EFFECTS OF LADDER TYPES ON ENERGY EXPENDITURE AND FOREARM FORCE EXERTION DURING LADDER CLIMBING

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1.0 Introduction:

Commercial heating, ventilation, and air conditioning (HVAC) technicians are required to climb vertical access ladders on a daily basis to access rooftop HVAC units or other elevated work platforms at customer locations. Vertical ladders can present safety risks for slips and falls because of their design (i.e. the rungs are thin and close to the wall), and not built within the Ontario's Building Code requirement. In some cases, the risk of fall injuries can increase because of the poor location of the fixed vertical ladder and its exposure to extreme environment conditions such as wet and icy weather, and bird droppings. Compounding these drawbacks when climbing on fixed vertical ladder is the potential higher energy expenditure and forearm force exertion than climbing a conventional portable ladder, where it is possible to stop and lean into the ladder when tired.

The main purpose of this project was to evaluate the differences in energy expenditure and forearm force exertion when climbing fixed vertical access ladders and portable extension ladders. A secondary objective was to compare two safety devices, Saf-T-Climb and the double lanyard safety system, in terms of their practicability in preventing slips and falls on a vertical fixed ladder.

2.0 Methods:

2.1 Participants:

Twenty (20) HVAC workers participated in this study. The age groups and the number of workers in each group are summarized in Table 1.

Table 1: Age categories and number of workers in each group.

Age Group	Number of workers
< 30 years	8
31-40 years	6
41-50 years	4
> 50 years	2

2.2 Procedure:

Before conducting the experiment, all participants were notified of the purpose of the study and any risks of injury involved. All participants were asked to sign a consent form and answer a health questionnaire before starting the work trials (see Appendix A).

After signing the consent form, participants took the modified Canadian Aerobic Fitness (mCAF) test. The mCAF test was developed in the mid-1970s as a simple home tool for the indirect measurement of maximum volume of oxygen intake (VO_{2max}) during exercise. The higher the VO_{2max} value, the better the person's fitness level. During the mCAF test, the participants were asked to climb and descend a standardized double 8-inch (20.3 cm) step at an age and gender-specific rate set by the music from a long-playing CD. At the end of each testing period, heart rate while recovering from the stepping exercise was used to estimate the VO_{2max}. This VO_{2max} was used to indicate the fitness level of the participants and also used to estimate the total energy expenditure (in unit kilocalories) during physical activities. The actual test duration was dependent on the physical fitness of the participant. Generally, the mCAF test lasted for approximately 15 to 20 minutes. To prevent risk of injury, only individuals showing a "fair" or greater fitness level were allowed to participate in the climbing experiment. Overall, two-thirds of the participants were allowed to take part.

All experiments were carried out at CSAO's training facility. To investigate the energy required to climb portable and fixed ladders at various heights, a simulated ladder-climbing activity was designed. A climbing height of 20 feet was used in this experiment. For the portable ladder trial, the ladder was set up at a slope of 75º or 4:1 ratio. Both ladder types, fixed and portable, were attached to a scaffold to simulate the climbing activities. A fall protection system, consisting of a full-body harness attached to a lifeline anchored to the structure overhead, was worn by all participants throughout the climbing activities. The purpose of wearing the fall protection system was to protect workers from injury in the event of a fall.

Participants were videotaped while performing the ladder-climbing tasks in this study. The purpose of the videotape was to evaluate the participant's climbing procedure. More specifically, the videotapes were used to determine the percentage of participants using the 3-point contact technique (i.e., two hands and one foot or one hand and two feet in contact with the ladder at all times).

For each ladder-climbing trial, participants were asked to perform continuous climbing for approximately five minutes without rest between each climbing cycle. Recording of heart rate and energy expenditure for a particular climbing trial was commenced when the participant's heart rate exceeded 90 beats per minute or was above 60% of the participant's maximum heart rate, whichever was less. The climbing period to exceed the 90 beats per minute threshold was treated as the warm-up period, or the time allowed to reach a steady state heart rate and oxygen uptake rate.

A Polar 625X (Polar Electro Oy, www.polar.fi) heart rate monitor was worn by all participants during all experimental trials. To measure the heart rate and energy expenditure through out the experimental trial, a strap containing the electrode was connected around the participant's chest, just below the chest muscles. A watch was attached to the participants' wrist to record and store the heart rate signal. Energy expenditure during the experimental trial was calculated based on: individual maximal oxygen uptake (VO_{2max}), individual maximum heart rate (HR_{max}), heart rate during exercise and body weight. Counting of the calories burned began when the participant's heart rate reached 90 beats per minute (bpm). All calculated energy expenditure was accomplished by the Polar 625X. After the experimental trial, the heart rate and energy expenditure measured by the Polar 625X during the experimental trial was downloaded to a PC for further analysis.

Muscle activity in the forearms was measured using surface electromyography (EMG) on each worker during all experimental trials. EMG signals were recorded by attaching surface electrodes (Ag/AgCI - electrode distance of 20 mm) on the skin surface above the left and right flexor digitorum superficialis. Positions for electrodes on the forearm muscles can be found in other references (Basmajian and Blumenstein, 1980).

Figure 1: A participant undertook a climbing task on a vertical fixed ladder.

After all the electrodes were secured on the skin, the participants were asked to relax their muscles for 5 –10 seconds to obtain baseline resting EMG signals. After collecting the resting baseline EMG, a series of maximal voluntary contractions (MVC) were performed in order to obtain EMG signals representing each muscle's MVC. These MVC EMG signals were then used to normalize (expressed as %MVC) the collected experimental trial EMG signals. Two-repeated MVC, with one minute rest between each MVC, were performed in pre-defined standing postures. For the forearm muscles, the participant's upper arms were in a neutral position, elbow 90º flexed, forearm fully supinated, and wrist and fingers fully extended. A strap was attached vertically across the participant's metacarpophalangeal joints and the participant was instructed to pull the strap upwards with maximum effort.

The EMG signals were recorded by a Biometric DataLog EMG system (Biometrics Ltd, Gwent, UK). The DataLog is a fully portable subject-worn data acquisition unit allowing a researcher to collect up to an 8-channel EMG signal. Muscle activity signals picked up by the electrodes were stored by the DataLog and were downloaded after the experiment. A sampling frequency of 1000 Hz was used in this study to transfer the analog signal to digital units for computer processing. After downloading the data, the EMG signals were subtracted by the DC levels (system noise), RMS converted, and low-pass Butterworth filtered at cut-off frequency of 6 Hz. Working EMG signals were obtained by subtracting the experimental trial EMG with the mean resting EMG levels. The work EMG signals were normalized by the signals obtained during the maximal voluntary contractions (MVC). The normalized signals were then averaged across the experimental trial.

After performing both ladder climbing trials, the participants were asked to climb on the vertical fixed ladder using two types of safety systems. One system was a SAF-T-CLIMB consisting of a metal carrier rail, ladder rung clamps and a Saf-T-Lok Sleeve (see Photo 1). According to North Safety Products (www.northsafety.com), the Saf-T-Climb system permits safe worker movement. Any slip or fall is stopped by the locking action of the Saf-T-Lok Sleeve, thereby preventing a fall. A second system to prevent falls from a ladder evaluated in this study was a six-foot double lanyard snap hook system (see Photo 2). The double lanyard system can prevent a fall by always being attached to a fixed ladder at any given point of the ladder-climbing process.

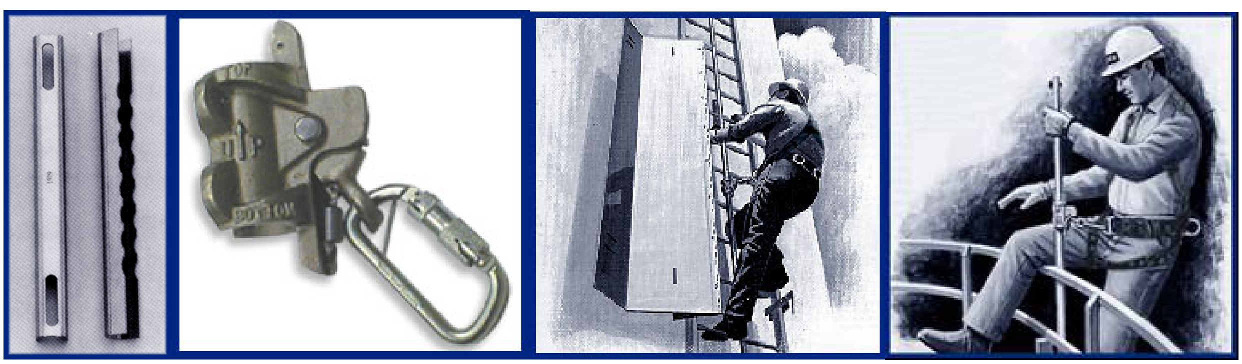

Photo 1: Components of a Saf-T-Climb system. Courtesy of North Safety Products Inc (www.northsafety.com).

Photo 2: A six-foot double lanyard containing two snap hooks. Courtesy of North Safety Product (www.northsafety.com)

3.0 Results & Discussions

3.1 Fitness Level (Predicted VO_2max)

A summary of the frequency distribution of the fitness level of all participants is shown in Figure 2. Fitness level was based on the mCAF test which grouped individuals into a particular level according to their predicted VO_2max and the participant's age group. Approximately 50% of the participants were classified in the "good" to "very good" categories. The other 50% of the participants, however, were classified from "fair" to below "fair" (see Figure 2).

In this study, approximately 35% of the participants were classified below the "fair" category. The high number of participants in the "needs improvement" and "failed" categories was above the norm found by Bailey et al (1976). Bailey et al (1976) conducted a large study across different age groups and found approximately 30% of Canadian were classified below the "fair" category.

The body mass index (BMI) was calculated in this study using the participants' mass and height values. The BMI is a good indicator in determining the body size characteristics of an individual. A BMI of between 20 and 25 is considered to be normal; whereas a BMI of 25 to 30 is "overweight" and above 30 is considered to be "obese". Approximately 45% of the participants were classified as "obese", 25% of the participants were "overweight", and 30% of the participants were "normal".

The relationship between predicted VO_2max and BMI was found to be inversely correlated. That is, the lower the BMI value, the higher the predicted VO_2max. As shown in Figure 3, majority of the participants were classified as "obese" and thus their predicted mean VO_2max was found to be lower than the "overweight" and "normal" group. The higher proportion of individuals in the "obese" category may be one explanation for the higher proportion of individuals in the below "fair" category in terms of physical fitness level.

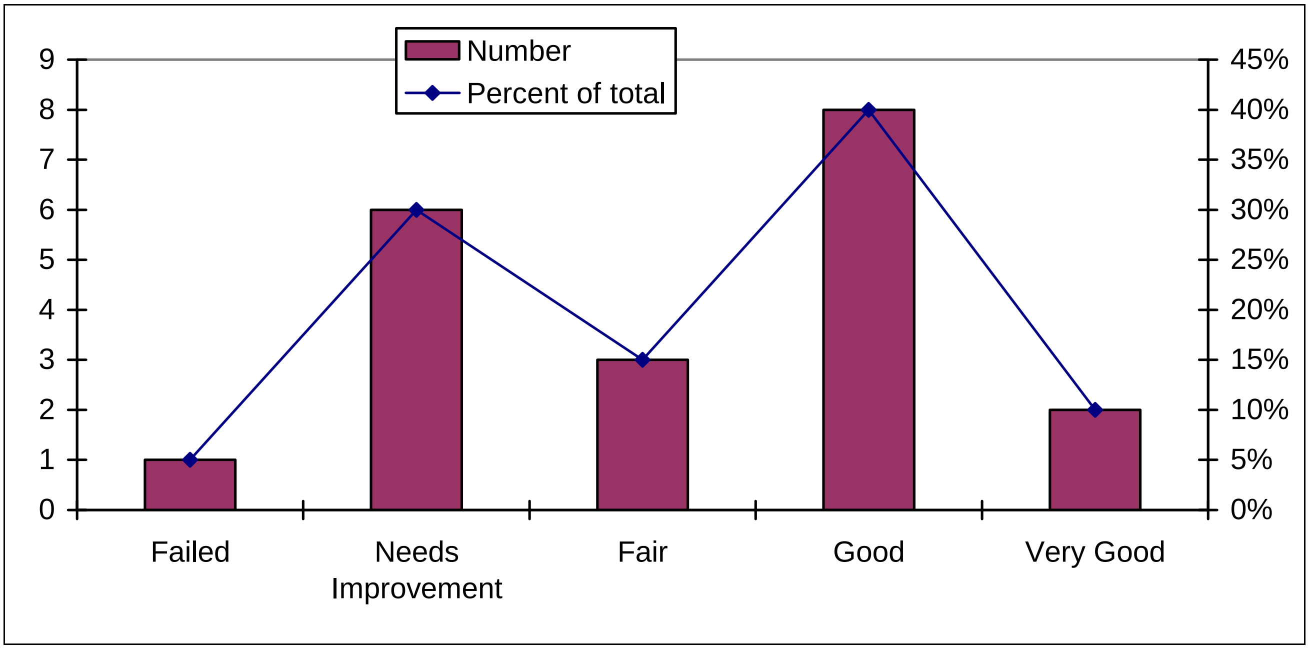

Figure 2: Fitness level distribution across all participants. The fitness level category was based on the mCAF test.

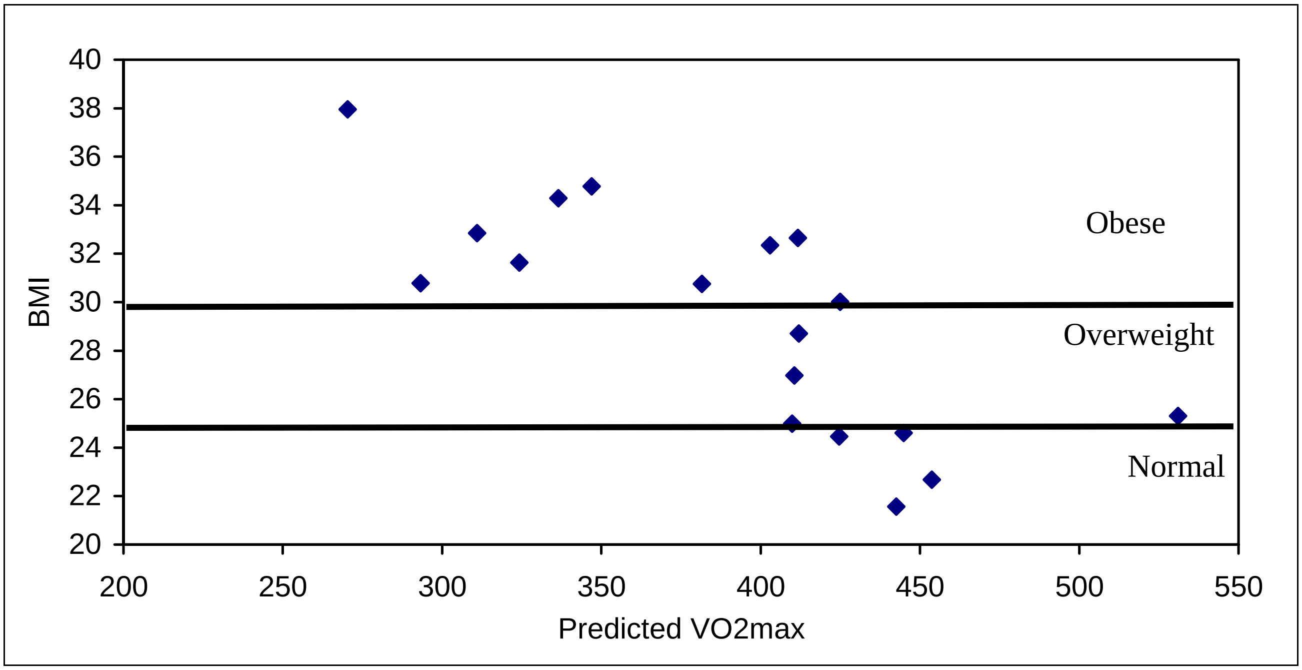

Figure 3: Fitness level versus body mass index (BMI). An inverse correlation was found.

3.2 Energy Expenditure And Heart Rate While Climbing Ladders

Energy expenditure and heart rate while cimbing vertical fixed and portable extension ladders are summarized in Figure 4 and 5. Climbing on portable and fixed ladders required a mean energy expenditure rate of 11.4 kcal/min and 13.1 kcal/min, respectively. The energy expenditure difference between the two ladder designs was found to be statistically significant ($p<0.05$) using the paired T-test statistical method. For comparison purposes, the maximum energy expenditure for male workers, as recognized by the Ontario Ministry of Labour, should not exceed 5 kcal/min for eight-hour work duration. Given this maximum level, ladder climbing tasks can be defined as highly physically challenging tasks from a physiological point of view.

Further evidence of higher physiological demands when climbing fixed vertical ladders can be found in the heart rate data (see Figure 5). *Mean peak* heart rate was found to be significantly ($p<0.05$ using pair T-test statistics) higher when participants climbed on the fixed ladder than on the portable ladder (172 b/min for the fixed ladder versus 160 b/min for the portable ladder). *Average* heart rate across the climbing trials were also found to be significantly ($p<0.05$) higher during the fixed ladder climbing task (see Figure 5).

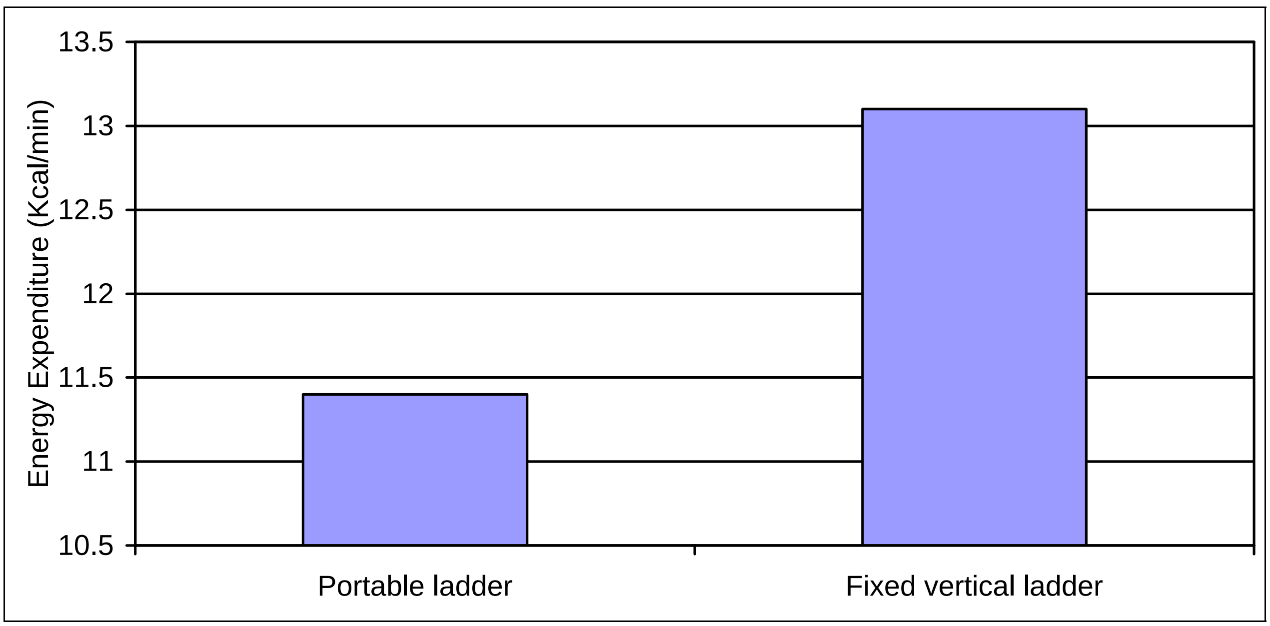

Figure 4: Energy expenditure while climbing on two different ladders. Climbing on portable ladder required significantly ($p<0.05$) lower energy expenditure than climbing on fixed vertical ladder.

3.3 Forearm Force Exertion While Climbing Ladders

Similar to the peak and average heart rate findings, the forearm force exertion was also found to be significantly ($p<0.05$ using pair T-test statistics) lower when participants climbed on the portable ladders (see Figure 6). This finding was true for both the left and right forearms. The high forearm force exertion when climbing fixed vertical ladder may due to the perpendicular slope characteristics of the ladder. Other factors which can result in a higher forearm force exertion when climbing on the fixed vertical ladders may due to the differences in ladder climbing procedure between the two ladder types (see Section 3.4 for further explanation).

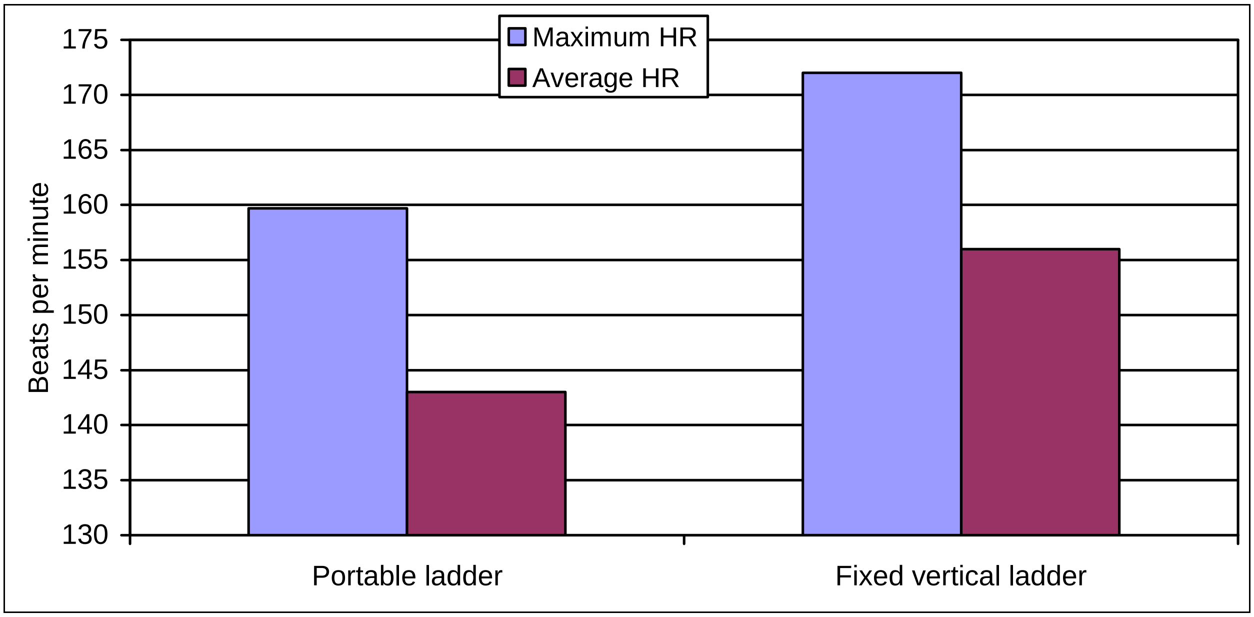

Figure 5: Average and peak heart rate (HR) while climbing on two different ladders. Climbing on portable ladder resulted in a significantly ($p<0.05$) lower peak and average heart rate than climbing on fixed vertical ladder.

3.4 Ladder Climbing Procedure

Using videotape analyses, this study found that 10% of the 20 participants used a 3-point contact technique when climbing the vertical fixed ladder. For portable ladder climbing, however, 80% of the participants maintained 3-point contact during climbing. The small proportion of individuals using 3-point contact during vertical fixed ladder climbing may be one explanation for the high forearm muscle exertion observed in the fixed ladder climbing condition (see Figure 6). That is, due to the two point contact on a fixed ladder (i.e., one hand and one foot), the forearm muscles must exert a greater amount of force in order to support and lift the body to the next rung level. For the portable ladder, however, most participants maintained 3-point contact and thereby were able to spread the forceful exertion to a greater amount of muscle groups throughout the upper and lower extremities.

Before conducting this study, it was expected that workers would maintain 3-point contact during the vertical fixed ladder climbing. The high proportion of workers utilizing 2-point contact is a major concern from a safety point of view. That is, 2-point contact would expose workers to a greater risk of slipping and falling off a ladder compared to maintaining 3-point contact at all times. Compounding to this risk is the greater muscle exertion of the forearm, larger amount of energy expenditure which can increase the risk of fatigue, poor location, and poor design (i.e., the rungs are thin and close to the wall) of the fixed ladders.

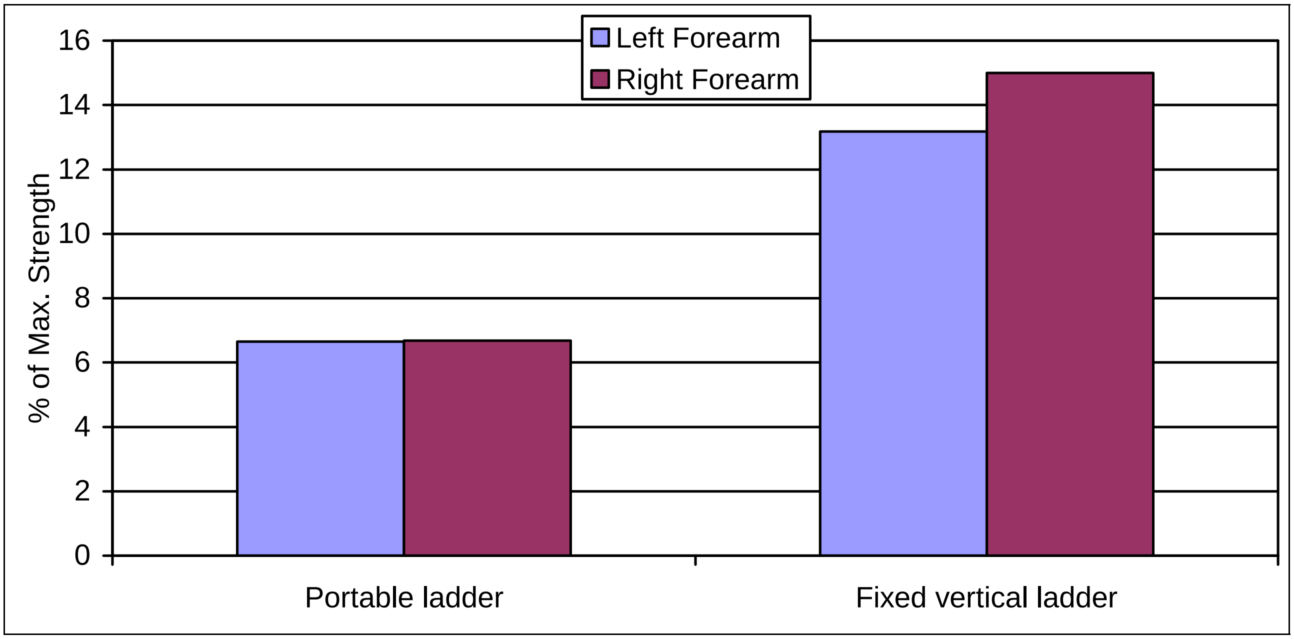

Figure 6: Average forearm force exertion while climbing portable and fixed vertical ladders. Fixed vertical ladder climbing required significantly ($p<0.05$) greater forearm muscle exertion.

3.5 Ladder Fall Prevention Systems

Two ladder fall prevention systems, SAF-T-CLIMB and double lanyard, were evaluated in this study. Approximately 85% of the participants indicated that they preferred to climb with the SAF-T-CLIMB system. Only 15% indicated that they preferred the double lanyard. Participants preferred the SAF-T-CLIMB system because it makes vertical climbing very quick and easy. Participants also indicated that the climbing process, when using the SAF-T-CLIMB, was similar to climbing on the fixed ladder without the safety system.

The second fall protection device evaluated in this study was the double lanyard system. Climbing with the double lanyard requires alternately connecting and disconnecting two lanyards as the worker climbs up and down. At any time during the ladder climbing, one lanyard is attached to the rung and thereby protecting the worker from falling. In this study, most participants did not prefer to climb with the double lanyard. They indicated that the double lanyard was too awkward, time-consuming to climb, and required greater muscle use than climbing without the double lanyard. Given these negative perceptions, workers indicated that they would not regularly use the double lanyard system unless there is enforcement or if the ladder on the job site contains many hazards such as bird droppings, wet ladder rung, damaged ladder, and the height of the ladder.

4.0 Limitation Of Conclusions

There were several limitations in this study which may limit the validity of the results. These limitations were:

1. Only ladder climbing task was evaluated in this study. The study did not evaluate energy expenditure and forearm force exertion when manual material handling of

portable extension ladder off service vehicle and setting up the ladder. The overall energy expenditure and forearm force required to unload, carry, and set up a portable ladder may be greater than using the fixed ladder provided by the clients.

2. Predicted energy expenditure and fitness level was based on participants' heart rate. Estimation of energy expenditure and fitness level using heart rate has been found to be a valid method. Large error, relating to underestimating the predicted energy expenditure and fitness level, can occur for those individuals with high VO_2max value.
3. Climbing and descending on a portable ladder may expose workers to slip and fall injuries if proper setup and work practices are not followed. Risk of falling off portable ladders may increase when workers improperly set up the ladder (i.e., not maintaining 3:1 or 4:1 slope ratio), no tie-off at the top and bottom, ladder is placed on an uneven ground, or ladder is not extended more than two rungs above the bearing point.

5.0 Conclusion

The main purpose of this study was to evaluate the differences in the energy expenditure and forearm force exertion while climbing on two ladder designs (portable ladder and vertical fixed ladder). This study hypothesized that the energy expenditure and forearm force exertion will be significantly higher when participants climbed on the fixed ladder design. Results from this study confirmed the initial hypothesis. Due to the higher energy expenditure, greater forearm forceful exertion, and 2-point contact technique, repetitive climbing on a vertical fixed ladder is more likely to increase the occurrence of whole body fatigue, localized forearm muscle fatigue, and higher risk of slip and fall than climbing on a portable ladder. Given these findings, it is recommended that workers should use portable ladders when the work environment permits. Safe work practices, as outlined by CSAO Construction Health and Safety Manual (#M029), CSA Z11, or ANSI A14.1-A14.3, should also be followed in order to prevent falls from ladders.

6.0 References

Bailey D., Shephard R., and Mirwald R., (1976). Validation of a self-administered home test of cardio-respiratory fitness. Canadian Journal of Applied Sport Sciences, 1:67-78.

Construction Safety Association of Ontario (1997). Construction Health and Safety Manual. Publication number (#M029).

Garg A., and Chaffin D., (1978). Prediction of metabolic rates for manual materials handling jobs. American Industrial Hygiene Association Journal, 39: 661-674.

Appendix A

Health Questionnaire:

	Yes	No
1. Has a doctor ever said that you have a heart condition and recommended only medically supervised activity?	☐	☐
2. Do you have chest pain brought on by physical activity?	☐	☐
3. Have you developed chest pain in the past month?	☐	☐
4. Do you tend to lose consciousness or fall over as a result of dizziness?	☐	☐
5. Do you have a bone or joint problem that could be aggravated by the proposed physical activity?	☐	☐
6. Has a doctor ever recommended medication for your blood pressure or a heart condition?	☐	☐
7. Are you aware through your own experience, or a doctor's advice, of any other physical reason against your exercising without medical supervison?	☐	☐

Note: If you have a temporary illness, such as a common cold, or are not feeling well at this time – please postpone.

Agreement to Participate

I have read and understood the information presented about the procedures and risks involved in this study and have received satisfactory answers to questions related to this study. I understand that any information I provide will be treated as confidential and not be shared with the company, the union(s), or anyone outside the research team and that all information will be reported in ways which ensure that I, and the company I work for, cannot be identified. I am aware that if I have comments or concerns regarding this study I may contact Peter Vi by phoning (416) 679-4050 or toll free: 1-800-781-2726. With full knowledge of all the foregoing, I agree to participate in this study.

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Signature of Participant

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Print Name