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Strength demands of line handlers on the Panama canal

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Abstract. Vessels transiting the Panama Canal are guided through the locks using locomotives attached by means of towlines (made of wire rope), which are fastened to bitts on the deck by line handlers. The latter activity requires high pulling strength demands and is thought to be a cause of the high incidence of low back disorders in these workers. At the invitation of the Panama Canal Commission, NIOSH researchers evaluated the strength demands of line handlers and the strength capabilities of a line handling crew. Strength demands measured during a transit indicated high pulling force demands for attaching ropes to the bow and stern bitts (> 1000 N), but lower force requirements for midships bitts (< 400 N). Tests of pulling strength capabilities of a line handling crew suggest that at least 4–5 line handlers are needed to perform the most demanding tasks. When pulling upwards or downwards on a rope in a team effort, ordering the crew according to stature appears important. Simulation of slippery deck conditions resulted in a 13% decrease in team pulling strength. Though the short duration of the study prevented an extensive evaluation, the data obtained provides insight into the design aspects of occupations where team-pulling activities are required.

Keywords: Ergonomics, musculoskeletal disorders

1. Introduction

The idea of digging a channel across a thin strip of land in what is now Panama was first suggested in the 16th century by King Carlos of Spain, who ordered the first survey of possible routes. It would take several attempts, cost several thousand lives, and require almost 400 years to make this dream a reality. However, on August 15, 1914, with the transit of the *Ancon*, the Panama Canal was officially opened. The Canal continues to play an integral role in world commerce and shipping.

In what is a testament to the remarkable feat of engineering associated with the construction of the Panama Canal, its operation today is almost identical to the manner in which the Canal operated when it first opened. In many respects this may be viewed as something quite favorable; however, it should be noted that certain aspects of Canal operation require tasks that involve significant physical demands for workers. Foremost among these is the job of the line handler. These workers must perform heavy isometric pulling exertions on lines (made of wire rope) so that they can be attached to bitts on the deck of ships. The reason these lines are attached to these vessels is to facilitate precise control of the vessels as they transit locks on the Canal. In response to the high rate of low back complaints among line handlers, the Panama Canal Commission contacted researchers at the National Institute for Occupational Safety

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and Health (NIOSH) late in 1998 to evaluate the risk factors for low back disorders associated with this occupation.

Research has indicated that jobs that require high strength demands may pose a risk for low-back disorders [1], and that the risk of injury is associated with such jobs depends on the relationship between the job's physical demands and the strength capabilities of the workers [3,4]. Bearing this relationship in mind, NIOSH researchers traveled to the Panama Canal in December of 1998 to evaluate both the job demands and the strength capabilities of a line handling crew. This paper describes results of tests of Line Handler pulling demands during transit of a Panamax vessel through the Miraflores and Pedro Miguel locks of the Panama Canal, as well as an examination of the strength capabilities of a typical line handling crew. Unfortunately, the limited time frame and logistical constraints associated with arranging Canal transits and Line Handler crew availability limited the extensiveness of the evaluation. Nonetheless, the data obtained in this investigation provided useful information towards serving its main purposes: evaluation of the strength demands and strength capabilities of Line Handlers, and the determination of the number of Line Handlers necessary to safely meet the significant pulling demands required in this job.

2. Background

The Panama Canal is approximately 50 miles (80 km) long from the Caribbean Sea on its Atlantic side to the Pacific. A vessel takes approximately 8 to 10 hours to pass through the Canal. The key to the operation of the canal is its three sets of locks – Gatun on the Atlantic side and Pedro Miguel and Miraflores on the Pacific side (Fig. 1). These three locks raise vessels over the continental divide and lower them to sea level again, a height of 85 feet (26 m).

2.1. Operation of the locks on the Panama canal

As a vessel approaches the locks (Fig. 2(A)) the valves of the first chamber are opened and water flows in by gravity from the higher chamber. When the water is at sea level the gates open and the vessel enters the first chamber. The gate closes behind the vessel. The valves of the second chambers are opened (Fig. 2(B)) to increase the water level of the first chamber. When the water levels of the first and second chamber are equal the gates open and the vessel enters the second chamber (Fig. 2(C)). This process is repeated to bring the vessel into the third chamber. Once the vessel is in the third chamber the water is leveled and the vessel exits the lock and enters the lake (Fig. 2(D)). On the other end of the canal the process is reversed and the vessel is lowered to sea level.

Panama Canal locks locomotives (Fig. (3)) assist vessels during their transit through the waterway. Their job is to tow, brake, and hold the vessels in precise alignment relative to the lock structures. The locomotives travel on tow tracks that run from one end of the locks walls to the other, going up and down inclines and maneuvering around curves. These locomotives, under the command of a Panama Canal Commission Captain, control the vessels in the locks by fine adjustments of the wire towlines attached to bitts on the deck of the vessel (as diagrammed in Fig. 4).

2.2. The role of the line handler

The Line Handlers primary job is to attach the towlines that go from the vessel to the lock locomotives. There is a crew of at least four Line Handlers assigned to each large vessel. The Line Handlers board

Fig. 1. Panama and the locations of the canal locks.

the vessel before it enters the locks, and stay on board throughout the transit. As the vessel approaches the lock, a 1.3 cm hemp leader line is tossed to the locomotive or a small dingy in the water, where it is attached to one of the locomotives 2.5 cm diameter wire towlines. A winch mounted on the vessels deck then draws in the leader line. As the leader line is pulled onto the vessel it draws the towline on board. The line handlers then must manually pull the towline and perform a significant isometric pulling exertion to hold the towline in place while the end of the line is looped over the bitt (a process known as "capping the bitt"). The winch on the locomotive then takes up any slack. As the locks are approached, the line handlers rapidly cap bitts from bow to stern. The bow bitts are the first capped, followed by the midship bitts, and lastly the stern bitts. Figure 5 shows a line handling crew pulling towlines on board a vessel prior to capping the midships bitts. Once the vessel clears the locks, the Line Handlers remove the towlines from the bitts and let them fall back into the water, where the locomotive's winch draws them in.

3. Methods

3.1. Evaluation of strength demands of line handling

In early December of 1998, representatives from NIOSH and the Panama Canal Commission boarded a Panamax vessel (the *Ever Racer*) along with a line handling crew to evaluate the strength demands associated with pulling the wire rope cable preparatory to capping bitts at various locations on the ship. Strength demands were evaluated using a portable Chatillon[1] CSD 300 strength dynamometer. This

[1]Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

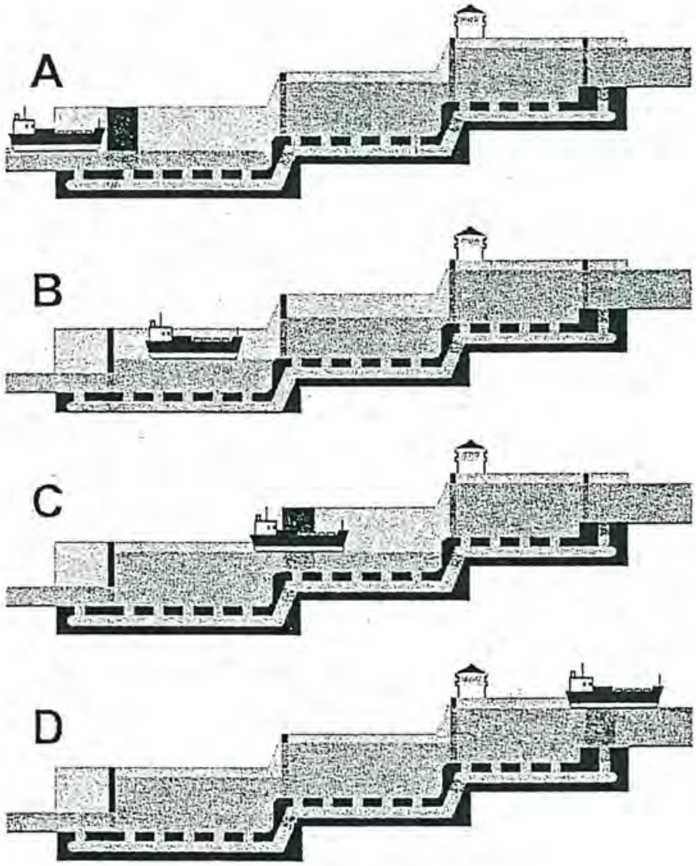

Fig. 2. Lock operating sequence.

dynamometer has a capacity of 500 pounds of force and an accuracy of ± 1 lb. Tests were performed by putting the dynamometer in line with the wire rope and having the workers pull on a hemp rope to estimate the forces required for various line handling tasks. The strength demand assessment consisted of a 5 second isometric exertion where the subjects quickly increased their strength exertion to that required for the task, and maintained that level of exertion for a 5 second period of time [2]. Peak and average force values were recorded for each test.

Measurements of strength demands were taken as line handlers capped bitts during approach of both Miraflores and Pedro Miguel Locks. Two force measurements for each bitt location were obtained except for the stern bitt, where one was obtained. At the Miraflores locks, the stern bitt was capped before researchers could reach the location.

3.2. *Evaluation of strength capabilities of a line handling crew*

After the partial transit was completed, a team of Panama Canal Commission and NIOSH personnel traveled to Davis Landing to perform a series of strength tests on a crew of 5 line handlers. The crew evaluated was composed of 4 men and 1 woman. Subject characteristics can be found in Table 1 below. The pulling tests consisted of an upward pull (in which the distal end of the rope was attached to point 0.2 m above the ground), a horizontal pull (distal end of the rope attached to a point 1.5 m above the ground), and a downward pull (distal end of the rope attached 2.7 m above the ground).

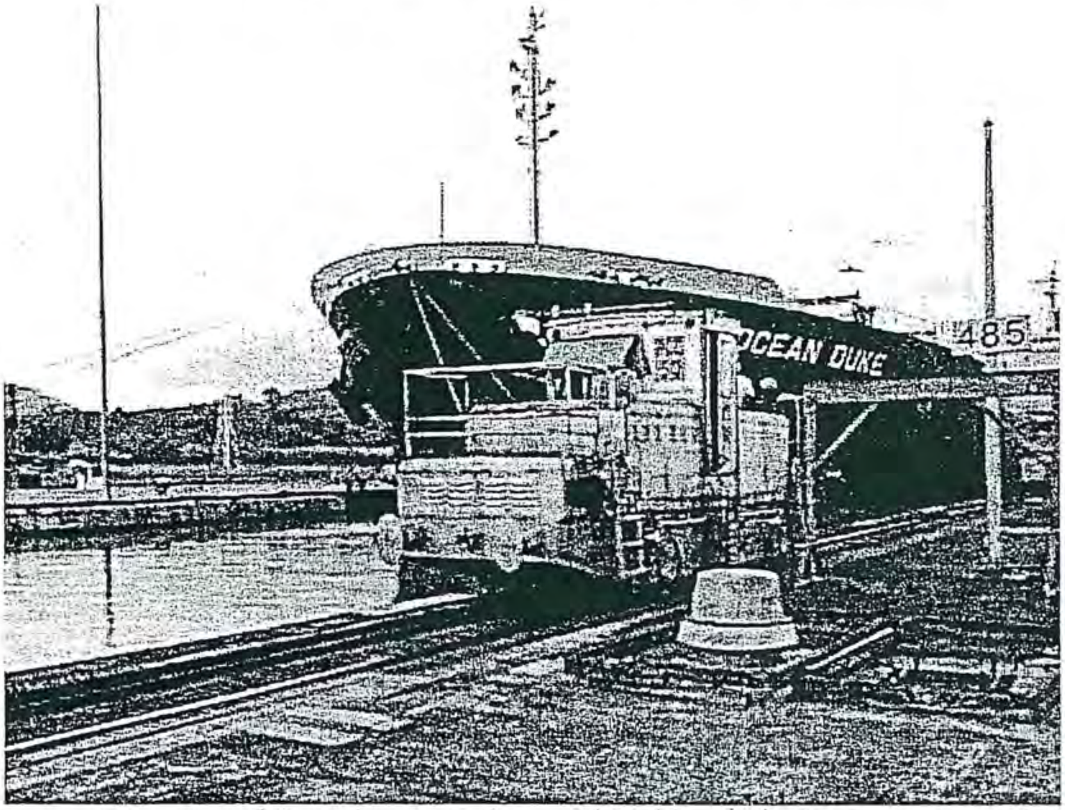

Fig. 3. Locomotive with towlines attached to a vessel.

3.2.1. *Individual strength*

Individual strength tests were first performed on the five line handlers on the crew. Each line handler was asked to perform three pulling exertions on a rope, all of which were measured via the dynamometer. The exertions included a pull upwards on the rope, a horizontal pull, and a pull downwards. Figure 6(A) shows a line handler performing one of the individual strength tests.

3.2.2. *Team strength*

Since line handlers are usually required to perform pulling tasks in tandem, it was of interest to determine the effect of the number of handlers pulling on the rope with respect to the strength capabilities observed. Therefore, a series of strength tests were performed using 2, 3, 4 and 5 line handlers pulling on a rope. Upward pulls, horizontal pulls, and downward pulls were performed using each number of handlers, with one exception. The upwards pull was not performed with five line handlers due to concerns that the amount of force generated would exceed the force capability of the digital strength gauge, resulting in possible damage to the unit. Figure 6(B) demonstrates an upward pull being performed by 4 line handlers.

3.2.3. *Effects of crew order on upward and downward pulls*

Since line handlers often must pull upwards or downwards on ropes, investigators were interested in whether the order of the workers pulling on the line might have an effect on strength capabilities. Specifically, the investigators were interested in the effects of ordering the workers by stature in upwards,

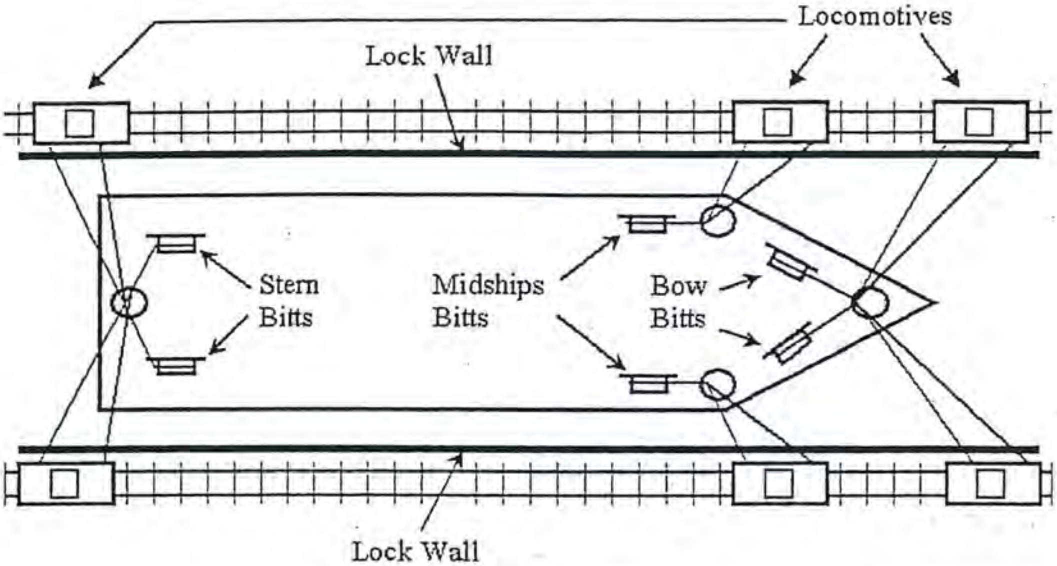

Fig. 4. Diagram detailing how towlines are attached to bitts on the vessel and how locomotives facilitate control of the vessel through the Canal locks.

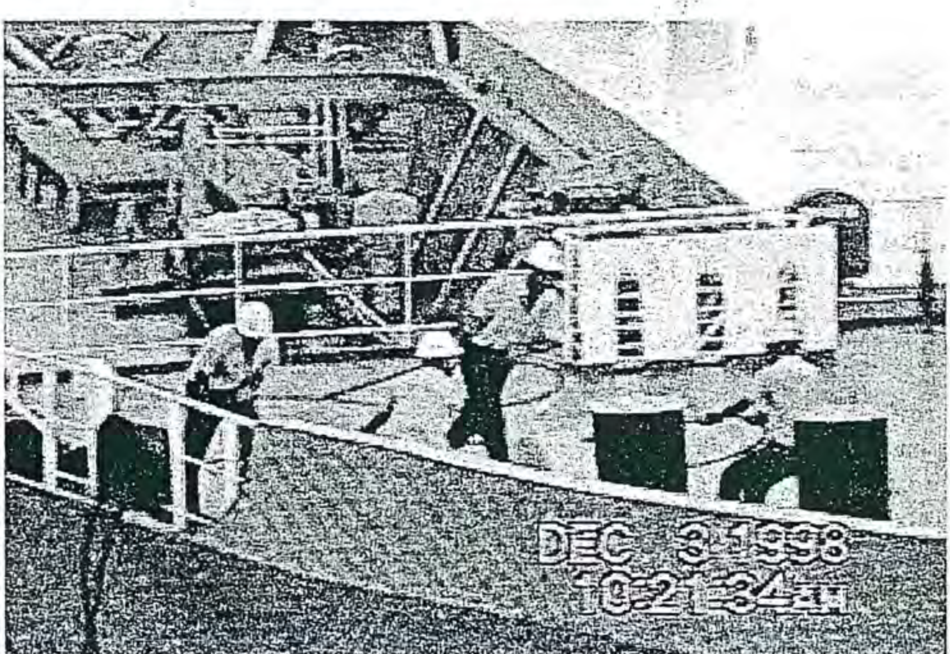

Fig. 5. Line Handlers pulling towline on board.

downwards and horizontal pulls. Within each angle of pull, one test was performed with the workers ordered from shortest in front to tallest in the back, the other was performed in the reverse stature order. Figure 6(C) illustrates a downward pull with the crew ordered tallest in the front to shortest in the back.

Table 1
Subject characteristics for isometric strength tests at Davis Landing

Subject	Gender	Age (yr)	Height (cm)	Weight (kg)
RE	M	28	170.2	73.5
RL	M	35	176.0	95.3
KF	M	27	188.0	119.7
AC	F	34	165.1	68.0
DF	M	27	185.4	116.1

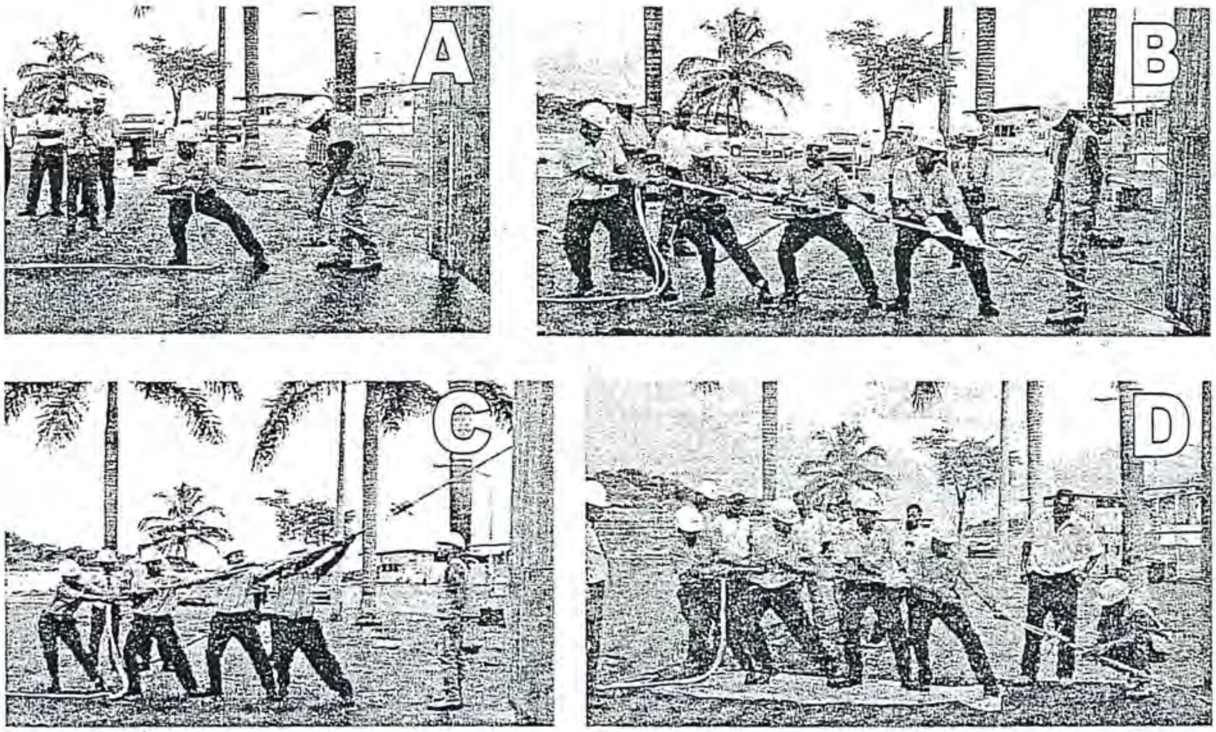

Fig. 6. Examples of various tests of strength performed on a line handling crew. A) Individual pulling strength test, B) Test of team pulling strength, C) Test of the effects of crew order on pulling strength, D) Pulling test on slippery surface.

3.2.4. Effects of slippery conditions on pulling strength

Line handlers often perform their jobs under inclement weather conditions. As a result, footing conditions are often less than ideal. To examine the effects of poor footing conditions, two strength tests were performed while workers stood on a plastic sheet (see Fig. 6(D)). Both strength tests were an upward pull – one involved 3 workers, the other used four.

4. Results

4.1. Strength demands associated with capping bitts

Figure 7 presents the average strength requirements for attaching (or "capping") the bitts at various locations on the Panamax vessel. Capping the bow bitts resulted in consistently higher strength requirements than any other task. At Miraflores, the peak force registered 1157 N with a mean force of 866 N.

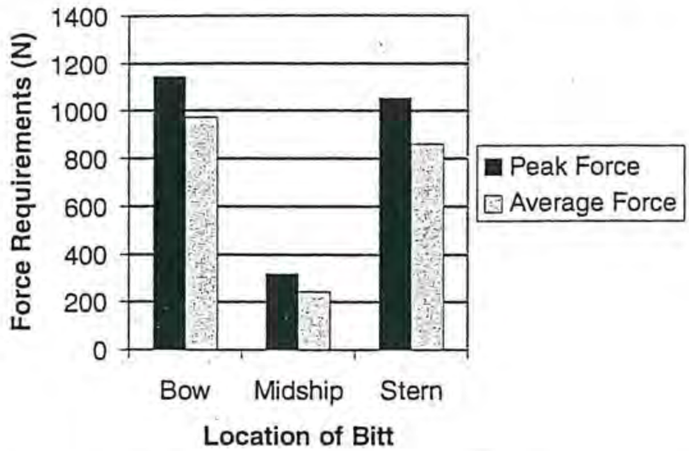

Fig. 7. Peak and average pulling force requirements associated with capping bitts at various deck locations.

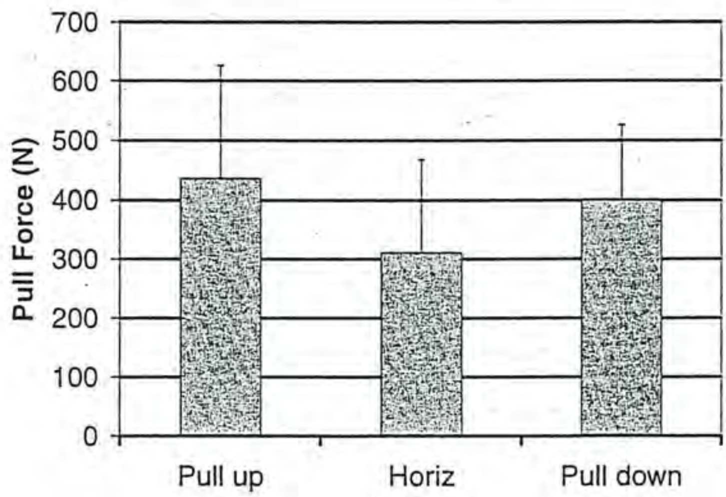

Fig. 8. Results of tests of individual pulling strength of line handler crew.

The results of this task at Pedro Miguel were very similar, with a peak force of 1135 N and an average force of 1081 N. Capping the port stern bitt required slightly less pulling force (peak: 1055 N, mean: 861 N) than the bow bitts. The midships bitts were consistently the least stressful, but appeared to have some variability in terms of pulling strength demands. During the Miraflores transit, the peak force for capping the midships bitt registered only 89 N (mean: 65 N). However, at the Pedro Miguel Locks capping the starboard midships bitts required 545 N of peak force, with an average of 423 N of force over the 5-second exertion. It is interesting to note that only 3 line handlers were used when capping the midships bitts, whereas 4 line handlers were employed when capping of the bow and stern bitts. This appears to be clear response to the relative force requirements associated with capping the bitts at the various positions on the vessel.

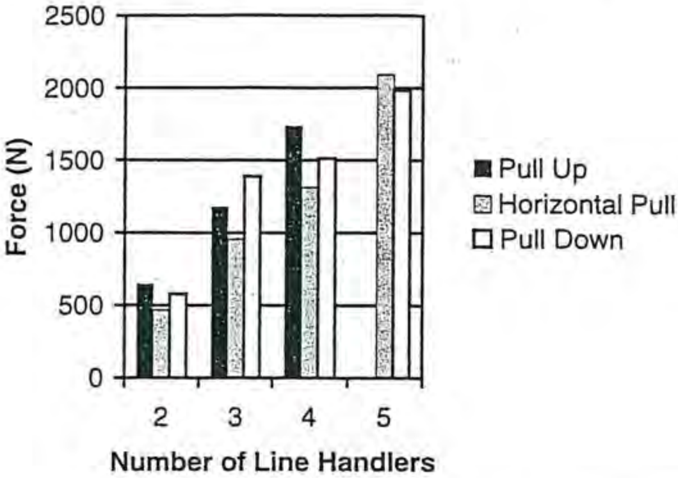

Fig. 9. Results of team pulling strength of the line handling crew.

4.2. *Strength tests*

4.2.1. *Individual strength*

Figure 8 presents the means and standard deviations of individual strength tests for upward, horizontal, and downward pulls. Inspection of the data indicates a reduced capability to exert force in horizontal pulling compared to either upward or downward exertions (approximately 25–30% less force exerted in horizontal pulls). Pulling upward on the rope resulted in the highest average force generation (436 N on average), with downward pulls averaging approximately 8% lower than upward pulls.

4.2.2. *Pulling tests using multiple line handlers*

Figure 9 displays the results of tests examining the effects of the number of line handlers performing the pull on strength capacity. This figure illustrates the significant increases in strength associated with increased numbers of handlers contributing to the exertion. A regression equation was performed to examine the relationship between strength, the number of line handlers and the type of pull (upwards, horizontal, and downwards). The number of handlers was found to be a significant predictor of pulling strength, but the direction of the exertion was not significant. The data were well described by the following regression equation, using a model forced through the origin (model significant at $p < 0.0001$):

$$\text{Pulling Strength } (N) = 383.2 * \text{Number of Line Handlers}$$

$$(R^2 = 0.98)$$

4.2.3. *Effects of ordering line handler by stature in pulling exertions*

There was a clear indication from the data that ordering of workers according to their stature can have a significant influence on the force that can be exerted by the team (Fig. 10). For upward pulls, ordering the workers with the shortest in front to tallest in back resulted in a 195 N increase in force that could be exerted by the team compared to the opposite order. When pulling downwards, having the tallest in front resulted in a 280 N increase in the force that could be exerted compared to having the shortest in front. As might be expected, ordering workers in accordance with their stature had no effect on horizontal pulls. However, this data suggests that ordering workers for upward or downward pulls does provide benefits. Putting workers in the proper order for such tasks has an effect equivalent to adding an additional half-person to a full-person to the team, compared to having them in an improper order.

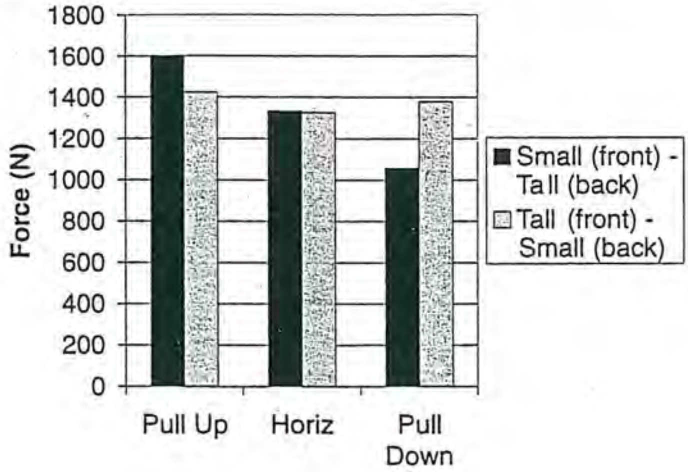

Fig. 10. Effects of ordering crew according to stature in upward, horizontal, and downward pulls.

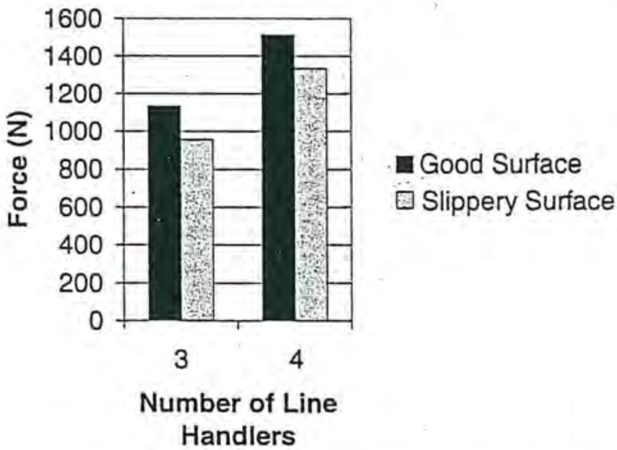

Fig. 11. Results of tests of team pulling strength on slippery surface compared to good (i.e., dry) surface.

4.2.4. *Effects of slippery surfaces on pulling strength*

Pulling tasks performed while line handlers stood on a slippery plastic surface indicated a 13% decrease in pulling strength compared to conditions (Fig. 11). The decreased pulling force observed on the slick surface was of a similar magnitude whether 3 or 4 line handlers performed the exertion.

5. Discussion

The most demanding line handling tasks evaluated were capping the bow and stern bitts, both of which required pulling forces of over 1000 N. Capping the midships bitts required significantly less force (< 400 N on average). The reason for the disparity in pulling forces has to do with the length of wire rope that must be supported by the workers for bitts in various locations on the ship. Both the bow and the stern bits are located close to the center of the ship (Fig. 4), requiring workers to support longer lengths of wire rope, leading to an increase in the required pulling forces. Midships bitts are located closer to the side of the ship (requiring less wire rope to be supported), leading to lower force requirements.

Tests of pulling strength uncovered several pieces of information useful in developing appropriate practices for line handling duties. One useful finding was the effects of ordering the workers by stature in upward or downward pulling activities. In the exertions NIOSH researchers observed during their transit, the pulls were performed at an upward angle. From the data collected in strength tests, it is apparent that the crew should be arranged from shortest in the front to the tallest in the back for these exertions. Doing so provides added strength capabilities for the crew (equivalent to an extra 0.5 crew member), without altering the size of the crew.

This reason for this effect can be easily understood if one considers the force contribution of each team member as a vector (a force in a specific direction). When the team is properly aligned, each member is able to generate a force vector more or less parallel to the rope being pulled. However, if workers are misaligned, only the worker in front can generate a force vector in the desired direction. The others are applying their forces at an angle to the desired direction. This reduces their force contributions, and makes the work of the team much less efficient than if all were able to apply their force contribution in the desired direction.

A critical question in the current analysis was the effect of the number of line handlers on the pulling strength capabilities. Tests indicated that, on average, each additional line handler added to the team contributed an additional 380 N worth of pulling force. When one compares this value to measured strength demands, it can be seen that 3 line handlers of average strength are not sufficient to handle the pulling demands associated with capping the bow or stern bitts. At least four line handlers would be recommended for these tasks. However, three line handlers are probably sufficient for the task of capping the midships bitts, based on the significantly lower force demands of this job.

It should be noted that the line handlers considered the vessel on which task demands were tested among the least stressful, compared to car carriers, for instance. In addition, the current analyses took place under favorable weather conditions. It is quite possible that additional line handlers may be necessary for vessels which are more stressful, or when environmental conditions (for example, slippery footing due to rainy weather, or during high heat conditions) warrant. Unfortunately, the time constraints of this study prevented a more comprehensive analysis of the job demands under more severe conditions.

The findings regarding influences on individual and team pulling strength capabilities obtained this study may have applicability to workers in occupations other than the Line Handlers studied here. Examples of occupations requiring significant pulling demands on wires or cables include power line crews (often pulling power line cable off of spools in inclement conditions), cable TV and fiber optic cable installers (pulling small diameter cables), movers (having to pull furniture and other heavy items using ropes) and miners (who often pull large diameter electrical cables). While the demands of each of these occupations is in its own way unique, it seems fair to speculate that several of the influences on pulling strength identified in this investigation would hold true. In each case, greater pulling force would be anticipated with a pull upward or downward compared to a horizontal pull, ordering workers in accordance with stature would be of benefit for pulls involving multiple team members for pulls in an upward and downward direction, and working on wet or slippery surfaces will adversely impact the amount of strength that can be expressed.

6. Conclusions

Though the data obtained in this evaluation of job demands and worker capabilities was necessarily limited by time and logistical constraints, results of the analyses provide information that is useful in design of team pulling tasks. The findings may be applicable not only to Line Handlers, but may provide useful guidance to other occupations where individual or team pulling tasks involving cables and ropes are present. The following conclusions may be drawn based upon the data obtained in this study:

1. The highest pulling strength demands experienced by line handlers are experienced when capping the bow and stern bitts, both of which required peak pulling forces greater than 1000 N. Capping the midships bitts required significantly lower pulling forces (< 400 N).
2. Tests of pulling strength on a line handling crew indicate lower force capabilities in horizontal pulls as opposed to both upward and downward pulls on a rope.
3. Ordering workers in accordance to stature appears to impact strength capabilities when multiple workers perform upwards and downwards pulls. When pulling upwards, having the shortest worker in the front and tallest in the back results in higher force production. When pulling downwards, the tallest should be in the front. Ordering workers according to stature has no impact on horizontal pulls.
4. Simulation of slippery surfaces decreased pulling strength capabilities by approximately 13% compared to more favorable (dry) conditions.
5. Analysis of the pulling tests suggests that each additional line handler pulling on a rope provides an additional 380 N of pulling force, on the average. When compared to the task demands, this suggests that at least 4 line handlers are needed for capping the bow and stern bitts; however, only 3 are necessary for the midships bitts. These recommendations pertain to demands experienced on a Panamax vessel in dry conditions. Additional handlers may be necessary for more demanding vessels (i.e., car carriers) or in inclement conditions.

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