Motivation

Falls from ladders are a major cause of worker injuries and fatalities. More than 20,000 American workers are injured every year by falls from ladders according to the Bureau of Labor Statistics (BLS 2005; Christensen and Cooper 2005). Liberty Mutual's 2005 Workplace Safety Index reported that the direct compensation and medical treatments associated with falls from elevation cost American businesses $4.6 billion. In addition, the indirect costs associated with increased absenteeism, worker replacement and productivity loss can cost up to two times as much as the direct costs, according to a recent survey of corporate financial decision-makers (Christensen and Cooper 2005). Finally, according to the US BLS, fatal workplace injuries due to falls from ladders and roofs increased by 17% in 2004, resulting in a new series high. There were 114 and 133 fatal injuries due to falls from ladders in 2003 and 2004, respectively (BLS 2005). These reports provide information about the frequency and cost of ladder fall injuries, but little information about causal factors.

Examples of ladders and fall hazards are shown in Figure 1. Falls from ladders can result from one or more factors acting together or independently. It is clear that falls are ultimately caused by a decoupling between the worker and the ladder so that workers are unable grasp the ladder and exert sufficient force to prevent falling. Quantifying the forces required to climb a ladder and to recover from a fall, and measuring a worker’s response time and strength capacity, will enable us to identify the hazardous elements of ladder climbing and to design procedural and engineering interventions.


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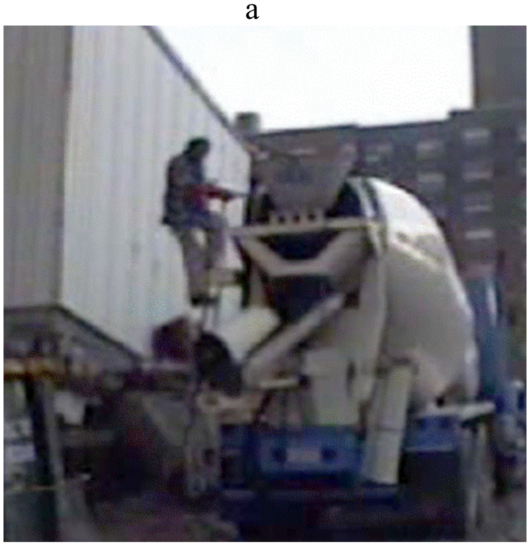

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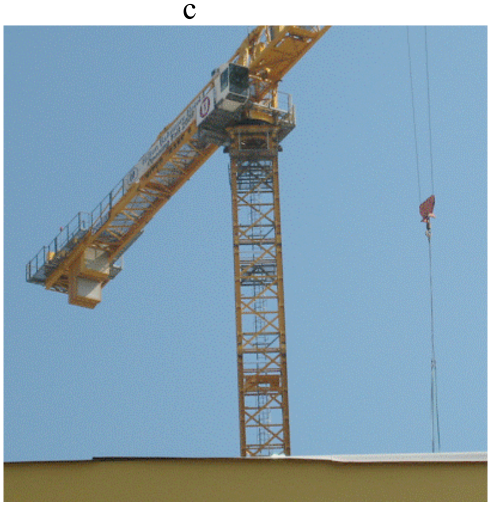

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Figure 1: Examples of fixed ladders and fall hazards: ready mix truck that unloads from front (a), ready mix truck that unloads from rear (b), worker climbing up ladder on ready mix truck with hose in one hand (c), worker sanding on ladder operating controls to unload ready mix truck (d), construction crane (e), worker climbing on fork lift to empty dumpster (f).

## 3.2 Background

There are many common methods of ladder climbing. Studies of the gait pattern of climbing on vertically tilted ladders have shown a large variation of the chosen method (Dewar, 1977; McIntyre, 1983). 'Lateral gait' (where the hands and feet on the same side of the body move together) and 'diagonal gait' (where the hands move with the opposite foot) were reported as the most common methods. Hammer and Schmalz (1992) also reported that there was a variation of climbing method, and that the same person may change climbing methods even within the same ladder climb. Both Dewar (1977) and Hakkinen (1988) observed that subjects often used the ladder rails as handholds as well as the rungs.

It has been shown that there are extended periods of time that only two limbs are in contact with the ladder (McIntyre, 1983). Hammer and Schmalz (1992) observed that three-point contact occurred 37 to 52 percent of the total climbing time on ladders tilted 60º and vertical ladders respectively.

Some studies have described different climbing techniques, but few have thoroughly quantified the climbing forces exerted on the ladder. Hand forces during climbing have been reported in a few studies (Ayoub and Bakken, 1979; McIntyre, 1983), but ladder orientation also varied between studies making the results difficult to extrapolate between scenarios. Bloswick and Chaffin (1990) conducted the most comprehensive biomechanical study to date, reporting climbing forces for both feet and hands on several different vertical ladder slants and rung separations. However, climbing methods only included hands using the rungs and force-time profiles were not reported (Bloswick and Chaffin, 1990).

Though ladders are commonly oriented vertically or tilted vertically, there are several workplace situations where ladders may be titled in more than one plane. For example, when fixed ladders are attached to vehicles, such as Ready-Mix Concrete trucks, attached ladders will be tilted according to the underlying ground. A high rate of injury in these workplace scenarios warrants investigation of climbing on ladders tilted in directions. Additionally, many fixed ladders on heavy equipment require the use of the side rails to climb.

There are many situations where reaching laterally from a ladder is necessary (e.g. painting). And though it is a common activity, it hasn't been studied thoroughly. Some studies have explored lateral reaching on stepladders (Clift and Navarro, 2002; Juptner, 1976) where the ladder may become unstable, however they do not address fixed ladders or the forces applied to the hands. Investigation of this common work activity is warranted.

Our hands are not only important as the primary interface used for climbing, but also as the only interface available to arrest the body after a fall has been initiated. If a person were to begin to fall, the ability for the hand to grasp an object and arrest the falling body provides the primary means of preventing injury; whether it is by grasping a stairway rail, a ladder, or a car handhold.

Barnett and Poczynk (2000) defined three distinct phases in a ladder falling scenario. The first is a freefall phase that is a function of reaction time, the second phase is the time it takes for the victim's muscle forces to increase to a maximum, and the third phase is where the victim decelerates to a stop. However, if the maximum coupling force that the victim's hand can exert on the ladder is smaller than the force of the body's weight and inertia, the victim will fail to arrest the fall. It is therefore important to understand the maximum strength of the couple between a hand and a ladder rung or rails when investigating ladder falls.

There are many studies that examine hand strength, though most are concerned with power grip strength. Power grip strength may be useful for predicting couple for the ladder side rails (the grip produces the friction), but may not address how the mechanical resistance of the fingers and friction acts when the hands are grasping a horizontal rung. Grip strength studies are therefore not suited for extrapolating the hand's ability in many scenarios. For investigation of the coupling between the hand and a ladder rung, quantification of the force need to pull a rung or rail out of the hand is needed. Only one study has measured this directly. Rejulu and Klute (1993) investigated coupling force, or "hand pull strength", for subjects wearing a glove from an astronaut's spacesuit. Using a mechanical device to force a handle from a subject's hand, they found that the coupling force was 1.7 times greater than grip strength on average.

When arresting a fall, the victim may grab onto either the vertical side rails or the horizontal rungs of the ladder. If the victim grasps the side rails of the ladder, the hand gripping force will produce friction against the rail which will act against the force of the falling body. If the rungs are grasped, a power or hook grip will provide the mechanical resistance to arrest the fall. Quantification of hand grasp capability in these different handhold postures may provide insight into the ability to arrest a fall once it occurs.

### 3.3 Specific Aims

The overall aim of this work is to minimize the risk of falls from fixed ladders. More specifically this work aims to conduct pilot studies that will lead to the development of models that describe the relationship between fall risk factors, equipment and task variables so that fixed ladders can be designed and used with minimum risk of falling. This work specifically aims to examine whether workers' abilities to exert forces to hold onto a ladder and their abilities to avert an impending fall is affected by the design of the ladder, the task they are performing, the climbing method they are using, and the environmental conditions.

This pilot project focuses on laboratory studies to evaluate experimental equipment and methods, for collecting pilot data that can be used for statistical power calculations in future studies. It includes discussions with the Center for Protection of Work Rights to explore future intervention studies to apply laboratory findings. Specific objectives of this study will be:

1. Assemble and test an instrumented ladder for measuring hand and foot forces as subjects climb and descend. The ladder will be designed so that rail and rung spacing and rung geometry can be varied. It also will be possible to vary ladder pitch fore and aft and side to side.
2. Assemble equipment for measuring maximum force that can be exerted to hold on to typical ladder handholds and to conduct a pilot study of subject strength.
3. Conduct pilot studies of hand and foot forces while:

   a. Climbing and descending the ladder using a hand over hand method versus sliding hands along the rails
   b. Climbing and descending ladder while carrying an object
   c. Performing a secondary task in which the subject stands on the ladder and performs a maximum lateral reach to one side

4. Conduct pilot study of overhead grasp strength for ladder handholds.
5. Design equipment for measuring grip reaction time and force
1. Develop future research recommendations

## 4 Objective 1: Construct Instrumented, Adjustable Ladder

An instrumented ladder for measuring selected rung and rail forces has been constructed (see Figure 2) to simulate the ladders shown in Figure 1. A center post is mounted on a two-axis joint and supported by outriggers at the sides and back. The bottom of the outriggers can be slid along channels to change the pitch and bank of the ladder. Nine 16” (0.4m) wide rungs are spaced 12” (0.3m) apart (OSHA, 1910.27 Fixed Ladder standards). Ladder rungs and rails are 1-inch diameter cylindrical steel rods and were cleaned with steel wool before testing. The ladder is ten feet long.

The ladder rungs are attached to the ladder frame at the center post. The rungs are mounted on 3-axis force and 3-axis moment transducers (AMTI® MC3 and ATI® Theta). Presently four of the rungs are instrumented – two for the feet (rungs 2 and 3) and two for the hands (rungs 7 and 8). The force transducers for the rungs can be moved between rungs as desired for future experiments. Each end of the rails is attached to the ladder frame via 3-axis force transducers. The outputs from the transducers are combined electronically to provide resultant x, y and z forces on the rails. All force transducers were tested and calibrated before the experiment.

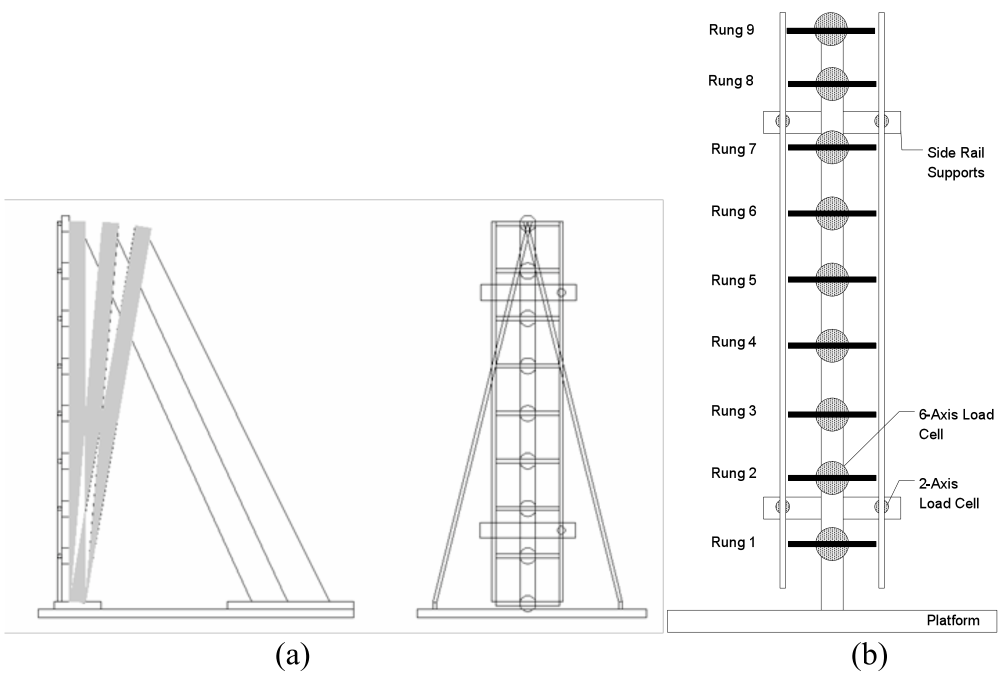
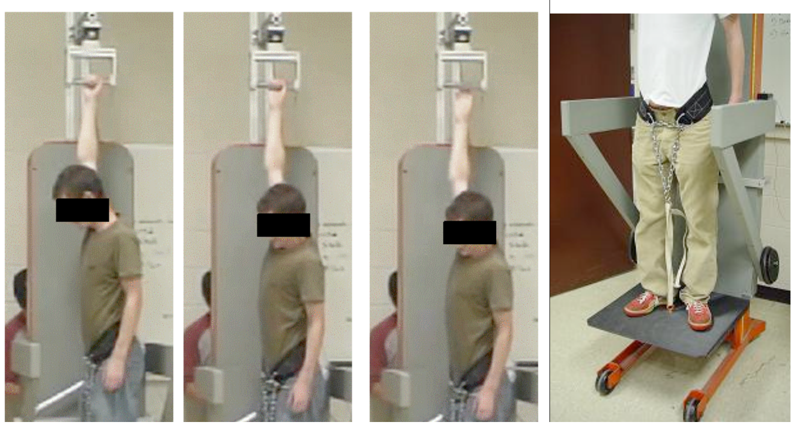



Figure 2: An adjustable ladder was constructed that can be tilted fore and aft (pitch) and side to side (bank) (a). The 2nd, 3rd, 7th and 8th rungs and the vertical rails were instrumented to record horizontal, vertical and lateral (x, y, and z) forces (b). The 2nd, 3rd, 7th and 8th rungs also recorded moments about the x, y and z axes.

A Northern Digital Instruments (Waterloo, Canada) OPTOTRAK® Certus™ infra-red active marker motion tracking system was used to measure selected arm segment kinematics; foot, heel, ankle, knee, hip, shoulder, elbow, wrist, back of hand, and head. A National Instruments USB-6218 32-channel data acquisition system, sampling at 110 Hz, was used for acquiring data in experiments in which hand force data were collected. Software provided with each system was used for the acquisition and to synchronize the measurements. LabView, MatLab, and MiniTab were used for data processing.

## 5 Objective 2: Construct Equipment for Measuring Coupling Strength

For the overhead grasp capability tests (objective 3), single-hand coupling strength to a rail or rung could be measured by subjects pulling on a handle that represents the rail or rung. However, it is desired for the task to be as realistic as possible and for subjects to demonstrate their maximum capacity without risk of injury. Initially it was planned to have subjects sit and pull against a handle using their legs for support. However, it was found that it was not possible to determine if the legs, back, shoulders or hands were the limiting strength factor, therefore the protocol was changed. Subjects now stand on a platform and hold an instrumented rung or rail mounted overhead with one hand (Figure 3).



a b c d

Figure 3: Coupling strength measurement. Subject fails to support his weighted body using the overhead handle after the foot platform is lowered (a-c). The stationary handle is mounted on a force transducer that measures vertical forces exerted by the hand. The subject is attached to the platform with a belt (d).

A weighted, height-adjustable platform (a modified passive hydraulic lift truck) was used to raise and lower each subject. An instrumented handle was fixed overhead above the platform. A weightlifter's dipping belt was used to secure the subject to the platform so that they could not flex their ankles or be lifted off the platform. Before each experiment, weights were attached to the sides of the platform to keep the combined weight of the subject and platform constant at 280 pounds. This insured that the lowering speed of the platform was constant (5.5 in/sec) and that full strength capability would be reached. A six-axis load cell (AMTI® MC-3), amplifier, data acquisition card (National Instruments USB-6008), and LabVIEW™ software were used to record forces (sampled at 100 Hz) exerted on the handle.

Three different handles were constructed for this experiment. Two vertically oriented handles simulated typical ladder rails (a 1" diameter cylinder and a 2½"× 3/8" plate). The third handle was a 1" diameter horizontally oriented cylinder that simulated a typical ladder rung. Handles were easily interchangeable and were cleaned before each session. A Jamar™ grip dynamometer (position 2, 4cm span) was used to measure the subject's grip strength. A video camera was used to record hand motion during each trial and was synchronized with the force recordings.

# 6 Objective 3: Conduct pilot studies of hand and foot forces while using ladders

## 6.1 Ladder Climbing (Ascending and Descending)

### 6.1.1 Methods

Twelve subjects (Table 1) recruited from the University community were tested climbing an instrumented ladder under conditions shown in Table 2. After collection of anthropometric and grip strength data, subjects were fitted with laboratory-supplied sneakers (New Balance™) and a climbing harness. Subjects were instructed to climb hand-over-hand at a comfortable pace up the ladder until their feet were on the $4^{th}$ rung, pause for 3-5 seconds, and then descend the ladder. Subjects were allowed to practice once before data collection began, but no further instruction was given as to specific climbing method. A fall arrestor was attached to the climbing harness during trials.

**Table 1: Ladder climbing subject statistics (n=12)**

| Subject # | Gender | Height (m) | Weight (kg) | Age(yrs) | Grip Strength Right (kg) | Grip Strength Left (kg) | Reach Span (cm) |
|---|---|---|---|---|---|---|---|
| 2* | F | 1.62 | 55.8 | 28 | 37 | 33 | 136 |
| 5* | F | 1.68 | 70.3 | 24 | 35 | 40 | 149 |
| 6 | F | 1.57 | 65.8 | 27 | 40 | 38 | 136 |
| 7* | F | 1.68 | 59.0 | 20 | 36 | 33 | 145 |
| 11 | F | 1.65 | 63.5 | 22 | 34 | 32 | 142 |
| 12 | F | 1.50 | 54.4 | 29 | 40 | 34 | 127 |
| | Females | 1.62 ± 0.07 | 61.5 ± 6.1 | 25 ± 4 | 37 ± 3 | 35 ± 3 | 139 ± 8 |
| 1 | M | 1.83 | 86.2 | 28 | 60 | 61 | 166 |
| 3* | M | 1.72 | 63.0 | 36 | 48 | 46 | 150 |
| 4* | M | 1.75 | 82.0 | 29 | 61 | 50 | 154 |
| 8* | M | 1.83 | 70.3 | 27 | 65 | 56 | 165 |
| 9 | M | 1.73 | 79.4 | 24 | 58 | 52 | 154 |
| 10 | M | 1.96 | 97.5 | 24 | 80 | 59 | 179 |
| | Males | 1.80 ± 0.09 | 79.7 ± 12.1 | 28 ± 4 | 62 ± 10 | 54 ± 6 | 161 ± 11 |
| | All | 1.71 ± 0.12 | 70.6 ± 13.2 | 27 ± 4 | 49.5 ± 14.9 | 44.5 ± 10.9 | 151 ± 15 |

* subjects with complete load and unload cycles for both hands and included in data subset

There were three ladder orientations: vertical (0°), vertical tilted (10° pitch), and lateral tilted (5° right tilt). Subjects climbed the ladder with either the rungs only or the rails only, or with a 10 lb toolbox in their non-dominant hand. (All subjects were right handed.) There were 3 repetitions for each treatment yielding a total of 30 ascend/descend climbing trials and 6 lateral reach tests. Trial order was randomized. The dependent variables measured in the study were orthogonal forces on the four rungs and orthogonal forces on the two rails, as well as tracking of joint segment movements. The lateral reach test results will be presented separately from the climbing trials, as this task is fundamentally different than climbing.

**Table 2: Ladder climbing experimental trials**

| Ladder Orientation | Vertical (0°) | 10° forward tilt | 5° right tilt |
|---|---|---|---|
| Treatments<br>(3 repetitions each) | Climb w/rungs<br>Climb w/rails<br>Climb w/toolbox<br>Reach test | Climb w/rungs<br>Climb w/rails<br>Climb w/toolbox<br>Reach test | Climb w/rungs<br>Climb w/rails |

### **6.1.2** Results & Discussion

#### *6.1.2.1 Climbing methods*

In general, there was subject variation in the observed climbing method. Subjects were only instructed to climbing hand over hand at a comfortable pace; otherwise each subject was free to climb as they felt comfortable. For example, taller subjects would often skip rungs with their hands because they could reach a higher one as they climbed. Because only two hand rungs (the 7$^{th}$ and 8$^{th}$ rung) were instrumented, subjects who skipped rungs didn't always grasp the instrumented rung. Correspondingly, the shorter subjects often did not reach higher than the 8$^{th}$ rung and thus stopped their climbing cycle while holding an instrumented rung. When examining force data, it was important to keep these methods in mind in order to make meaningful comparisons. A subset of six subjects who all climbed past the 7$^{th}$ and 8$^{th}$ rungs was selected for detailed analysis (see Table 1). Additional analysis will be performed on the remaining subjects to assess the hand and foot forces at specific times in the climbing cycle and to assess the effects of climbing.

For climbing with a toolbox, it was necessary to relax the hand over hand climbing method constraint. Subjects found this condition too difficult. For these trials subjects were instructed to use whatever method was necessary to climb up and down the ladder safely. They were also instructed to not wrap the toolbox around the back of ladder and to only use their free hand to climb.

#### *6.1.2.2 Sample climbing data*

The photos of Subject 12 and the corresponding hand and foot forces in Figures 4 and 5 illustrate the climbing trials and apparatus for climbing with the rungs and rails respectively. Force data for the hands on the rails is recorded for the entire duration of the climbing task. Note in Figure 5 that because the rails are continuous, the subject is not constrained by the dimensions of the rung spacing when climbing.

## Rung Climbing – Vertical

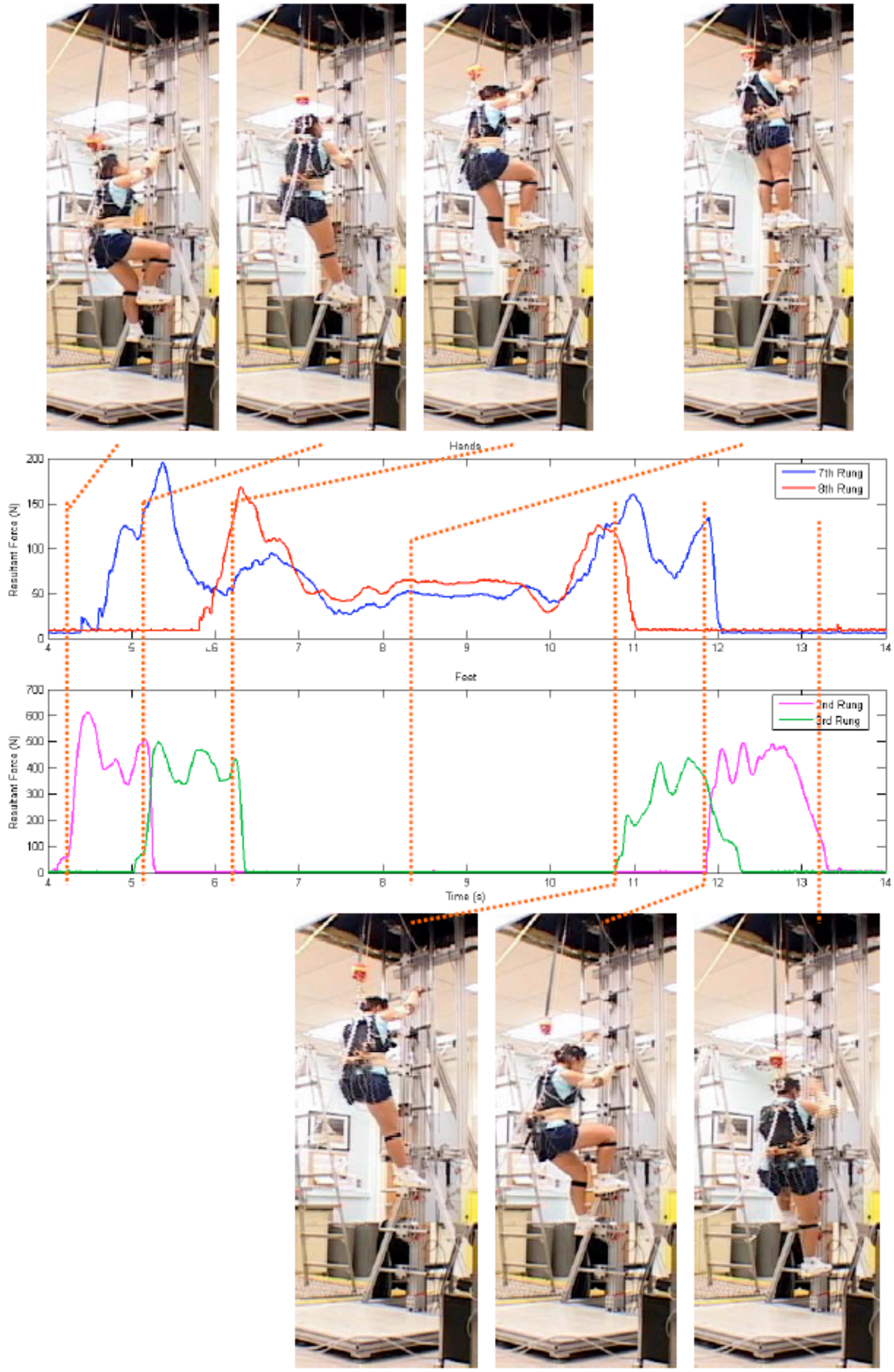



Figure 4: Climbing with the rungs on a vertical ladder (Subject 12). Dashed lines indicate the time on the force plots (total resultant force) when the connected picture was taken. In this trial, the subject pauses while holding both the 7th and 8th rung and does not pass the 8th rung.

**Rail Climbing -- Vertical**

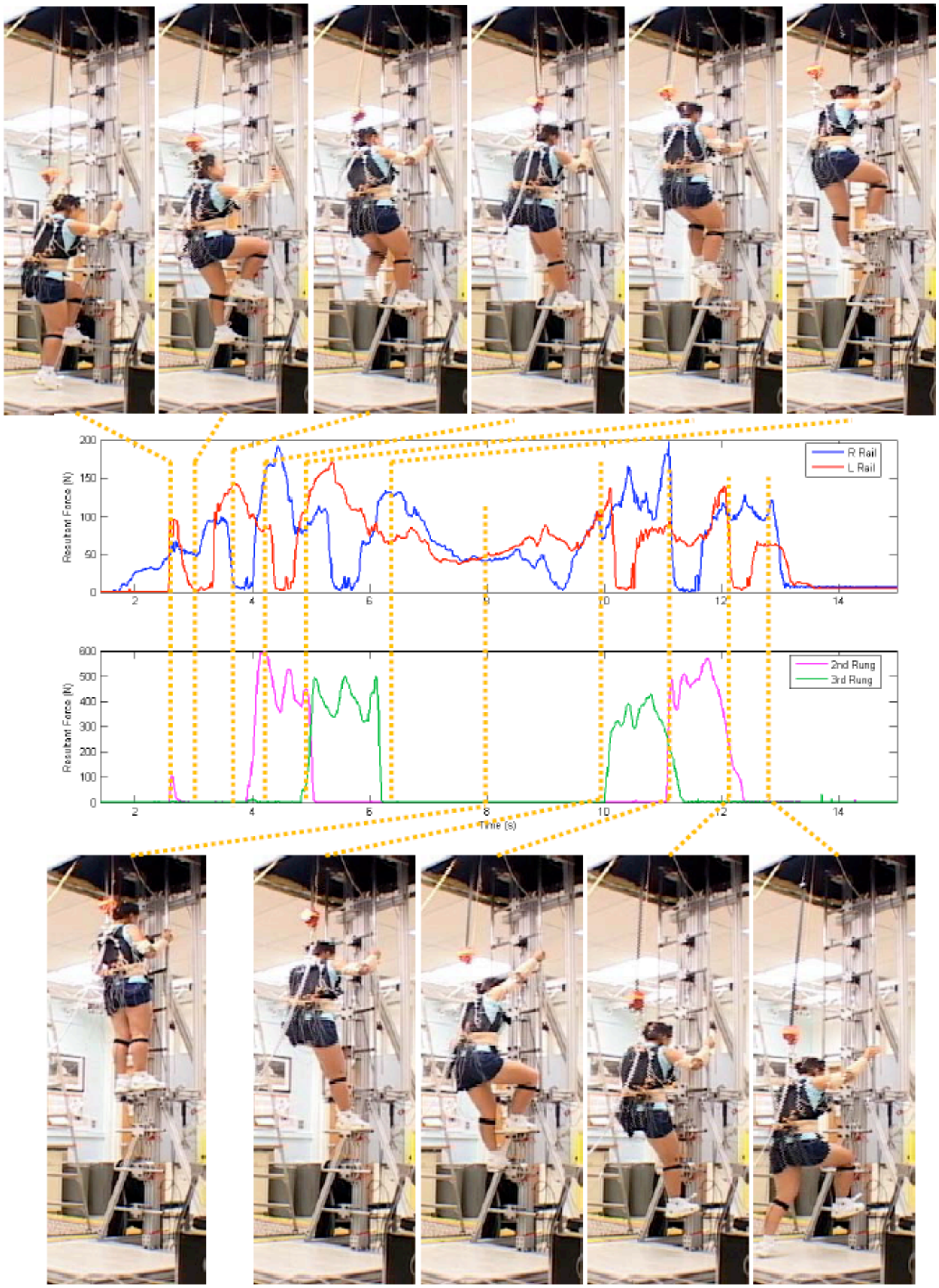



Figure 5: Climbing with the rails on a vertical ladder (Subject 12). Dashed lines indicate the time on the force plots (total resultant force) when the connected picture was taken.

Figures 6 and 7 illustrate data from Subject 5 using rung and rail climbing respectively. It can be seen that the force between the ladder and the body follows a cyclical pattern. The force builds up to a maximum as the hand or foot contacts the ladder and then drops to zero as when the hand or foot reaches for the next rung or next position on the rail. In Figure 6 the subject climbs past rungs 7 and 8 so that complete load/unload cycles are obtained for the right and left hand. Dashed lines indicate the predicted unload and load patterns for the $1^{st}$ and $4^{th}$, $7^{th}$ and $9^{th}$ rungs. Predictions are based on the assumption that during steady state climbing the hand and foot forces follow a consistent pattern. They are shown only to give a complete picture of how the forces are transferred between the hands and the feet. (In future studies it will be desirable to instrument additional rungs.)

Preliminary observations show that most subjects tend to alternate between movements of the right and left side of the body during rung climbing. Additional analyses of the posture and force data will be performed to evaluate inter subject differences in rung climbing style. Figure 7 shows the load/unload patterns for the rail climbing. These loading profiles will be examined individually. Preliminary analysis shows clear overlap between each hand and each foot transition. Both hands grasp the rails as the feet transition between the rungs. Additional analyses of the posture and force data will be performed to evaluate inter subject differences in rail climbing style.

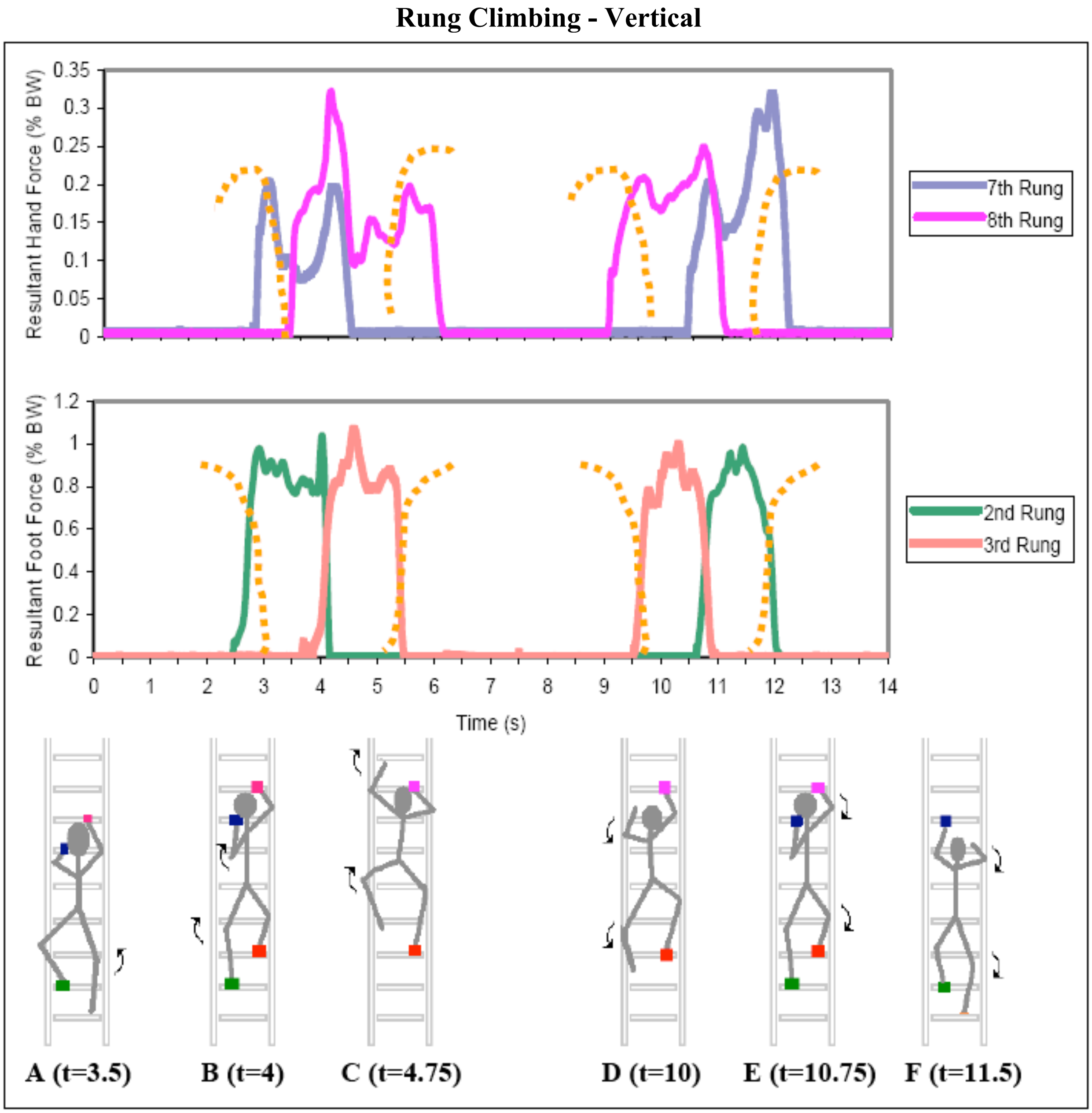



Figure 6: Typical results from a ladder climbing trial (Subject 5). This subject is climbing a vertical ladder using the rungs. Resultant hand forces (7th and 8th rung) are shown in the top graph; resultant forces for feet (2nd and 3rd rung) are shown on the bottom graph. The dashed lines show what the forces would look like if the rungs before and after the instrumented rungs were also instrumented. Ascending: A. The subject has one foot on the rung 2 and has both hands on the instrumented rungs (7 and 8). B. Four points of contact on the ladders instrumented rungs. This only occurs for a very short duration when the load is being transferred from the left hand and foot to the right. C. The subject moves the left hand and foot to higher rungs. There are only two points of contact on the ladder (rungs 3 and 8). Descending: D. The subject moves the left hand and foot to lower rungs. There are only two points of contact on the ladder (rungs 3 and 8). E. Four points of contact on the ladder on all instrumented rungs. This only occurs for a very short duration when the load is being transferred from the right hand and foot to the left. F. The subject has one foot on the 2nd rung and has the left hand on the 7th rung. The right hand and foot are moving to lower rungs.

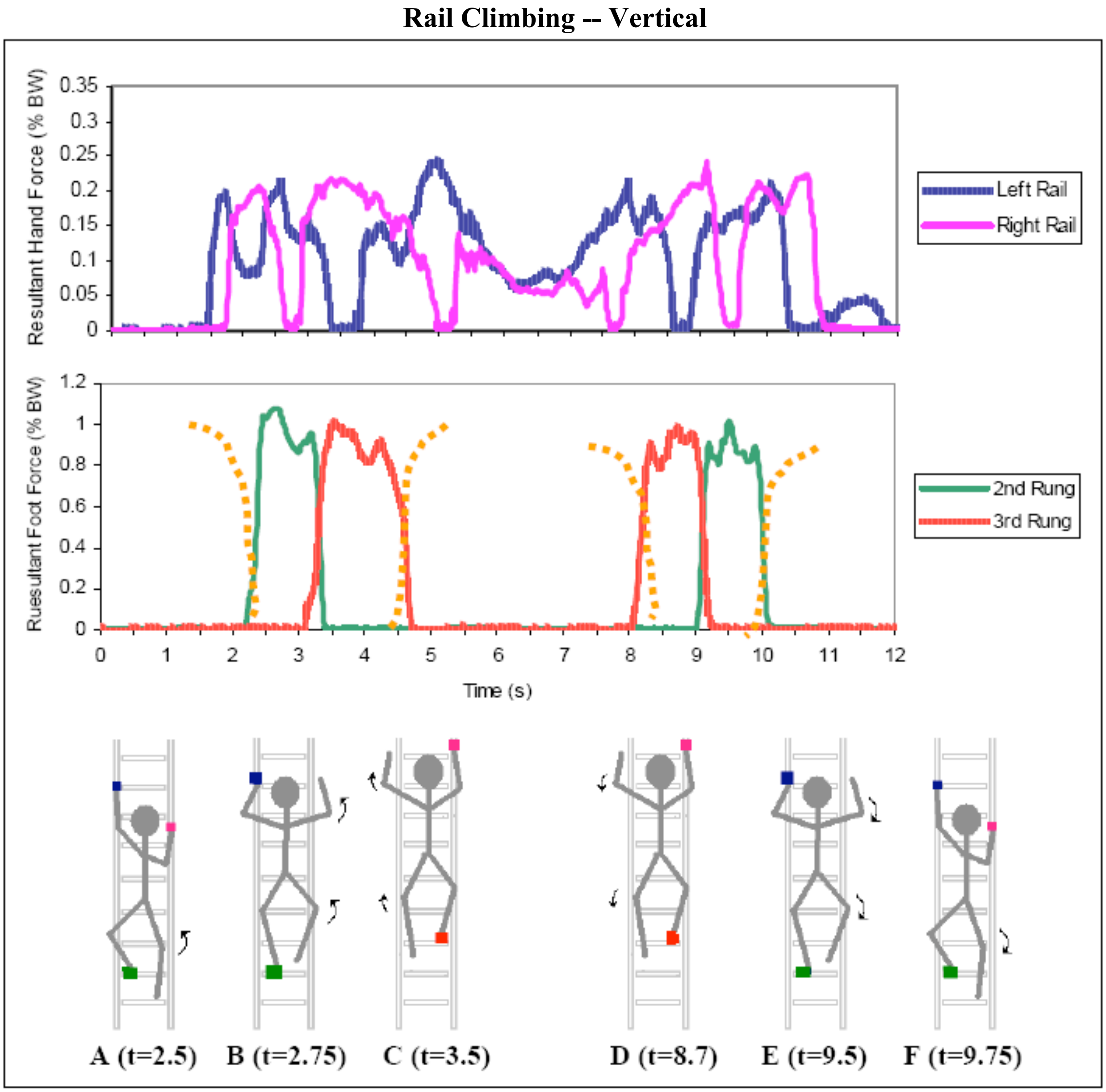



Figure 7: Typical results from a ladder climbing trial (Subject 5). This subject is climbing a vertical ladder using the side rails. Resultant hand forces (right and left rails) are shown in the top graph; resultant forces for feet (2nd and 3rd rung) are shown on the bottom graph. The dashed lines show what the forces would look like if the rungs before and after the instrumented rungs were also instrumented. Ascending: A. The subject has one foot on the rung 2 and has both hands on the rails, moving the right foot to the 3rd rung. B. The subject moves the right hand and foot higher. There are only two points of contact on the ladder (rung 2 and the left rail). C. The subject moves the left hand and foot to higher rungs. There are only two points of contact on the ladder (rungs 3 and the right rail). Descending: D. The subject moves the left hand and foot to lower rungs. There are only two points of contact on the ladder (rungs 3 and the right rail). E. The subject moves the right hand and foot to lower rungs. There are only two points of contact on the ladder (rungs 2 and the left rail). F. The subject has one foot on the 2nd rung and has both hands on the rails. The subjects is about to step on the 1st rung.

*6.1.2.3 Peak Climbing Forces (all subjects, n=12 – Table 1)*

One method of quantifying the difficulty of a climbing scenario is to compare the maximum peak force that the subject exerted on the ladder while climbing in that scenario. Increased hand force is associated with localize fatigue, repetitive trauma disorders of the hand and wrist, and increased fall risk.

The inward/outward (z) force transducer for the right rail failed when the ladder was pitched forward 10°. Consequently, it was not possible to compute resultant hand forces for the right rail so only left hand data are reported for the 10° pitch condition. Additionally it means that it is not possible to analyze hand forces for rail climbing with the toolbox for the pitched ladder. All subjects used their left hand to carry the toolbox and their right hand to grasp the rail.

Table 3 shows the averages and standard deviations for the peak hand force that occurred during the ladder climb (up or down) for either hand for all 12 subjects. A repeated measures ANOVA was performed on the peak hand force data and it was found that both the ladder tilt ($p<0.001$) and climbing method (rungs/rails) ($p<0.001$), as well as their interaction ($p=0.038$) had a significant effect on the peak resultant force observed. **Peak forces on the hands were lower for climbing with the rails than with the rungs for all ladder orientations** (10-15% bodyweight). **Climbing with the toolbox resulted in higher hand forces on the vertical ladder for both rungs and rails** (2% bodyweight for rungs and 13% bodyweight for rails on vertical ladder). For the ladder tilted forward, the peak forces exerted on rungs were slightly lower while carrying a toolbox. One explanation for this is that the weight of the toolbox is forward of the center of pressure on the foot so that weight of the toolbox causes the worker to lean towards the tilted ladder. Further analyses of body postures will be performed to test this hypothesis.

**Table 3: Mean peak resultant hand force (% bodyweight) exerted by either hand during the climbing task for all subjects, n=12 (Table 1)**

| | Vertical (0°) | 10° Forward Pitch | Lateral Tilt (5° Bank) |
|---|---|---|---|
| Climb Rungs | 0.424 ± 0.084 | 0.437 ± 0.110 | 0.468 ± 0.103 |
| Climb Rails | 0.322 ± 0.040 | 0.284 ± 0.056* | 0.338 ± 0.044 |
| Toolbox Rungs | 0.445 ± 0.071 | 0.433 ± 0.089 | -- |
| Toolbox Rails | 0.453 ± 0.104 | -- | -- |

* left rail forces only

The values shown on Table 3 are averages of the peaks observed for three trials of twelve subjects for each condition. The standard deviations range from 15-25% of the mean. This implies that there is significant variability among trials and subjects. For example, the average hand force for rung climbing with 10° pitch is 43.7% of bodyweight; the corresponding ninety-five percentile hand force is 61.7% of bodyweight. These differences could affect workers ability to hold onto the ladder and their risk of falling in one case versus another. Further analyses will be performed to examine inter and intra subject hand and foot force variations.

The highest forces were found when climbing while carrying a toolbox. After the experiment, subjects were informally questioned about the difficulty of climbing with the toolbox. **Subjects consistently responded that climbing with the toolbox was easiest when the ladder was**

**pitched forward 10° and the most difficult ladder was vertical (0° pitch). Most subjects agreed that climbing with the rail was more difficult than with the rungs while holding the toolbox.** This observation appears to agree with the peak hand forces shown in Table 3 for rung and rail climbing with the toolbox on the vertical and pitched ladder. Rung climbing with one hand means that the climbers' feet are in contact with the ladder during the reach to the next rung. We believe that one-handed climbing is less safe than two-handed climbing and we will perform additional analysis of posture and force data to identify possible interventions for reducing fall risk.

*6.1.2.4 Peak Forces during Load/Unload Cycles (data subset, n=6)*

In addition to peak forces, the forces exerted on rungs and rails by the climber has been examined over the time-course of a complete load/unload exertion cycle for both hands and feet as shown in Figures 6 and 7. Because this analysis requires a complete load/unload cycle representative of the normal climbing gait (subjects needed to climb past the $7^{th}$ and $8^{th}$ rung while still climbing and not stopping on them), a subset of subjects (refer to Table 1) was chosen for this more detailed analysis. Mean subject statistics for this data subset are shown in Table 4. Ascending and descending forces were examined for the vertical (0°) and laterally tilted (5° right bank) ladder orientations.

**Table 4: Descriptive statistics for the subset of 3 female and 3 male subjects with complete load and unload climbing cycles on the $7^{th}$ and $8^{th}$ rungs (n=6)**

| | | Height (m) | Weight (kg) | Age (yrs) | Grip Strength Right (kg) | Grip Strength Left (kg) | Reach Span (cm) |
|---|---|---|---|---|---|---|---|
| N=3 | Females | 1.66 ± 0.03 | 61.7 ± 7.6 | 24 ± 4 | 36 ± 1 | 35 ± 4 | 143 ± 7 |
| N=3 | Males | 1.77 ± 0.06 | 71.8 ± 9.6 | 31 ± 5 | 58 ± 9 | 51 ± 5 | 156 ± 8 |
| N=6 | All | 1.71 ± 0.07 | 66.7 ± 9.5 | 27 ± 5 | 47 ± 13 | 43 ± 9 | 150 ± 10 |

Independent variables and levels included in the subset study are as follows:

Ladder tilt: vertical (0°), lateral tilt (5° bank, clockwise)
Climb method: hands on rungs, hands on side rails
Climb direction: up, down

Table 5 shows the average peak hand force that occurred at any point during the ladder climb (up or down) for either hand for the subset of six subjects. This is the same calculation as was used for Table 3, but for only the subset of six subjects in the subset.

**Table 5: Mean peak resultant hand force exerted anytime during the climbing task (% bodyweight) for data subset, n=6**

| | Vertical (0°) | 10° Forward Pitch | 5° Lateral Tilt |
|---|---|---|---|
| Climb Rungs | 0.442 ± 0.087 | 0.326 ± 0.104 | 0.478 ± 0.100 |
| Climb Rails | 0.326 ± 0.049 | 0.284 ± 0.056* | 0.350 ± 0.054 |

*left rail forces only

For this subset, we have divided the climbing cycle into ascent and descent and analyzed the peak forces for each of those phases. In addition, the data can then further be divided into the peak forces exerted with each hand (left and right rail, or $7^{th}$ and $8^{th}$ rung). Maximum climbing forces were recorded for each ascent and decent and on each rung or rail (which corresponds to each foot or hand). Maximum forces were averaged over each of the hands or feet and normalized by the subject's bodyweight. This can be thought of as the average maximum load that would typically occur during a load/unload cycle on a rung or rail as the subject ascends or descends the ladder. This value is not the same as the overall peak force reported in Table 4, which was based on a single greatest peak for the entire trial.

The values in Tables 6 and 7 are based on the average of the peaks for each load/unload cycle as can be seen in Figure 6. Normalized maximum foot forces ranged from 0.73 to 1.43 over all ladder-climbing trials and normalized maximum hand forces ranged from 0.15 to 0.69 over all ladder climbing trials. Average maximum foot forces do not change significantly across treatments, though forces during descent are slightly lower than during ascent (Table 6). The foot forces are conspicuously higher than hand forces and suggest that most of the work to elevate the body is performed with the lower extremities. Measured average peak foot forces in this study were also larger than reported by Bloswick and Chaffin (1990), though they were similar to those reported by McIntrye *et al.* (1983). Average maximum foot forces were smaller during descent, which would agree with inertial characteristics of ascent and descent.

**Table 6: Average maximum resultant foot force (% bodyweight) during cycle for data subset, n=6**

| | Climb w/ Rungs | | Climb w/ Side Rails | |
|---|---|---|---|---|
| | Ascent | Descent | Ascent | Descent |
| Vertical (0°) | 1.05 ± 0.15 | 0.97 ± 0.11 | 1.00 ± 0.11 | 0.96 ± 0.12 |
| Lateral Tilt (5° Bank) | 1.01 ± 0.13 | 0.95 ± 0.11 | 1.00 ± 0.14 | 0.94 ± 0.12 |

**Table 7: Average maximum resultant hand force (% bodyweight) during cycle for data subset, n=6**

| | Climb w/ Rungs | | Climb w/ Side Rails | |
|---|---|---|---|---|
| | Ascent | Descent | Ascent | Descent |
| Vertical (0°) | 0.34 ± 0.01 | 0.36 ± 0.12 | 0.29 ± 0.04 | 0.29 ± 0.05 |
| Lateral Tilt (5° Bank) | 0.32 ± 0.07 | 0.39 ± 0.16 | 0.31 ± 0.06 | 0.28 ± 0.06 |

Average maximum hand forces are lower for rail climbing than for rung climbing (see Table 7). Average peak hand forces are more variable (standard deviation 0.12-0.16) for descending with rungs than for any other condition (standard deviation 0.01-0.07). Peak resultant hand forces were not much different for the laterally tilted ladder than for the vertical ladder. This study found that average resultant peak hand force on the rungs for climbing vertical ladders was 34-36% of bodyweight. This result is higher than the 30% peak hand force reported for vertical ladders by Bloswick and Chaffin (1990). It is very close to the 36% value reported by Ayoub and Bakken (1978). Higher levels of force in the hands during climbing may be dangerous in situations where friction is low, such as during inclement weather.

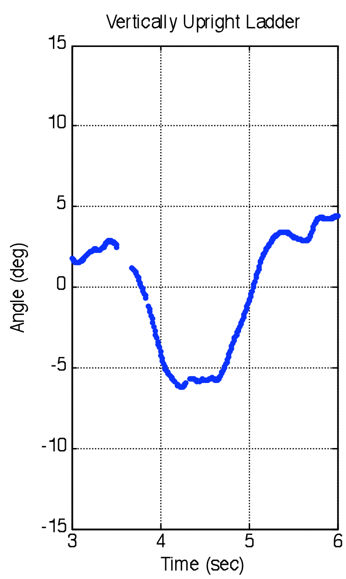
Climbing with the side rails has not been previously studied. Our data show that the average peak resultant hand forces both in the overall data pool (Table 3) and the subset (Table 5 and 7) are lower for rails than for rungs. Correspondingly, average peak foot forces are greater when the rails are used for hand support than when the rungs are used (Table 6). This means that when climbing with the rails, more of the work to elevate the body comes form the lower extremities than when climbing with rungs. Because the ladder rails are continuous, subjects may grasp the ladder at any vertical level they feel is comfortable. When climbing with the rungs, however, subjects are constrained by the rung spacing. This may influence how the subject shares forces between the hands and the feet. Using the rails produces less stress on the hands. Foot-rung interaction may provide a possible intervention for reducing fall risk.

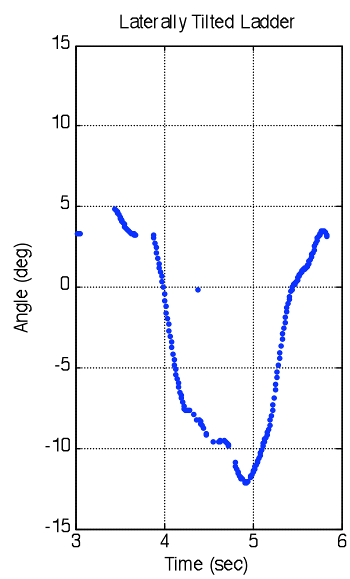
For the laterally tilted ladder (5º right bank), mean peak hand forces are higher (5-9% of bodyweight) for the left side rail than the right side rail both during ascent and descent (Table 8). This effect is not seen in the vertical ladder (Table 8). The effect of lateral ladder tilt has not been previously reported and has important implications to ladders used on equipment that are not always parked on level ground.

**Table 8: Average maximum resultant hand force using the side rails only (% bodyweight) during cycle for data subset, n=6**

| | Left Side Rail | | Right Side Rail | |
|---|---|---|---|---|
| | Ascent | Descent | Ascent | Descent |
| Vertical (0°) | 0.30 ± 0.05 | 0.27 ± 0.05 | 0.29 ± 0.03 | 0.30 ± 0.04 |
| Lateral Tilt (5° Bank) | 0.33 ± 0.05 | 0.33 ± 0.04 | 0.28 ± 0.03 | 0.24 ± 0.04 |

To investigate the effect of ladder tilt on right and left hand forces, the angle of the torso was examined as subjects climbed (Figure 8). If the subjects keep their body upright when climbing, it may cause them to use the near side rail (left rail in this case) to bear more load than the far rail. Figure 8 shows that the torso moves farther toward the tilted side (right) in the right laterally tilted ladder than vertically upright ladder. However, subjects tried to move the torso back to upright position immediately after stepping up one rung. Further analysis of the kinematics is needed to fully determine why a difference in left and right rail hand forces is observed in this ladder orientation.




(a) (b)

Figure 8: An example of torso angle side to side in transverse plane for a subject climbing a vertical ladder (a) and a 5° right laterally tilted ladder (b). Both plots are for the one cycle of climbing one rung in the ladder. The torso angles are calculated from the center points between right and left Acromion (shoulder) and between left and right Greater Trochanter (hip).

*6.1.2.5 Hand and Foot Force Periods (data subset, n=6)*

Tables 9 and 10 show the average duration of foot and hand force that was observed during each climb cycle. For trials where the subject climbed with the side rails, a single force profile from the steady-state climbing period (i.e. not at the beginning or end of an ascent or descent) was chosen. Starting and ending times corresponded to that time at which the force on the rung or rail increased from zero and decreased to zero. The average force period for the feet, hand/rungs, or hands/rails varies with climbing method and ladder tilt. Mean foot force period are longest for ascending laterally tilted ladders and shortest for descending using the rungs (Table 9). Mean hand force periods are longer for climbing using the rungs rather than the rails. The longest mean hand force cycle times were observed for climbing with the rungs on the laterally tilted ladder (Table 10). Based on the duration of the force periods, it appears that subjects were much more deliberate about placement of their hands and feet for 1) rung climbing with the laterally tilted ladder than for the vertical ladder, 2) rung climbing and descending the laterally tilted ladder than for rails rail climbing, and 3) for climbing than for descending. Further analyses will be performed to examine the temporal relationship between hand and foot forces for different conditions and climbing styles and their relationship with falls and recoveries. Additional analysis of the posture data will be performed to determine the total cycle time and climbing rates for each condition.

**Table 9: Mean cycle time (s) for foot loading/unloading profiles for data subset, n=6**

| | Climb w/ Rungs | | Climb w/ Side Rails | |
|---|---|---|---|---|
| | Ascent | Descent | Ascent | Descent |
| Vertical (0°) | 1.58 ± 0.35 | 1.58 ± 0.39 | 1.57 ± 0.46 | 1.50 ± 0.33 |
| Lateral Tilt (5° Bank) | 1.75 ± 0.55 | 1.56 ± 0.44 | 1.65 ± 0.79 | 1.51 ± 0.35 |

**Table 10: Mean cycle time (s) for hand loading/unloading profiles for data subset, n=6**

| | Climb w/ Rungs | | Climb w/ Side Rails | |
|---|---|---|---|---|
| | Ascent | Descent | Ascent | Descent |
| Vertical (0°) | 2.26±0.89 | 2.12±0.51 | 1.93±0.63 | 1.76±0.39 |
| Lateral Tilt (5° Bank) | 2.46±0.77 | 2.40±0.50 | 2.00±0.61 | 1.87±0.52 |

*6.1.2.6 Force Profiles (data subset, n=6)*

To examine force profiles (during the period that the hand or foot is in contact with the ladder) across subjects and treatments, the force data was sampled at 50 evenly spaced points over the total cycle time for each profile. Normalized force profiles were averaged over all subjects and for each set of force transducers (foot rungs 2 and 3, hand rungs 7 and 8, and hand rails L and R). Force profiles for ascending and descending the vertical ladder are presented in Figure 9. Force profiles for the laterally tilted ladder are presented in Figure 10.

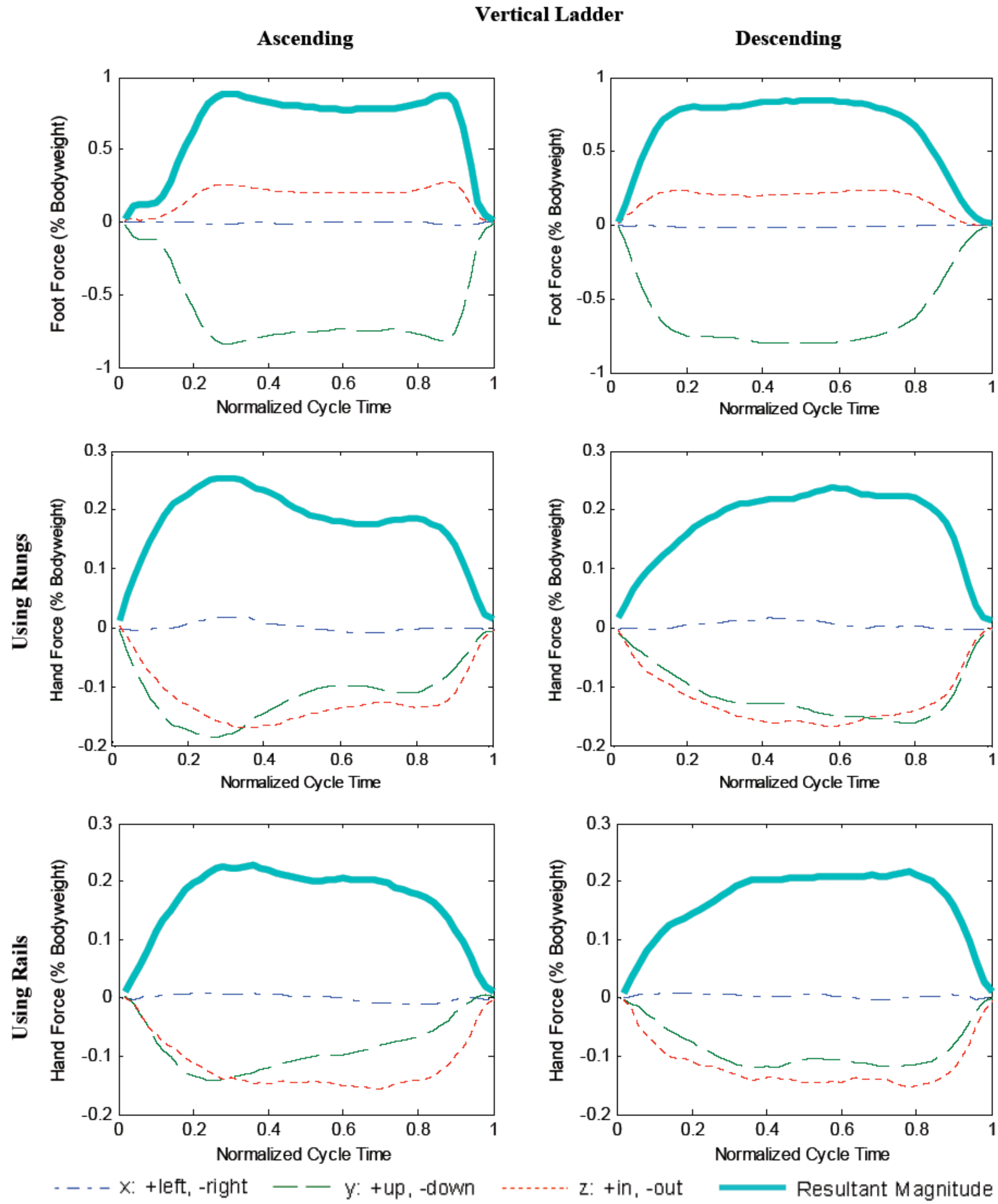



Figure 9: Force profiles for load/unload cycles on the vertical (0°) ladder. The first column displays profiles for the ascending phase and the second column displays profiles for the descending phase. Force profiles for the feet are displayed in the first row, for the hand using rungs in the second, and for the hand using rails in the third row. The resultant force is the thick line, whereas the dashed lines are component x, y, and z forces. Profiles are average values at each normalized time point from data subset (n=6).

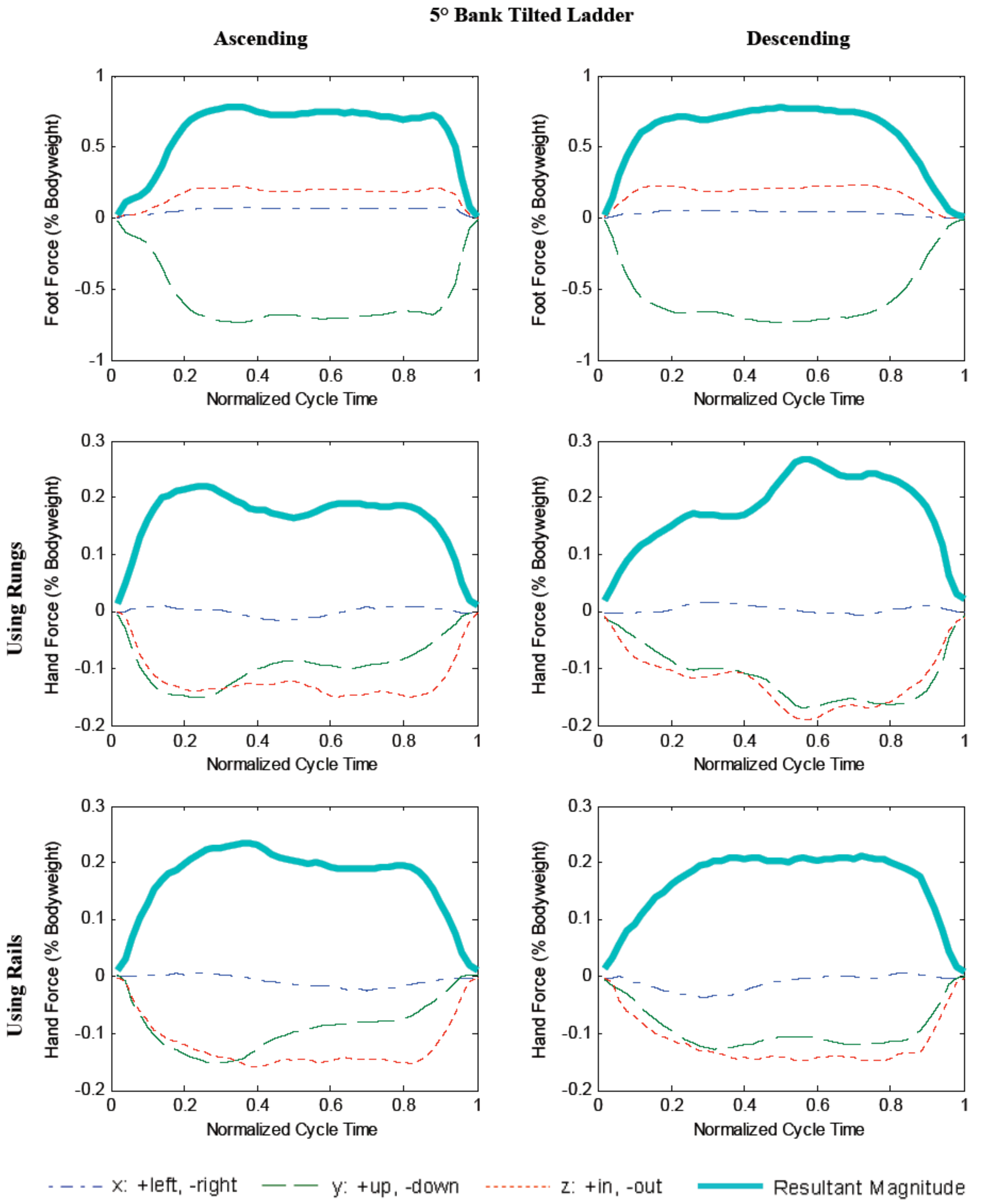



Figure 10: Force profiles for load/unload cycles on the laterally tilted (5° bank) ladder. The first column displays profiles for the ascending phase and the second column displays profiles for the descending phase. Force profiles for the feet are displayed in the first row, for the hand using rungs in the second, and for the hand using rails in the third row. The resultant force is the thick line, whereas the dashed lines are component x, y, and z forces. Profiles are average values at each normalized time point from data subset (n=6).

There are two distinctive parts of each force profile. There is a peak force that occurs near the beginning and a second that occurs near the end. The first one is generally greater than the second one for ascending; the second one is generally greater than the first for descending. Additionally, there is an initial small force plateau that occurs within the first 10% of the force period for the feet while ascending. This initial force is more pronounced for the vertical ladder than for the laterally tilted ladder. This may be due to passive ankle dorsiflexion that occurs as the climber's weight is transferred to the foot and signals to the climber that the foot is on a rung before committing full force ramp-up. The climber may be at increased risk during this transition period. If the foot slips after this initial period, when the climber is committed to placing all force on that foot and lifting the other off, all weight would be transferred to the hands. This mechanism could play an important role in accidents in which the climber's feet slip from a rung. Further analysis of force and posture will be performed to examine this behavior.

Looking at the component forces in the vertical hand force profiles (Figures 9 and 10), we see that during ascending, initial forces are dominated by the vertical component (y direction) and then give way to the outward component (z direction). This suggests that initial propulsive hand forces are up and in followed by a mostly inward force to bring the body center of mass back to the ladder. During ladder descent, hand force profiles indicate the hands are primarily pulling inward, stabilizing the body. The foot forces are dominated by the vertical component across the entire period; inward/outward and lateral force components change very little with respect to each other. The lateral forces (x) are averaged across two rungs for hands (7 & 8) and feet (2 & 3) or both rails for the hands in the figures presented. This means that zero (x) force doesn't necessarily indicate that there were no lateral forces, but rather it presents the degree of negative-symmetry between the forces exerted on the two rungs or rails. To examine this, 3D plots of left and right hand force profiles are shown in Figures 11 and 12. The lateral forces while climbing with the rails are high, but not with the rungs.

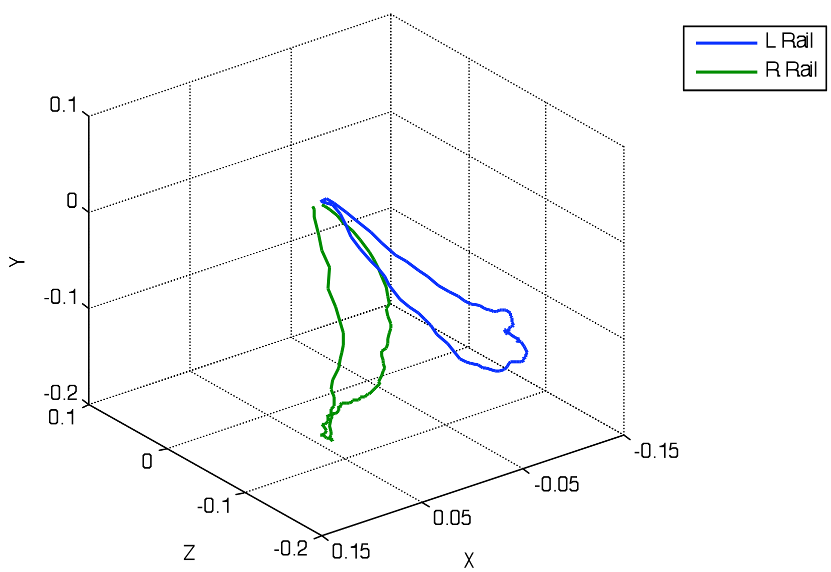



Figure 11: Average hand forces (% bodyweight) exerted on the rails while climbing the vertical ladder. The figure shows a 3D representation of orthogonal forces acting over the course of the loading period on the left or right rail. Forces are average values at each normalized time point from data subset (n=6).

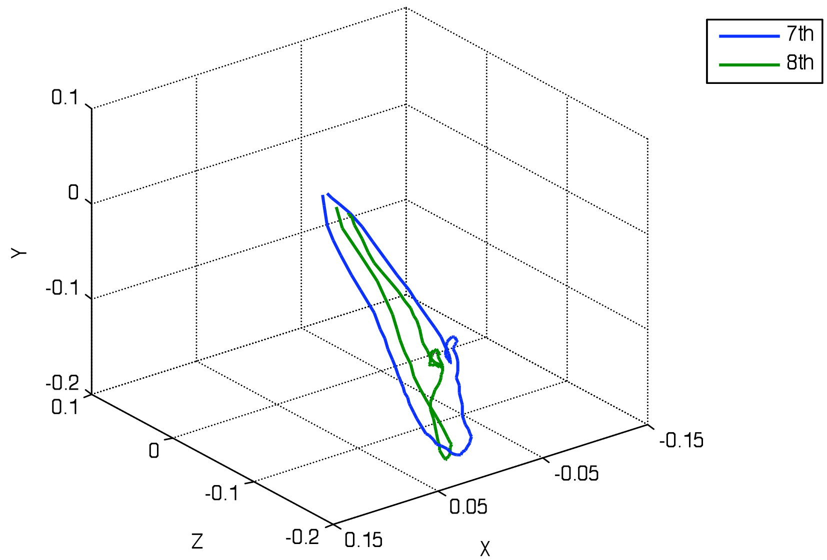



Figure 12: Average hand forces (% bodyweight) exerted on the rungs while climbing the vertical ladder. The figure shows a 3D representation of orthogonal forces acting over the course of the loading period on the 7th or 8th rung. Forces are average values at each normalized time point from data subset (n=6).

### *6.1.2.7 Body Posture*

Body postures and motions were recorded for all 12 subjects (see Table 1) and for all climbing conditions (Table 2). For the sake of brevity, we only report the descriptive statistics for the major joint motions for rung and rail climbing of the vertical ladders. Paired, two-sided, t tests were used to compare joint motions in the two climbing styles, with $p<0.05$ being considered significant.

Figure 13 shows data from one climbing movement cycle from a representative trial of a subject beginning a climb while grasping the side rails. The cycle starts with the onset of right knee and hip flexion and ends in full knee and hip extension after climbing one step. In general, hip and knee flexion are out of phase with elbow and shoulder extension. This movement pattern was universally observed whether climbing with rungs or side rails in this study.

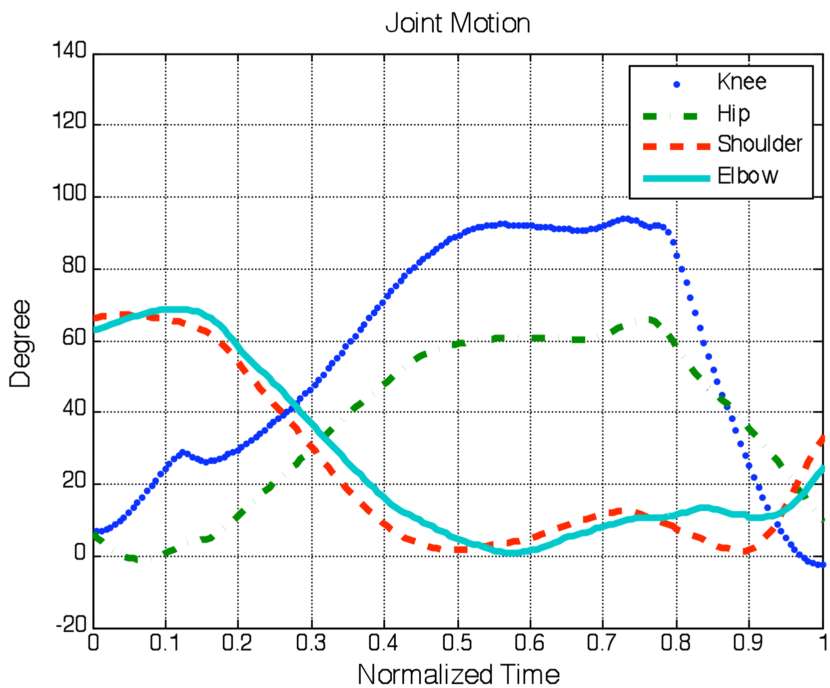



Figure 13: Sample data from a male showing contralateral style of vertical climbing using side rails. Positive (+) direction denotes flexion, negative (-) direction is extension.

Mean (SD) range of joint motion data for one climbing cycle [mean (SD) time: 2.27 (0.35 s)] for the 12 subjects climbing with each climbing style (rung vs. rail hand-holds) are shown in Table 11. There were no significant differences in the ranges of motion used, although less variability was observed in climbing with rungs than with the rails. Greater kinematic variability in hip joint motion is noticeable when climbing with side rails. Variability in lower limb use was generally smaller than that with the upper limb.

Table 11: Mean (SD) joint range of motion (in deg.) used for the two climbing styles. (n=12)

| **Joint** | **Climbing with rungs** | **Climbing with side rails** |
|---|---|---|
| Elbow | 24.1 (11.5) | 29.8 (16.1)* |
| Shoulder | 38.8 (13.4) | 36.8 (15.3) |
| Hip | 55.0 (6.7) | 54.7 (11.4) |
| Knee | 56.7 (5.9) | 53.9 (8.1) |

* p = 0.139

Although Table 11 gives a summary of the kinematic data by climbing style, systematic differences in anthropometry (height and arm span) between the males and females would have increased the data scatter in that table. Joint ranges of motion may well be determined by stature and rung spacing. In the future we hope to expand group sizes and investigate the effect of anthropometry, age, ladder inclination and rail design on the kinematic and kinetic variables.

## 6.2 Lateral Reaching

### 6.2.1 Methods

All twelve subjects completed the lateral reaching experiment. Subject statistics are shown in Table 1.

While standing with both feet on the ladder, subjects were instructed to reach to their left and touch a target that was one full arm span away from the centerline of the ladder (Figure 14). Subjects then returned back to the ladder after a short pause. Two lateral reaching exercises (holding the rail or holding the rung) were performed on two fixed ladder orientations (oriented vertically or pitched 10 degrees forward from vertical). There were three repetitions of each treatment. Orthogonal forces on the rungs or rail were recorded over the duration of the reach/return exercises.

Figure 14: Photo of a subject reaching laterally to a target (the side of another ladder) one full arm span away from the center line of the ladder. The subject is holding the left rail.

For data analysis purposes, the duration of a reach exercise was defined as the point when a left-lateral force was positive. Forces were normalized by each subject's bodyweight, and sampled evenly over the duration of the reach exercise.

### 6.2.2 Results & Discussion

Normalized hand force-time plots are shown for the vertical ladder in Figure 15 and for the laterally tilted ladder in Figure 16. Normalized foot force-time plots are shown for the vertical ladder in Figure 17 and for the laterally tilted ladder in Figure 18. Peak resultant forces during reach exercises are between 27 and 34 percent of bodyweight with rail forces being higher than rungs and the vertical ladder force higher than on the tilted (repeated measures ANOVA, $p<0.05$). Component forces are dominated by lateral forces (x), but on the vertical rail, in/out (z) forces are larger during the initial reach and the return phase of the exercise. This is not the case for the tilted ladder. These results show a significant amount of force is required to perform a reach one arm span from the center of the ladder. Holding the rails may have resulted in greater force by allowing the body's center of mass to move more laterally. These reach exercises were slow, mostly quasi-static, and if the subject were to increase speed, we would see larger forces on the hand. If the ladder is slippery, the required reaching force may exceed the grasp capability of the hand, or the required friction for the feet to resist lateral load.

On vertical ladders we see a difference in the component forces as compared to the tilted ladder. On a vertical ladder, the body's center of mass is outside the vertical plane. When reaching we see the subject exert a large inward force pulling themselves toward the ladder at the beginning and ends of the reach task. On tilted ladders, the subject can balance their center of mass over their feet and use minimal inward force when reaching.

Foot forces while reaching are very similar for vertical and tilted ladders. Lateral forces (x forces) increase as the body reaches to touch the target and are maximum while the subject is at full reach. **Average maximum lateral foot force values range from 17-21% of bodyweight**.

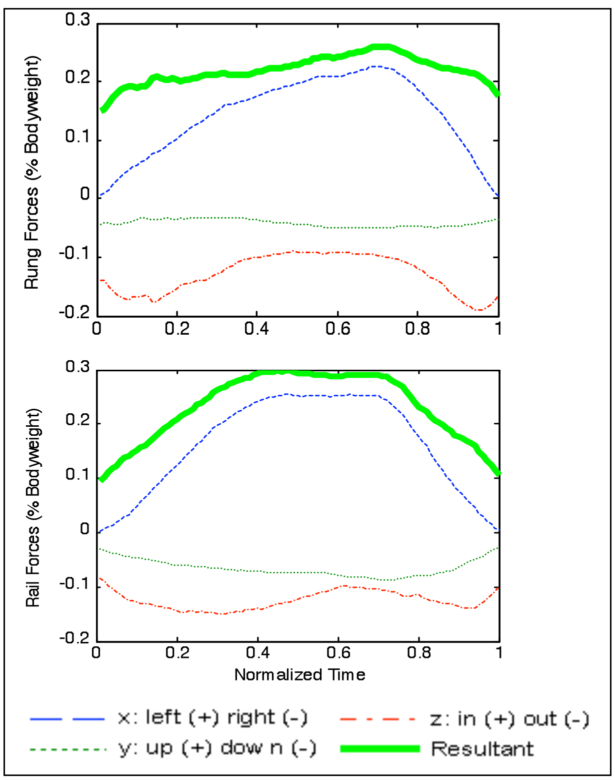



Figure 15: Vertical (0°) ladder: Mean hand force (% bodyweight) applied to the ladder rung (above) and ladder rail (below) during a reach/return exercise.

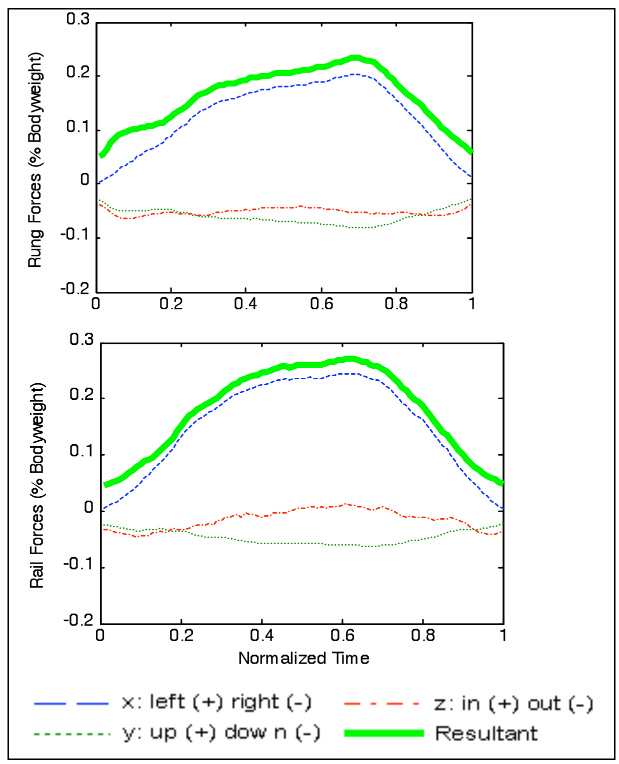



Figure 16: Ladder tilted 10º forward: Mean hand force (% bodyweight) applied to the ladder rung (above) and ladder rail (below) during a reach/return exercise.

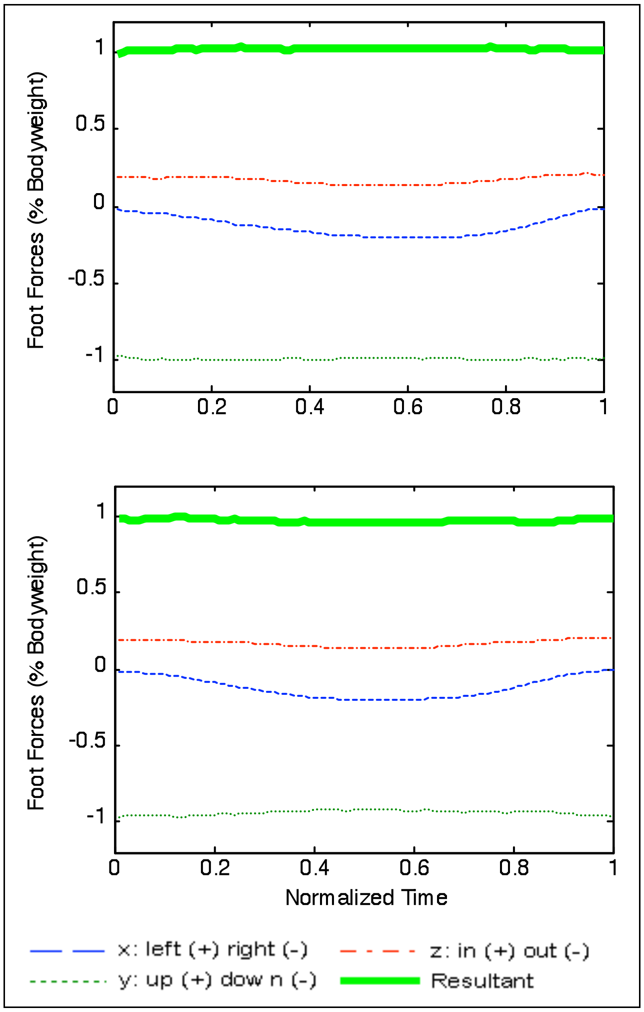



Figure 17: Vertical (0°) ladder: Mean foot force (% bodyweight) while performing a reach/return exercise using the rung (above) or ladder rail (below) with the hands.

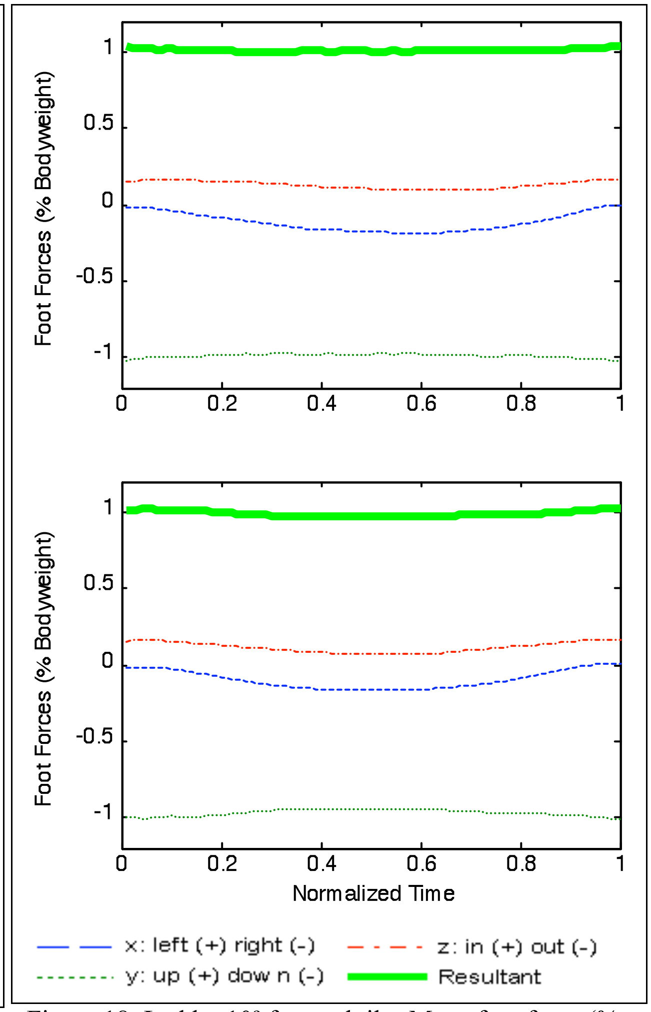



Figure 18: Ladder 10º forward tilt: Mean foot force (% bodyweight) while performing a reach/return exercise using the rung (above) or ladder rail (below) with the hands.

# 7 Objective 4: Conduct Pilot Study of Overhead Grasp Strength

## 7.1 Methods

Twelve (6 males, 6 females) University of Michigan students were recruited to participate in this study. Subjects were paid for their involvement. All subjects were in good health and had no previous injuries or surgeries that would affect upper limb performance. Eleven subjects were right hand dominant while one was left hand dominant. Subject characteristics are presented in Table 12.

**Table 12: Grasp Strength Subject Profile**

| Gender | Height (m) | Weight (kg) | Hand Length (mm) | Age (yrs) | Dom. Grip Strength (kg) | Non-Dom. Grip Strength (kg) |
|---|---|---|---|---|---|---|
| F | 1.63 | 53.1 | 168 | 19 | 36 | 37 |
| F | 1.57 | 54.4 | 166 | 20 | 33 | 29 |
| F | 1.78 | 72.6 | 182 | 21 | 34 | 31 |
| F | 1.63 | 52.2 | 176 | 21 | 34 | 31 |
| F | 1.60 | 44.5 | 164 | 18 | 26 | 24 |
| F | 1.70 | 50.3 | 171 | 25 | 33 | 27 |
| Females (N=6) | 1.65 ± 0.08 | 54.5 ± 9.5 | 171 ± 7 | 21 ± 2 | 33 ± 3 | 30 ± 5 |
| M | 1.88 | 93.4 | 197 | 22 | 61 | 66 |
| M | 1.85 | 81.6 | 195 | 23 | 62 | 56 |
| M | 1.83 | 50.8 | 200 | 20 | 61 | 48 |
| M | 1.80 | 68.0 | 183 | 20 | 49 | 44 |
| M | 1.63 | 54.4 | 191 | 18 | 51 | 44 |
| M | 1.80 | 65.8 | 183 | 20 | 53 | 50 |
| Males (N=6) | 1.80 ± 0.09 | 69.0 ± 16.2 | 192 ± 7 | 21 ± 2 | 56 ± 6 | 51 ± 9 |
| All (N=12) | 1.73 ± 0.11 | 61.8 ± 14.8 | 181 ± 13 | 21 ± 2 | 44 ± 13 | 41 ± 13 |

Prior to the experiment, subjects completed an informed consent document approved by the University of Michigan's IRB. Subjects washed and dried their hands and anthropometric data was recorded. The experiment consisted of a total of fifteen maximum strength trials: three grip strength tests and twelve overhead grasp strength tests. Each of the three handles was tested for the dominant hand. The horizontal rung was also tested for the non-dominant hand. Grip strength was measured for both hands. There were three repetitions for each treatment. The order of the trials was randomized.

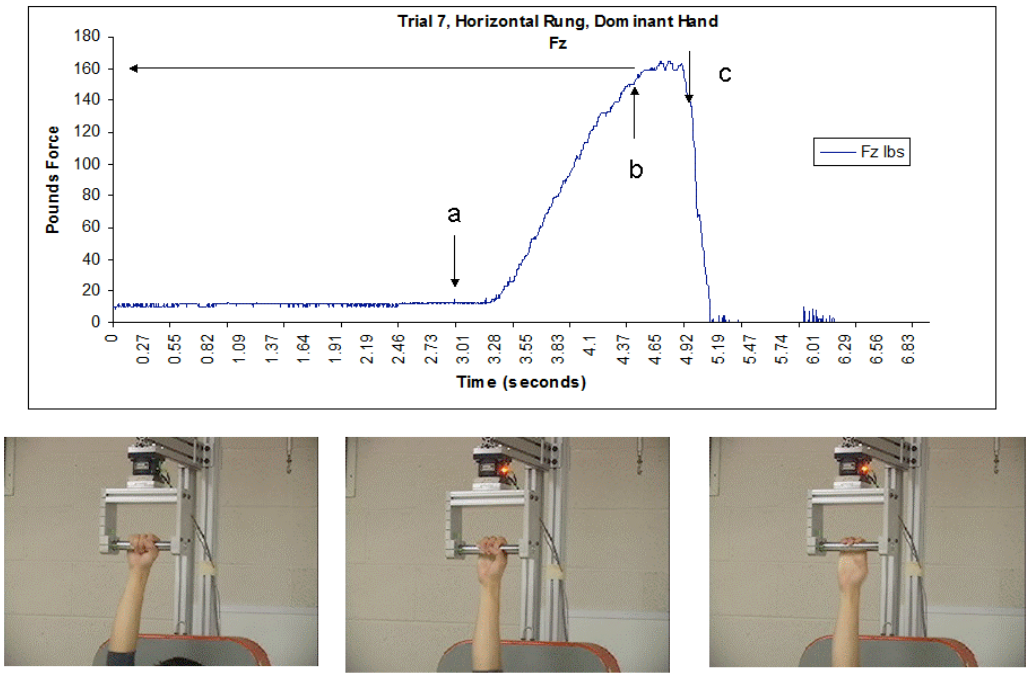
Independent Variables: Handle, hand, gender
Dependent Variables: Grasp strength, grip strength

For each of the grasp strength tests, subjects stood on the adjustable platform and were secured using the dipping belt. The subject was then raised until he or she could firmly grasp the overhead handle with a slight bend the elbow. Subject was instructed to exert their maximum strength capability and hold onto the handle as long as possible. Subjects were asked if they were ready and were then lowered at a steady rate until their hand decoupled from the handle. The forces exerted on the handle were recorded. Subjects were given clean paper towels to dry their hands prior to each trial.

The grip strength tests were performed off of the platform. For these tests, the subject stood on the ground with arms relaxed at their side. The subject was instructed to squeeze the dynamometer as hard as possible for five seconds. Experimenters provided verbal encouragement. One grip strength trial consisted of a test of both the dominant and non-dominant hands. In between each trial the subjects were given breaks of at least two minutes.

## 7.2 Observations

Force data and video recordings have been synchronized to examine the hand as it decouples from the handle. Figures 19-21 illustrate peak force profiles and the corresponding hand positions for a few selected trials on one subject. Peak coupling strengths of 160, 92 and 105 pounds are shown for these examples.




a b c

Figure 19: The above figure shows a subject grasping a horizontal rung until the subject can no longer hold on. The pictures correspond to the hand position of the subject at various times during the trial: (a) the subject stands ready with elbow slightly bent (b) vertical force ramps up as the subject is lowered (c) the couple between the hand and handle is broken and the force on the handle rapidly drops to zero.

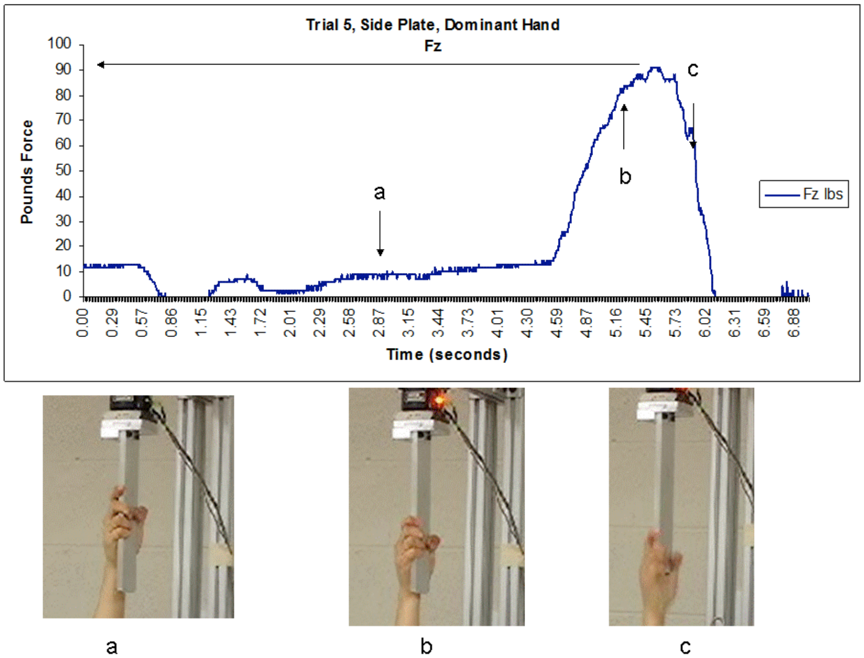



Figure 20: The above figure shows a subject grasping a <u>vertical plate</u> until the subject can no longer hold on. The pictures correspond to the hand position of the subject at various times during the trial: (a) the subject stands ready with elbow slightly bent (b) vertical force ramps up as the subject is lowered (c) the couple between the hand and handle is broken and the force on the handle rapidly drops to zero.

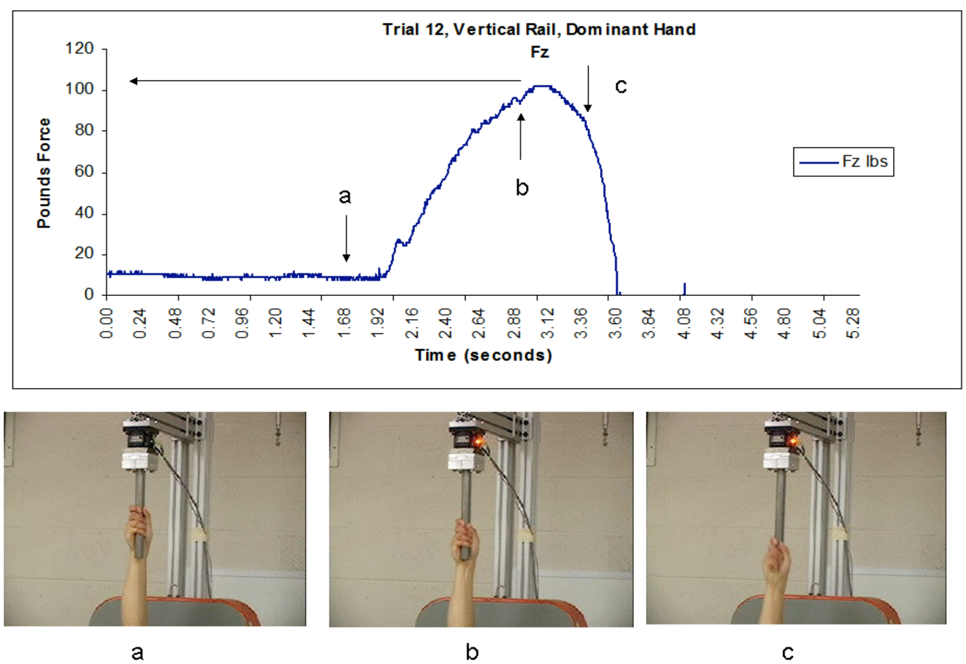



Figure 21: The above figure shows a subject grasping a <u>vertical rail</u> until the subject can no longer hold on. The pictures correspond to the hand position of the subject at various times during the trial: (a) the subject stands ready with elbow slightly bent (b) vertical force ramps up as the subject is lowered (c) the couple between the hand and handle is broken and the force on the handle rapidly drops to zero.

### 7.3 Results & Discussion

The peak vertical forces that subjects were able to exert on the overhead handles with their dominant hand are presented in Table 13 and Figure 22. Peak grasp force normalized by subject bodyweight and grip strength is also presented. Maximum grasp strength is greatest when holding onto the horizontal rung, followed by the vertical rail and then the vertical plate. Subjects could exert greater than their bodyweight only for the horizontal rung. Average grasp strength for the horizontal rung was 1.52 times a subject's grip strength.

**Table 13: Grasp Strength for the Dominant Hand (all subjects)**

| Handle | Grasp Force (N) | Grasp Strength/ Bodyweight | Grasp Strength/ Grip Strength |
|---|---|---|---|
| 1" horizontal rung | 667.9 ± 237.0 | 1.05 ± 0.20 | 1.52 ± 0.23 |
| 1" vertical rail | 434.7 ± 121.3 | 0.70 ± 0.11 | 1.02 ± 0.17 |
| 1" x ¼" vertical plate | 336.9 ± 146.3 | 0.53 ± 0.13 | 0.77 ± 0.22 |

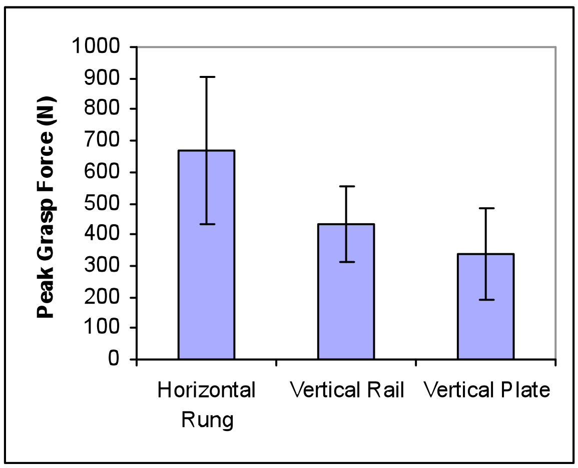



**Figure 22: Grasp strength (N) for all subjects.**

Table 14 shows grasp strength stratified by gender. Results show that peak grasp strength is lower for females than males. Grasp force is greatest when holding onto the horizontal rung for both genders. Only males have average peak grasp strength greater than their bodyweight (horizontal rung only). Differences in peak grasp strength between genders are reduced or reversed when normalizing by grip strength. These trends are illustrated in figures 23-25.

**Table 14: Grasp Strength for the Dominant Hand by Gender**

| | Grasp Strength (N) | | Grasp Strength / Bodyweight | | Grasp Strength / Grip Strength | |
|---|---|---|---|---|---|---|
| | Males | Females | Males | Females | Males | Females |
| 1" Horizontal rung | 841.8 ± 207.2 | 494.0 ± 92.9 | 1.17 ± 0.13 | 0.94 ± 0.18 | 1.52 ± 0.26 | 1.53 ± 0.20 |
| 1" vertical rail | 515.7 ± 119.5 | 353.6 ± 46.1 | 0.72 ± 0.10 | 0.68 ± 0.12 | 0.93 ± 0.15 | 1.10 ± 0.13 |
| 1" x ¼" vertical plate | 409.7 ± 165.9 | 264.1 ± 73.0 | 0.55 ± 0.14 | 0.50 ± 0.13 | 0.73 ± 0.23 | 0.81 ± 0.19 |

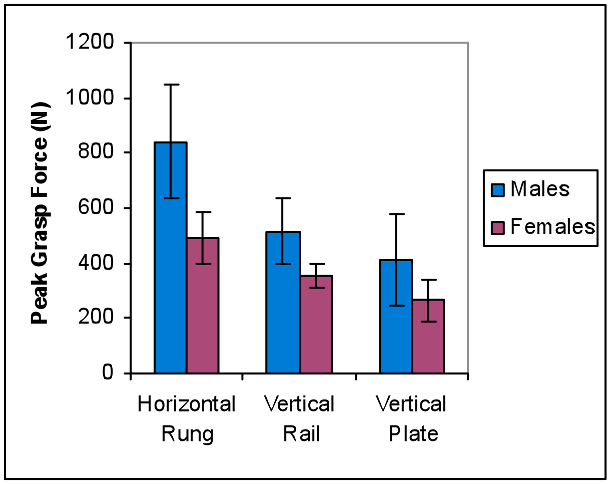



**Figure 23: Grasp strength (N) for all subjects, by gender.**

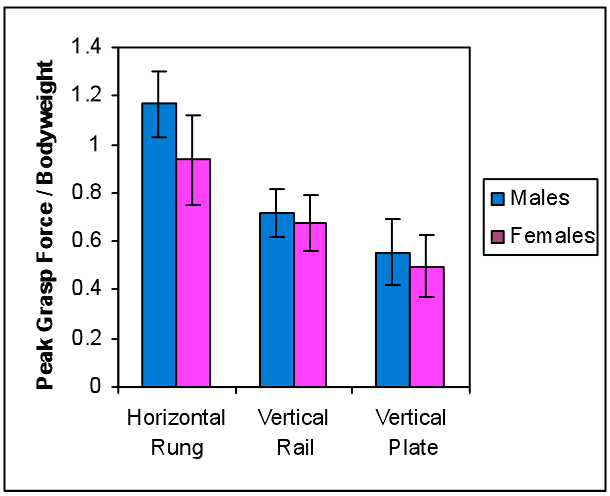



Figure 24: Grasp strength (% bodyweight) for all subjects, by gender.

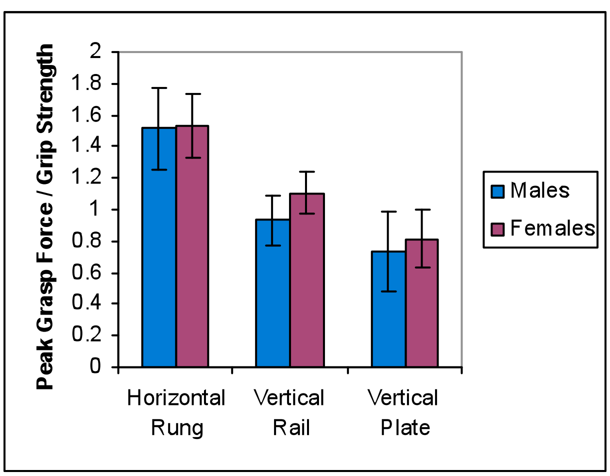



Figure 25: Grasp strength (% grip strength) for all subjects, by gender.

Grasp strength was also measured for the non-dominant hand on the horizontal rung only. Results show that there was a trend for non-dominant grasp strength to be slightly lower than that of the dominant hand, but this difference was not significant (One-way ANOVA, F=0.34, p=0.564). Thought the effect was not significant, it would suggest that non-dominant hand may be weaker than the dominant in a fall situation. The non-dominant hand was not tested for the vertically oriented handles for two reasons: (1) to reduce the number of trials in the experiment and (2) friction provides the resistance in the vertical orientation and differences in the surfaces of the two hands may introduce a high level of variability in grasp strength measurements.

These results show that handle orientation (horizontal or vertical) affects grasp strength. Additionally, handle shape (cylinder or plate) affects grasp strength. The horizontal rung afforded the highest coupling strength between the hand and handle and was 1.52 times greater than grip strength on average. These findings agree with Rejulu and Klute (1993), who reported average grasp strength of 1.7 times grip strength for subjects grasping a handle perpendicular to the forearm while wearing gloves. This shows that the total capability of a hand to grasp an object depends on more than grip strength capability alone.

When the handle is oriented perpendicular to the forearm (e.g. the horizontal rung), both the mechanical resistance of the hand (i.e. grip strength) and a frictional component will act together to form the couple between the two. Grasp strength (eccentric contraction and frictional resistance) in this situation then should be greater than the grip strength, as our results show. When the handle is oriented parallel to the forearm (vertical), active grip strength will provide a normal force that will act to increase friction as the hand slides from the handle. In this situation, friction drives grasp strength. Between the two vertical handles (vertical rail and vertical plate), subjects were able to achieve better friction with the vertical rail.

When examining temporal loading of the hand during the trials, the time it took for the hand/handle couple to reach peak strength was recorded. This time was defined by the time when the vertical force began to ramp-up steeply from a steady pre-loading phase to when the maximum vertical force occurred. This was determined for the horizontal rung only (Table 15).

**Table 15: Time (seconds) from beginning of loading to peak grasp force (horizontal rung only)**

| | Overall | Males | Females |
|---|---|---|---|
| Dominant Hand | 1.45 ± 0.31 | 1.61 ± 0.30 | 1.29 ± 0.26 |
| Non-Dominant | 1.26 ± 0.30 | 1.42 ± 0.26 | 1.10 ± 0.27 |

Males took longer to reach peak force than females. The non-dominant hand reached the peak force faster than dominant for both males and females. When normalized by hand length, these trends are the same (not shown). It’s possible that total strength allows for the increased total time to peak loading.

Some limitations of this study are the ability to control the coefficient of friction between the hand and the handle for each subject. Differences in skin surface properties (perspiration rate) may have introduced error despite attempts to control this. Additionally, maximal effort may be different between subjects, with some subjects “giving up” and letting go before their true maximum grasp capability is reached.

## 8 Objective 5: Equipment for Measuring Grip Reaction Force and Time

This pilot study has focused on measuring the dynamics and magnitudes of forces experienced while climbing under normal circumstances. An important consideration in fall safety is how fast a climber can respond to apply additional force if there is a force perturbation due to a slip or sudden movement of the rungs or rails. Many of the ladders of interest are attached to construction equipment. In many cases, such as the ready-mix truck shown in Figure 1, the ladder may move. Ladders on construction sites may be contaminated with water, ice, mud or oil, which can cause a climber to slip.

To measure grip response times, we have design a device in which selected handles can be attached to a hanging weight. By dropping the weight, we can simulate the same dynamics that would be experienced by a falling worker. The velocity and inertia of the weight increases with distance that the weight drops (v^2 = 2gy, where: v= velocity, g=9.8 m/s^2, y = drop distance). The force that will be required to stop the weight can be controlled by the mass of the weight. A force transducer in series with the handle measures response time and hand force. We can adjust the mass and the fall distance so that we don't overload the subject's hand, while still measuring their response time and strength.

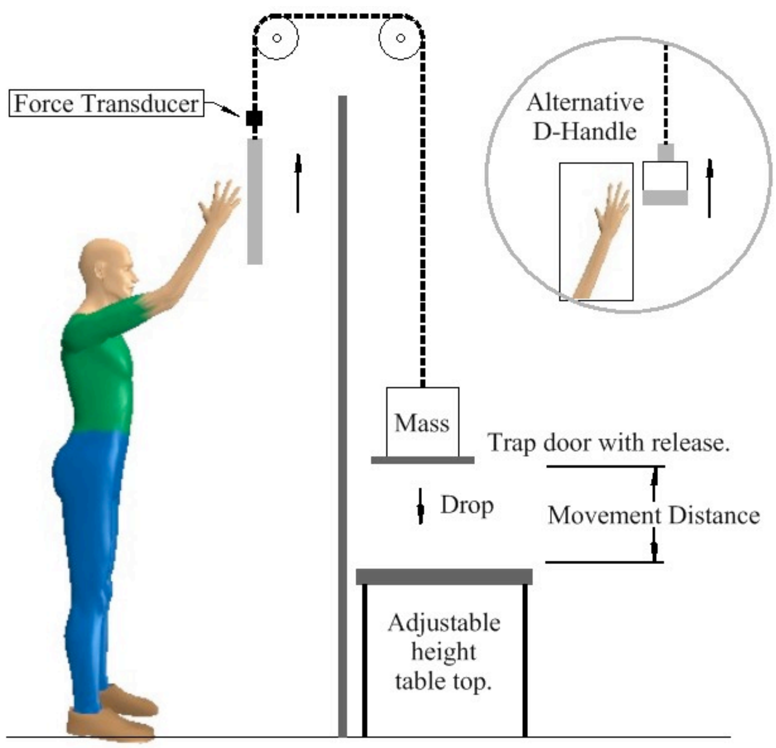



Figure 26: Proposed equipment for evaluating grasp time and force. Rails and rungs are attached to weight via two pulleys. A force transducer between the weight and the handle measures hand force and response time. The mass of the weight and the drop distance can be adjusted to control the forces and speed of motion of the handle.

# 9 Conclusions and Recommendations for Future Research

## 9.1 Ladder Climbing

The average peak resultant foot forces (the vector sum of the forces acting in the vertical, horizontal and lateral direction) for 12 subjects ascending or descending the ladder were (94-100% of bodyweight) were consistently greater than average peak resultant hand forces (28-39% of body weight) (Tables 6 and 7, p 17). Significant variations in climbing style were observed among the 12 subjects. These variations are consistent with previous studies by Dewar (1977), McIntyre (1983), and Hammer and Schmalz (1992) who also report a large variation in climbing styles between persons, and that a person may change styles within the same climb. **Future studies should examine the effect of these variations on hand and foot forces are their implications to climbing safety.**

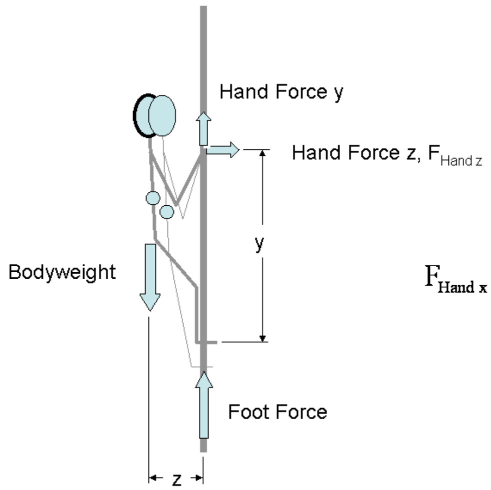
A subset of six subjects with complete data for rungs 1 and 2 (the feet) and 7 and 8 (the hands) were selected for further analysis. Hand force periods (Tables 9 and 10, p 19) are longer than foot force periods, indicating that hands move faster than the feet during transitions. This allows both hands to grasp the ladder during the entire transition of load from one foot to the next. Additionally, the force periods for the hands were longer for climbing with the rungs that for climbing with the rails (Tables 9 and 10), and climbing forces were reduced for climbing with the rails.

Hand and foot force profiles exhibit two distinct peaks near the beginning and end of the loading period (Figures 9 and 10; pp 20-21). These peaks follow placement of the foot or hand on the ladder and the release. The mechanism may involve cyclical changes in body inertia in the climbing cycle. They are important because the feet and hands are at greatest risk of slipping during these peak forces. Further examination of the hand forces during ascent shows that the dominant hand force is upward at the beginning of the force period and shifts to an inward force at the end of the force period. During descent, inward forces are dominant. The vertical force helps to lift the body, while the horizontal force prevents the climber from falling backwards. The horizontal hand force is related to the Body weight, the horizontal (z) distance between point of foot-rung contact and the body's center of gravity, and the vertical (y) distance between the point of foot-rung contact and the hand point of hand-ladder contact (see Figure 27 below). From Figure 13 (p 25) it can be seen that the hip flexes from 0 to 60º as the foot is lifted to the next rung. This forces the climbers center of gravity further from the ladder and increases the required horizontal hand force (see Figure 27).

Peak resultant hand forces are significantly less for rail climbing than rung climbing (Table 3 and 7; pp 15, 17). **It appears that rail climbing is less strenuous on the upper body than rung climbing.** Further studies should be performed to compare the risk of falling in rail versus rung climbing.

These results suggest that the feet do most of the work to elevate or lower the body, while the hand stabilizes the body. This has important implications to the design of ladders. **A rung that is optimized for hand force will not be optimal for foot force and visa versa. Research is**

**needed to support guidelines for designing optimal rungs for the feet and optimal rails for the hands. Further studies should be performed using three-dimensional biomechanical models to examine the relationship between body motions and hand forces. Such models can help identify the best ladder designs and methods for a given task, setting and body size.**




$$F_{Hand\ x} = \frac{z}{y} Bodyweight$$

Figure 27: The horizontal hand force is related to the Bodyweight, the horizontal (z) distance between point of foot-rung contact and the body's center of gravity, and the vertical (y) distance between the point of foot-rung contact and the hand point of hand-ladder contact.

An initial force plateau that corresponds to contact between the foot and the rung precedes the initial force peak (Figures 9 and 10, pp. 20-21). It appears that ankle dorsiflexion from contact with the rung, may be a signal for applying full foot force. The climber may be at increased risk of slipping during this transition period. It is possible that there is sufficient contact between the foot and rung to produce angle dorsi flexion, but not sufficient contact to support the weight of the body. If one foot slips while the second foot is reaching for the next rung, the climbers full bodyweight will be suddenly transferred to the hands. This is one explanation for the observations shown in Figures 6 and 7 (pp 13-14) where subjects have both hands on the ladder when they lift their foot off a rung. **Rung design and training should be explored as possible interventions for prevent applying force before there is adequate contact between the feet and rungs to support the body.**

**Further studies of climbing behavior are needed to understand how to best optimize rung and rail design for a given task by a given group of users. The study should focus on the different ways people synchronize their movements as they go up and down ladders. It also should examine the effect of experience. It is likely that climbing behavior changes as the climber becomes familiar with the task and becomes accustom to working above the ground. The study should examine how forces are transferred to the rungs and rails and the effect of various rung and rail designs on performance. For example, both steel rods and flat tread plates are used for making rungs.**

It appears that climbing a ladder tilted sideways is more difficulty than climbing a vertical ladder. Hand cycle times were the longest for the laterally tilted ladders. Foot cycle times were also increased, which indicates subjects climbed more slowly on the laterally tilted ladder than on the vertical ladder. The effects of ladder tilt are a particular concern for ladders mounted on mobile equipment. F**urther studies should be performed to determine if training workers to take extra time would help reduce fall risk for tilted ladders. Further studies of ladder tilt should consider the effects of rung spacing, anthropometry and climbing styles.**

Climbing with the toolbox yields the greatest overall peak forces on the hands (Table 3; p 15). This was also reflected in the subject's opinions and indicates that this is a very difficult task. Subjects indicated that climbing with a toolbox was easiest when the ladder was pitched forward 10°. This orientation allows the subject to balance the weight of the body over the ladder rung, which greatly reduces the force required to hold onto the ladder. **Tilting ladders forward is a potential intervention for situations where workers are expected to carry equipment up the ladder. Further studies should be performed to determine the minimum pitch angle needed to affect climbing behavior. Also, alternatives to hand carrying objects to reduce fall risk should be explored.**

## 9.2 Lateral Reaching

The **average hand force exerted while reaching laterally off a ladder is between 23-30% of bodyweight** (Figures 15 and 16; p 27), with peak values as high as 34% of bodyweight. These are similar to the forces exerted during climbing. Although these hand forces are well within the climber's capability, they may need to be sustained for a period of time while the climber performs a secondary task. A prolonged exertion at these force levels will lead to fatigue and diminished hand strength.

The average vertical foot force is equal to bodyweight – slightly less than the foot forces for climbing; however, in contrast to climbing, there is a substantial lateral (x direction) foot force 17-21% of bodyweight (Figures 17 and 18; p 28). The lateral foot force can be explained by the location of the body mass as the climber reaches to their far left. This lateral foot force is important. There are only two points of contact during this reach maneuver. If the foot or hand slips, a fall is highly probably. The 1" (2.5cm) diameter steel rods commonly used for fixed ladder rungs have very poor friction characteristics – especially if they are contaminated with water, ice, mud or grease.

Forward ladder tilt appears to affect inward hand force at the beginning and end of the reach (Figure 15 and 16, p. 27). On vertical ladders it appears that the worker's body falls backward away from the ladder as they reach for the target on their left. **The greatest risk of falling may come at the beginning or end of the reach. The end could be particularly problematic if the hand is fatigued from a prolonged exertion.**

This study may be useful in predicting the effort a worker will have to exert while performing a lateral reach task such as painting. In future studies we will increase sample sizes, and explore the effects of reaching with different tools, and wearing tool belts. **The difficulty of the task requiring the reach may also change how the subject reaches to the task**. **Since reaching and climbing ladders is common for the general population doing household chores, the**

**effects of aging and the measurement of torques at the base of the ladder should be considered.**

## 9.3 Grasp Capability

This study examined the ability of subjects to hold onto a rung or a rail as it was subjected to an ever-increasing external load. Strength was measured both as the maximum force that could be exerted before the handle slipped out of the hand (Figures 19-21, pp 30-31) and as the maximum grip strength measured using the widely used Jamar™ grip dynamometer. The greatest strength was observed for the 1” diameter horizontal rung, followed by the 1” diameter vertical rail, and followed by the 1”x ¼” vertical plate (Table 13; Figure 22 p. 32). Strength for a horizontal rung was significantly greater than that measured on the Jamar™ grip dynamometer.

**These results show that some strong subjects can support their full bodyweight with one hand on a 1” fixed steel rung. Most people should be able to support their full body weight with two hands using a 1” steel rung. Few if any people can support their full body weight with one hand using either a 1” diameter rod or a 1” x ¼” bar type rail. Most people should be able to at least briefly support their full bodyweight with two hands using either a rod or bar rail. These results also show that traditional grip strength measures do not predict peoples’ ability to hang by their hands well.**

Most hand strength studies are based on devices such as the Jamar™ grip dynamometer. As can be seen from the aforementioned results, The Jamar™ significantly under predicts the ability of subjects to hold onto a rung. The Jamar™ on measures finger flexion force – it does not measure the friction that is produced as the hand sides off from the rung (see Figure x below). Consequently the amount of force that can be exerted to support the body from the rung will be much greater than grip force measured using the Jamar™ grip dynamometer. In the case of the vertical rail, friction forces along the long axis of the rail support the bodyweight. Friction forces are related to, but not equal to grip force (Seo et al 2008).

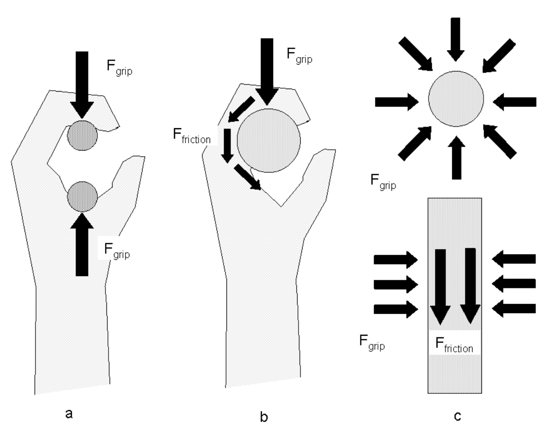



Figure 28: The Jamar™ grip dynamometer on measures finger flexion force against a handle held in the palm (a). Hanging from a rung produces friction force as the hand begins to slip that helps support the bodyweight (b). Hanging from a vertical rail relies entirely on friction force along the long axis of the rail, which is produced as the hand begins to slide on the rail (c).

These strength measurements were all based on loading at 5.5 inches per second. Much higher rates of loading could occur during a fall. Based on the friction characteristics of the hand, we hypothesize that strength capability increases with friction. This study only examined a small number of rail and rung sizes and shapes. **Further studies are needed to develop models for predicting strength for a given handle size, shape, orientation and material.** Such studies should also consider the effect of gloves, which could be used to enhance friction and strength. By developing a comprehensive model of hand strength in these high-loading grasp environments, the best shape and size for ladder rungs and rails, as well as safety handholds and rails in other situations can be recommended.

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## 11 Appendix: NACOB Abstracts

Formal citation:

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Young, J., Kim, H., Woolley C., Armstrong, T., and Ashton-Miller, J. (2008) "Lateral Reaching From Fixed Ladders". Presented at The North American Congress of Biomechanics (NACOB), Ann Arbor, MI, USA. Aug. 5, 2008.

Young, J., Sackllah, M., Woolley C., Armstrong, T., and Ashton-Miller, J. (2008) "Overhead Grasp Capability for Typical Ladder Handholds". Presented at The North American Congress of Biomechanics (NACOB), Ann Arbor, MI, USA. Aug. 5, 2008.

# A COMPARISON OF THE KINEMATICS OF LADDER CLIMBING USING RUNGS VS SIDE RAILS

Hogene Kim[1], Justin Young[2], Chuck Woolley[2], Tom Armstrong[1,2] and James A. Ashton-Miller[1,3]

[1]Department of Biomedical Engineering, [2]Department of Industrial & Operations Engineering, [3]Department of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan, USA.
hogenek@umich.edu, URL: http://me.engin.umich.edu/brl/mailto:jkrich@umich.edu

## INTRODUCTION

More than 20,000 American workers are injured, and over 100 die, every year as a result of falls from ladders (BLS 2005). Studies of the gait pattern of climbing on vertically tilted ladders have shown a large variation of the chosen method (McIntyre, 1983). 'Lateral gait' (i.e., synchronous ipsilateral hands and feet movement) and 'diagonal gait' (i.e., synchronus contralateral hand and foot movement) were reported as the most common climbing styles. However, an individual can change his/her climbing style even within the same ladder climb (Hammer 1992) . Both Dewar (1977) and Hakkinen (1988) reported the use of both ladder rungs and rails as handholds. Bloswick (1992) studied vertical fixed ladder climbing, but only with the use of rungs.

The goal of this study was to contrast and compare the kinematics of climbing a fixed vertical ladder using two different climbing strategies: grasping rungs or grasping rails.

## METHODS AND PROCEDURES

A custom-made, instrumented, fixed vertical ladder 10' in length was constructed. Nine 16" wide rungs were spaced 12" apart (OSHA, 1910.27 Fixed Ladder standards). Ladder rungs and rails were 1-inch diameter cylindrical steel rods and were cleaned with steel wool before testing. The ladder rungs were attached to the ladder frame at the center post so the rungs could be mounted on 3-axis force and 3-axis moment transducers (AMTI® MC3 and ATI® Theta). Four of the rungs were instrumented – two for the feet and two for the hands. Twelve healthy subjects (6 males, 6 females, age: 21±2 years, height: 172±11cm, weight: 625.2±139.2 N and arm span: 150±4 cm) volunteered for this study. Subjects were instructed to climb a vertical fixed ladder at a comfortable speed using one of two climbing styles: grasping the rungs or the side rails. From a bipedal stance on the ground, subjects climbed 5 rungs, paused, and then return to the ground. Three repetitions of each treatment were conducted.

Bilateral optoelectric cameras (Optotrak 3020) recorded body kinematics at 100 Hz using 22 infrared markers placed on body landmarks including the head, acromion, lateral epicondyle, wrist, hand, greater trochanter, knee, malleolus, and feet. For the sake of brevity, we only report the descriptive statistics for the major joint motions. Paired, two-sided, t tests were used to compare joint motions in the two climbing styles, with $p<0.05$ being considered significant.

## RESULTS

Figure 1 shows data from one climbing movement cycle from a representative trial of a subject beginning a climb while grasping the side rails. The cycle starts with the onset of right knee and hip flexion and ends in full knee and hip extension after climbing one step. In general, hip and knee flexion are out of phase with elbow and shoulder extension.

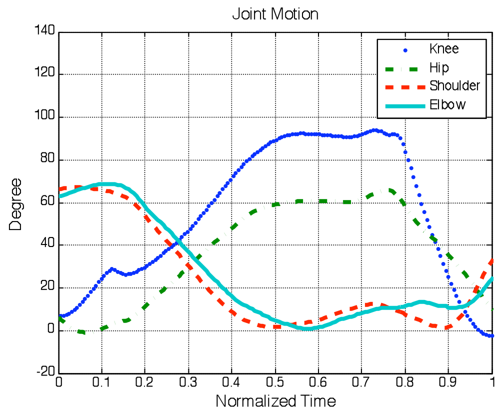


**Figure 1.** Sample data from a male showing contralateral style of vertical climbing using side rails. Positive (+) direction denotes flexion, negative (-) direction is extension.

This movement pattern was universally observed whether climbing with rungs or side rails in this study.

Mean (SD) range of joint motion data for one climbing cycle [mean (SD) time: 2.27 (0.35 s)] for the 12 subjects climbing with each climbing style (rung vs rail hand-holds) are shown in Table 1. There were no significant difference in the ranges of motion used, although less variability was observed in climbing with rungs than with the rails. Greater kinematic variability in hip joint motion is noticeable when climbing with side rails. Variability in lower limb use was generally smaller than that with the upper limb.

| Joint | Climbing with center rungs N=10 | Climbing with side rails N=10 |
|---|---|---|
| **Elbow** | **24.1 (11.5)** | **29.8 (16.1)*** |
| **Shoulder** | **38.8 (13.4)** | **36.8 (15.3)** |
| **Hip** | **55.0 (6.7)** | **54.7 (11.4)** |
| **Knee** | **56.7 (5.9)** | **53.9 (8.1)** |

**Table 1.** Mean (SD) joint range of motion (in deg.) used for the two climbing styles.
* p = 0.139

**DISCUSSION**

Although Table 1 gives a summary of the kinemetic data by climbing style, systematic differences in anthropometry (height and arm span) between the males and females will have increased the data scatter in that table. Joint ranges of motion may well be determined by stature and rung spacing. In the future we hope to expand group sizes and investigate the effect of anthropometry, age, ladder inclination and rail design on the kinematic and kinetic variables.

**SUMMARY**

No significant differences were found in joint ranges of motion used to climb by grasping the rungs or the rails. Perhaps the kinematics were largely determined by rung spacing.

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# LATERAL REACHING FROM FIXED LADDERS

Justin Young[1], Hogene Kim[2], Chuck Woolley[1], Tom Armstrong[1], James Ashton-Miller[2]

[1] Department of Industrial & Operations Engineering, [2] Department of Mechanical Engineering,
University of Michigan, Ann Arbor, Michigan, USA, jgy@umich.edu
URL: http://www.engin.umich.edu/dept/ioe/C4E/index.html

## INTRODUCTION

The incidence rate of injuries among ladder users is very high, and though reaching laterally from a ladder is a common activity, it hasn't been studied thoroughly. Some studies have explored lateral reaching on stepladders (Clift and Navarro, 2002; Juptner, 1976) where the ladder may become unstable, however they do not address fixed ladders or the forces applied to the hands. This aim of this study is to quantify the forces exerted by workers on fixed ladders as they perform a lateral reaching task.

## METHODS AND PROCEDURES

Twelve healthy subjects (6 males, 6 females) were recruited for this study. Their mean (± SD) age, height, weight, and arm span was 21±2 years, 172±11 cm, 625.2±139.2 N and 150±14 cm respectively. While standing with both feet on the ladder, subjects were instructed to reach to their left and touch a target that was one full arm span away from the centerline of the ladder. Subjects then returned back to the ladder after a short pause. Two lateral reaching exercises (holding the left rail or holding the rung) were performed on two fixed ladder orientations (oriented vertically or pitched 10 degrees forward from vertical). There were three repetitions of each treatment. Orthogonal forces on the rungs or rail were recorded over the duration of the reach/return exercises. For data analysis purposes, the duration of a reach exercise was defined as the point when a left-lateral force was positive. Forces were normalized by each subject's bodyweight, and sampled evenly over the duration of the reach exercise.

## RESULTS

Peak resultant forces during reach exercises were between 27 and 34 percent of body-weight, with rail forces being higher than rungs and the vertical ladder force higher than on the tilted (repeated measures ANOVA, $p<0.05$).

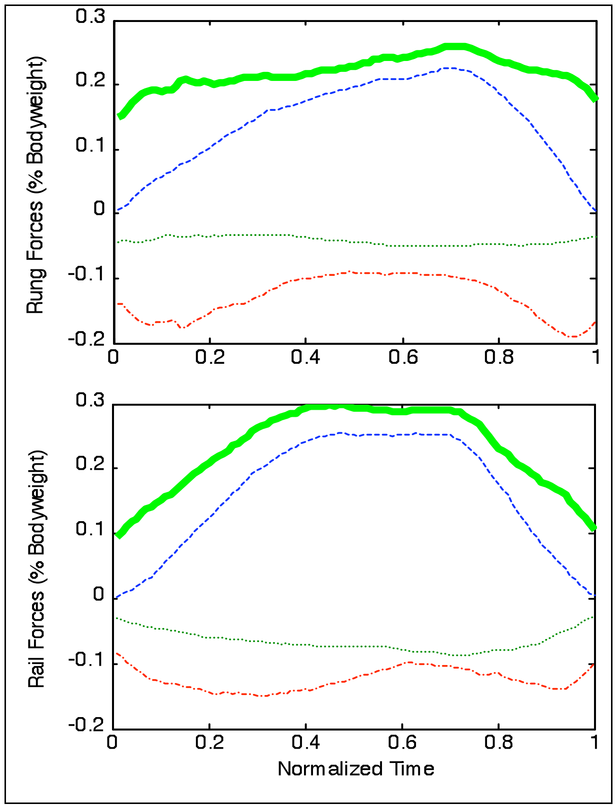


**Figure 1.** Vertical ladder: Mean hand force (% bodyweight) applied to the ladder rung (above) and ladder rail (below) during a reach/return exercise. See legend (Figure 3).

Component forces were dominated by lateral forces (x), but on the vertical rail, in/out (z) forces were larger during the initial reach and the return phase of the exercise. This was not the case for the tilted ladder.

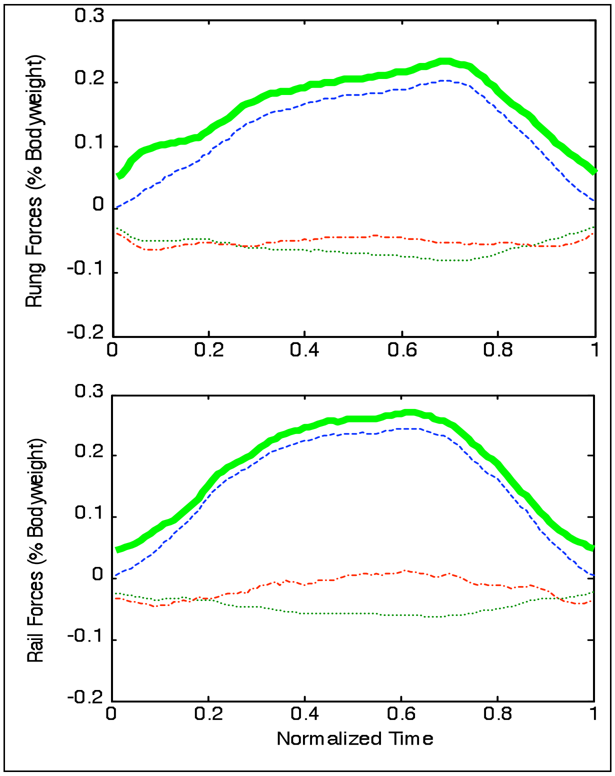


**Figure 2.** Ladder tilted 10º: Mean hand force (% bodyweight) applied to the ladder rung (above) and ladder rail (below) during a reach/return exercise. See legend (Figure 3).

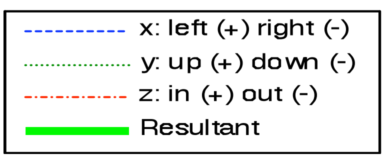


**Figure 3.** Legend: Resultant force is the thick line and component forces are dashed lines.

**DISCUSSION**

These results show a significant amount of force is required to perform a reach one arm span from the center of the ladder. Holding the rails may have resulted in greater force by allowing the body's center of mass to move more laterally. These reach exercises were slow, mostly quasistatic, and if the subject were to increase speed, we would see larger forces on the hand. If the ladder is slippery, the required reaching force may exceed the grasp capability of the hand, or the required friction for the feet to resist lateral load.

On vertical ladders we see a difference in the component forces as compared to the tilted ladder. On a vertical ladder, the body's center of mass is outside the vertical plane. When reaching we see the subject exert a large inward force pulling themselves toward the ladder at the beginning and ends of the reach task. On tilted ladders, the subject can balance their center of mass over their feet and use minimal inward force when reaching.

This study may be useful in predicting the effort a worker will have to exert while performing a lateral reach task such as painting. Fixed ladders are also a good analogue for climbing on fixed equipment such as trucks or racks. In future studies we will increase sample sizes, and explore the effects of reaching with tools, difficulty of the task requiring the reach, and the effects of aging. We may also examine friction on the rungs and torques at the base of the ladder.

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# OVERHEAD GRASP CAPABILITY FOR TYPICAL LADDER HANDHOLDS

Justin Young[1], Michael Sackllah[1], Chuck Woolley[1], Tom Armstrong[1], James Ashton-Miller[2]

[1] Department of Industrial & Operations Engineering, [2] Department of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan, USA, jgy@umich.edu
URL: http://www.engin.umich.edu/dept/ioe/C4E/index.html

## INTRODUCTION

Performance of the hand is central to safety during ladder climbing. According to the Bureau of Labor Statistics, more than 20,000 American workers are injured every year by falls from ladders (BLS 2005). Barnett and Poczynk (2000) defined three distinct phases after a ladder fall event has started: (I) A freefall phase that is a function of reaction time and the grasping movement; (II) The time it takes for the victim's muscle forces to increase to a maximum, (III) The interval when the victim decelerates to a stop. If the maximum coupling force that the victim's hand can exert on the ladder in the third phase is less than the force of the body's weight and inertia, then victim will fail to arrest the fall.

In trying to stop a fall from a ladder, an individual may try to hold onto either the vertical side rails or the horizontal rungs of the ladder. If the hands are on the side rails when the feet slip, friction will be produced between the hand and the rail which will act against the force of the falling body. If the rung is grasped, a power or hook grip will provide the friction plus mechanical interference to arrest the fall. The aim of this study examined how much vertical force subjects could exert on overhead rails and rungs.

## METHODS AND PROCEDURES

To achieve the aim of this study, twelve (6 male, 6 females) subjects stood on a weighted, height-adjustable platform which lowered at a constant 14.5 cm/sec. A weightlifter's dipping belt was used to secure the subject to the platform so that they could not flex their ankles or lift themselves off the platform. Three instrumented handles could be fixed overhead. Two vertically-oriented handles simulated typical ladder rails (a 1" diameter cylinder and a 2½"× 3/8" plate). The third handle was a 1" diameter horizontally-oriented cylinder that simulated a typical ladder rung.

The experiment consisted of a total of fifteen maximum strength trials: three grip strength tests and twelve overhead grasp strength tests. Grip strength was measured for both hands. Subjects were tested grasping each of the three handles using the dominant hand, and the also the horizontal rung in the non-dominant hand. There were three repetitions for each treatment. The order of the trials was randomized. Between each trial the subjects were given breaks of at least two minutes.

For each of the overhead grasp strength tests, the subject was instructed to exert their maximum strength capability and hold onto the handle as long as possible. Subjects were asked if they were ready and were then lowered at a steady rate until their hand decoupled from the overhead handle. The forces exerted on the handle were recorded. Data were analyzed using repeated measures ANOVA with $p<0.05$ being significant.

Subjects were recruited to participate in this study. Their mean (± SD) age, height, weight, and dominant hand grip strength was 21±2 years, 172±11 cm, 625.2±139.2 N and 426.3±123.5 N respectively. On average, males were 196 N heavier, 15 cm taller and had mean grip strengths 245 N greater than females.

## RESULTS

| Handle Type | Grasp Strength (N) | Grasp Strength / Body-weight | Grasp Strength / Grip Strength |
|---|---|---|---|
| Horizontal Rung | 667.9 (237.0) | 1.05 (0.20) | 1.52 (0.23) |
| Vertical Rail | 434.7 (121.3) | 0.70 (0.11) | 1.02 (0.17) |
| Vertical Plate | 336.9 (146.3) | 0.53 (0.13) | 0.78 (0.22) |

**Table 1.** Mean (SD) grasp strength results by handhold type (all subjects, dominant hand).

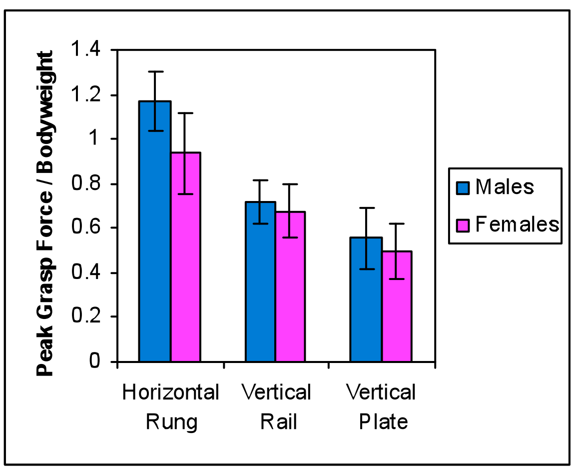


**Figure 1.** Mean (SD) grasp strength divided by the subject's bodyweight for each type of handhold, by gender.

The peak forces exerted on the three overhead handles (grasp strength) were significantly different ($p<0.05$): largest for the horizontal handle and smallest for the vertical plate (Table 1). Similar results were found when normalized by bodyweight and grip strength and when stratified by gender (Figure 1).

## DISCUSSION

The aim of this research was to examine the total strength capability of the hand as it grasps an overhead handle of varying shape and orientation, similar to that found on industrial fixed ladders. It was shown that, on average, only males would be able to support their own bodyweight with one hand, and only when grasping a horizontal rung. For any other handle type, bodyweight exceeds the maximum grasp force. Females, on average, were not able to support their bodyweight with one hand for any of the handles. The grasp strength developed with the non-dominant hand was not significantly less than the dominant hand.

These results imply that only relatively strong persons, or relatively light persons would be able to arrest themselves with one hand if they fell while climbing a ladder, and only if they were holding a ladder rung. In the future we plan to increase group sizes and address the effect of heavy tool belts, advancing age and certain disease conditions. Other factors such as wearing gloves and different rail/rung materials and surfaces will be examined.

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