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Revisited: Comparison of two techniques to establish maximum acceptable forces of dynamic pushing for male industrial workers

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Abstract

The purpose of this experiment was to replicate a previous psychophysical experiment [Ciriello, V.M., McGorry, R.W., Martin, S.E., Bezverkny, I.B., 1999b. Maximum acceptable forces of dynamic pushing: comparison of two techniques. Ergonomics 42, 32–39] which investigated maximum acceptable initial and sustained forces while performing a 7.6 m pushing task at a frequency of 1 min^{-1} on a magnetic particle brake treadmill versus pushing on a high-inertia pushcart. Fourteen male industrial workers performed both a 40-min treadmill pushing task and a 2-h pushcart task, with a unique water loading system, in the context of a larger experiment. During pushing, the subjects were asked to select a workload they could sustain for 8 h without "straining themselves or without becoming unusually tired, weakened, overheated or out of breath." The results revealed that similar to the previous study maximum acceptable sustained forces of pushing determined on the high inertia cart were significantly higher (21%) than the forces determined from the magnetic particle brake treadmill. These results were countered by an 18% decrease in maximum acceptable forces for the criterion magnetic particle brake treadmill task, perhaps due to secular changes in the industrial population. Based on the present findings, it is concluded that the existing pushing data [Snook, S.H., Ciriello, V.M., 1991. The design of manual tasks: revised tables of maximum acceptable weights and forces. Ergonomics 34, 1197–1213] still provides an accurate estimate of maximal acceptable forces for this pushing distance and frequency.

Relevance to industry

Jobs are often redesigned to eliminate lifting and to include carts for transporting loads. Our database on maximum acceptable forces of pushing on a magnetic particle braked treadmill has been used as a tool to design manual handling tasks. This article links the existing database with actual cart pushing.

Keywords: Psychophysics; Cart pushing; Manual materials handling

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1. Introduction

Ergonomic redesign of manual materials handling (MMH) tasks has the two-fold advantage of accommodating the work place to a high percentage of the industrial population with and without low back disability (Snook et al., 1978; Benson, 1986, 1987; Snook, 1987; Ciriello and Snook, 1999; Ciriello et al., 1999a). This strategy is important due to: (1) the most frequent (36% of all claims) and costly (35% of total cost) category of workers' compensation losses is MMH (Leamon and Murphy, 1994; Murphy et al., 1996; Dempsey and Hashemi, 1999), (2) MMH claims are also associated with the largest proportion (63–70%) of compensable low back disability (Snook et al., 1978; Bigos et al., 1986; Murphy and Courtney, 2000), (3) a small percentage of the most costly low back claims (10%) are reported to be responsible for a large percentage of the total cost (86%), and (4) days of disability for low back pain are skewed to long durations with an average and median of 303 and 39 days, respectively (Hashemi et al., 1997).

Acceptable loads in MMH have been established using a wide spectrum of techniques (Kemper et al., 1990; Kivi and

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Mattila, 1991; Waikar et al., 1991; Burdorf et al., 1992; Waters et al., 1993; de Looze et al., 1994; Winkel and Mathiassen, 1994). This study was conducted as part of an on-going research effort to establish and refine recommendations for maximum forces and weights to be required of workers in industrial settings. In this institute, the scientific principle used to establish criteria for industry has been a psychophysical technique wherein subjects choose maximum acceptable forces or loads that can be maintained over an 8-h shift (Snook and Ciriello, 1991). The accumulated results of such studies have provided the basis for workplace and task redesign recommendations across a number of industries (Benson, 1986, 1987; Ciriello and Snook, 1999; Ciriello et al., 1999a).

Ergonomic redesign strategies sometimes call for changing lifting, lowering, and carrying tasks to pushing and pulling tasks. A well-designed cart can transfer heavy weights with forces that are acceptable to a high percentage of males and females. The psychophysical pushing data that have been generated at this institute remain the most comprehensive source to date (Snook and Ciriello, 1991). However, further study was necessary to confirm the maximum acceptable forces that have been established on our magnetic particle brake (MPB) treadmill are the same as with that of pushing a cart that has high inertia. Ciriello et al. (1999b) demonstrated that for male industrial workers, the maximum acceptable forces on the pushcart were significantly greater than MPB treadmill values. The purpose of this study was to replicate the methodology of Ciriello et al. (1999b) with a larger number of subjects, and establish if the relationship between the two methods remains similar.

2. Method

2.1. Subjects

Fourteen male industrial workers were recruited from local industries to participate in this study which was approved by our institutional review committee. Candidates were excluded from the experiment if they had experienced previous significant low back pain or musculoskeletal problems of the extremities. Following initial screening and upon giving written informed consent, the subjects were examined by a nurse practitioner to ensure that they had no serious cardiovascular problems or musculoskeletal conditions. Several anthropometric measurements were taken to set the handle of the pushcart midway between knuckle and elbow height (Table 1). These measurements were compared with military and industrial populations to ensure similarity with our population and others (Snook, 1971; Ciriello and Snook, 1978; Ciriello et al., 1990; Eastman Kodak Co., 1986; Gordon et al., 1989). All subjects were dressed in surgical type "scrub suits" to control for heat dissipation. They were provided with identical shoes to ensure consistent coefficients of friction on the treadmill belt and the runway for the pushcart.

Table 1
Subject characteristics ($n = 14$)

	$\bar{x}$	SD
Age (years)	38.4	12.6
Weight (kg)	91.8	14.8
Stature (cm)	177.8	5.7
Elbow height (cm)	113.7	4.5
Knuckle height (cm)	80.1	4.8

2.2. Apparatus

The following describes the two apparati used in this experiment. Dynamic pushing was simulated on a specially constructed MPB treadmill. During pushing, the MPB treadmill was powered by the subject while pushing against a stationary bar. The bar was set midway between knuckle and elbow height for each subject. Knuckle and elbow height were determined by the vertical distances from the standing surface to the tip of the third metacarpal (at the metacarpo-phalangeal joint) and to the most proximal edge of the radius, respectively. Both measurements were taken while the subjects stood erect with their arms hanging naturally by their sides. A load cell on the stationary bar measured the horizontal force being exerted. Subjects controlled the resistance of the treadmill belt by varying the amount of electric current flowing into the MPB linked to the treadmill belt. The control was devoid of positional cues and located within arm's length of the subject. Subjects turned the control knob clockwise to increase the resistance and counterclockwise to decrease resistance. The control knob could be adjusted before, during, or after each push. Pushing tasks were performed for a distance of 7.6 m and at a frequency of 1 task min^{-1}. This system has been used in all the previous manual handling experiments performed in our laboratory to establish criteria for pushing (Ciriello and Snook, 1978, 1983; Ciriello et al., 1990, 1993; Snook, 1978; Snook et al., 1970; Snook and Ciriello, 1991, 1974).

Dynamic cart pushing was performed with a specially constructed pushcart which was designed with an 'on demand' water loading system. This system was described and illustrated in a previous publication (Ciriello et al., 1999b). In summary, the pushcart was 117 cm high, 142 cm wide and 206 cm deep and had empty and full weights of 262 and 780 kg, respectively. The pushcart was equipped with four 20 cm diameter tubeless rubber wheels, inflated to 207 kPa. At this inflation pressure, the rubber wheels minimized rolling of the cart after the push task and thus did not require the test subject to exert any force to stop the cart. Instrumented handles were adjustable in height from 66 to 127 cm and were located at each end of the cart. Each handle was equipped with two 2225 N rated load cells configured to measure the horizontal forces applied by the subject. The water was contained in a 610 l polyethylene tank, baffled with a motion suppressing open cell foam. The water tank was mounted on a wooden frame.

The pneumatically actuated diaphragm pump delivered a minimum of 145 kg min^{-1} of water to and from the cart through the single hose via a manifold containing four electronically actuated solenoid valves. A high-pressure hose (3.8 cm inside diameter), connecting the cart tank to the pump/manifold assembly, was mounted to an overhead carriage which traveled with the cart to minimize drag. Water was off-loaded from the cart to the reservoir by opening and closing the valves. Reversal of flow direction was achieved by reversing the actuation of the valves. The cart weight was adjusted by depressing buttons on the cart labeled "More" or "Less." The button selection sent a signal to a personal computer which in turn activated the pump and appropriate solenoids. Computer control of this process also allowed the experimenter to change the cart weight when required by the protocol.

The reservoir was mounted on a base resting on top of two 454 kg rated load cells. The outputs of the two load cells provided a measure of the water weight contained in the reservoir. In this closed system, the full cart weight, measured during system calibration, was reduced by the reservoir water weight to determine the present cart weight. The reservoir and pump/manifold assembly were contained in an acoustically insulated housing.

The outputs of the eight handle and the two reservoir load cells were transmitted to the personal computer equipped with a 16 channel analog-to-digital converter, and were sampled at a minimum rate of 100 Hz. In-house custom software was written to control data acquisition during the experimental sessions and to perform data analysis functions. The statistics reported on a per trial basis were: initial and sustained horizontal forces, time period of the pushing trial, and cart weight. The force required to get the MPB treadmill belt or cart moving is called "initial force." The initial force was the peak force observed during a 1-s time period after a 22.2 N threshold was surpassed on the horizontal transducers. The force required to maintain the MPB treadmill belt or cart movement is called "sustained force." The sustained force was the average of the fluctuating forces on the handle throughout the time period of the push beginning one half second after the observed initial force. The experimental statistics were also written to an Excel-compatible data file. Horizontal handle forces and tire pressure were verified prior to each experimental session.

The runway consisted of six 244 cm long, 86 cm wide, and 2 cm thick interchangeable plywood panels. A U-shaped aluminum channel alongside of the 15 m long runway served as a guide to two of the pushcart wheels, eliminating the need for steering. The coefficient of friction between the shoe sole material and the floors were determined by a Brungraber Slip-Tester (Model Mark II) and resulted in coefficient of friction measurements of .68 and .86, respectively, for the plywood floor and the treadmill belt.

2.3. Procedure

The subjects performed the two dynamic pushing tasks within a larger experiment that had two phases. The first phase determined psychophysical limits for 20 tasks which included lifting, lowering, pushing, pulling and carrying. The second phase determined energy expenditure values for over 300 MMH tasks. The psychophysical methodology described by Ciriello and Snook (1983), Ciriello et al. (1993), and Snook and Ciriello (1991) was used in the first phase. Subjects were instructed to adjust the amount of weight or force until it represented the maximum they could handle for 8 h without "straining themselves or without becoming unusually tired, weakened, overheated, or out of breath." (Complete instructions are given in the Appendix.) Three training sessions in the larger experiment were conducted to gradually condition the subjects to the different tasks and to enable them to gain experience in adjusting weight and force. The training progressed as follows: on Day 1, subjects performed six 10-min tasks, which included a 7.6 m push, performed at a frequency of 1 push min^{-1}; on Day 2, six 20-min tasks, which included a 7.6 m pull, performed at a frequency of 1 push min^{-1}; and on Day 3, six 30-min tasks which included a 7.6 m push, performed at a frequency of 1 push min^{-1}. All of the training pushing and pulling tasks were performed on the MPB treadmill.

Subjects in the first phase performed five 40-min tasks in 4 h. At the beginning of each task, subjects were given a box weight or treadmill force that was randomly selected and alternately high (32–45 kg) or low (2–18 kg). During the next 20 min, subjects adjusted the weight or force according to instructions (Appendix). At the end of 20 min, subjects received a new random weight or force and began the adjustment process again. During the 4-h test session, 10 weight or force selections were made by each subject (two for each task). The first phase required each subject to work two 4-h days per week for 4 weeks, for a total of eight 4-h days. The experiment reported here required the subjects to perform the 40 min MPB treadmill session, sometimes two sessions, within the context of the first phase of the experiment with details below.

In the experimental schedule of the first phase, each subject was randomly presented to the 7.6 m, 1 push min^{-1} on the MPB treadmill. The force values from the last 10 min of every 20 min segment were averaged if the subject had finished the force selection process. If the force selection process was still occurring in the last 10 min of the segment, the average of the last selections that did not change was taken as data. If the two 20-min values were within a 15% difference, the median of those selections was taken as the datum for that trial. If the two judgements were greater than 15% difference, the test was re-run at a later time. If the re-run selections were greater than 15%

difference, the median of the four selections from the two tests was included in the data.

During the second phase of the experiment (last 12 days of the 20-day schedule), the subjects were presented to the 7.6 m, 1 push min^{-1} cart pushing task. The task was 2 h long and contained six 20-min segments. At the beginning of each 20-min segment, subjects were presented with a cart weight that was randomly selected and alternately high (454–726 kg) or low (263–363 kg). During the 20-min segment, the subject adjusted the force according to the instructions. At the end of each 20-min segment, subjects received a new random weight and began the process again. The data were determined using the same procedure for the MPB treadmill task. During the 2-h task, six weight selections were made by each subject (a total of six adjustments for the two pushcart sessions). The median of the six values was included in the data. After the pushcart task, the subject would return to another section of the laboratory for continuing energy expenditure measurements.

2.4. Data analysis

The dependent variables were initial and sustained force and task duration; independent variable was the type of push task (MPB treadmill or pushcart). The data were analyzed using one-way analyses of variance with repeated measures (Ferguson, 1971; Winer, 1971). The repeated measures were the dependent variables repeated for each type of push task for each subject. Significance for all statistical analyses was set at $P<.05$.

3. Results

The results of the two dynamic pushing tasks are presented in Table 2 for the present, previous and combined experiments. The maximum acceptable sustained force of pushing 7.6 m on the pushcart was significantly greater (21%) than the maximum acceptable sustained force on the MPB treadmill. Task duration on the pushcart was also significantly greater (37%) than the task duration on the MPB treadmill. The maximum acceptable initial force on the pushcart was 18% greater than the maximum acceptable initial force on the MPB treadmill, however, this increase was not significant. The results of the present experiment were very similar to the results of our previous experiment (Ciriello et al., 1999b). The analysis of the combined experiments revealed significant increases of 21%, 22%, and 33% for initial force, sustained force, and task duration, respectively. Table 2 also contains the average cart weight selected in the pushcart task and the criteria forces for the MPB treadmill.

4. Discussion

In this experiment, we were able to replicate the findings of an earlier study (Ciriello et al., 1999b). The combined results of the two studies (Table 2) may indicate a need to adjust our existing database of acceptable forces for pushing and pulling tasks for male industrial workers (Snook and Ciriello, 1991) which is based on results from research on the MPB treadmill. Before the two experiments, the authors hypothesized that the two techniques

Table 2
Maximum acceptable forces (N) when pushing on the MPB treadmill versus pushing on the push cart (7.6 m. push, 1 min^{-1} frequency)

	MPB treadmill		Push cart		Sign[c]	Percent increase (%)
	$\bar{x}$	SD	$\bar{x}$	SD		
Present experiment ($n = 14$)						
Initial force[a] (N)	331.4	77.5	389.5	114.4	NS	18
Sustained force[b] (N)	177.9	51.2	215.1	61.5	$P = .0428$	21
Task duration (s)	9.4	2.2	12.9	3.3	$P = .0010$	37
Previous experiment ($n = 8$)						
Initial force (N)	314.6	51.9	403.8	129.4	NS	28
Sustained force (N)	179.3	24.5	221.5	31.4	$P<.001$	24
Task duration (s)	10.2	2.7	13.0	1.7	$P = .016$	27
Combined experiments ($n = 22$)						
Initial force (N)	325.3	68.4	394.7	117.4	$P = .0126$	21
Sustained force (N)	178.6	42.7	217.6	51.8	$P = .0015$	22
Task duration (s)	9.7	2.4	12.9	2.8	$P = .0000$	33
Criteria[d] ($n = 63$)						
Initial force (N)	368.4	108.6				
Sustained force (N)	217.9	72.6				–

[a] Amount of force needed to get the treadmill or cart moving.
[b] Amount of force needed to maintain the treadmill or cart movement.
[c] Significance between MPB treadmill and push cart. NS, non-significant ($P>.05$).
[d] Snook and Ciriello (1991).

would yield similar acceptable forces. However, the results have shown that the subjects' perceived exertion of the pushcart task was significantly different than pushing on the MPB treadmill. Perception differences could be the result of several factors, namely: the two tasks were performed in two separate laboratories, the two tasks were often monitored by different technicians, and/or the pushcart task was curiously unique in its design. These perception differences between the two tasks are not shared by female industrial workers. In a recently reported study from this laboratory (Ciriello, 2004), maximum acceptable initial and sustained forces on the pushcart were not significantly different than initial and sustained forces on the MPB treadmill.

Comparison of the MPB treadmill results in the combined experiments with the authors' past pushing criteria (for males) for initial and sustained forces for the 7.6 m push performed at the once per minute frequency (Snook and Ciriello, 1991) indicated that the subjects in the combined experiments chose acceptable forces that are significantly ($P<.019$) lower (18%) than the published criteria of 218 N for sustained forces and nonsignificantly lower (12%) than the criteria for the initial forces. The subjects were exposed to the same experimental techniques and used the same MPB treadmill set-up as in previous experiments. Their psychophysical performance may reflect secular changes in the recent pool of male industrial workers. We are presently investigating other MMH tasks that may present similar secular changes. These decreases in acceptable forces for the criterion MPB treadmill task were countered by the increases in acceptable forces for the pushcart task. With the above considerations, the existing pushing data (Snook and Ciriello, 1991) still provides an accurate estimate of maximal acceptable forces.

The results also emphasize the importance of load capabilities of pushcarts. Our pushcart was not designed with the most efficient wheels for reasons of permitting higher horizontal loading without a heavy load in the cart. Even with this constraint, the average load selected in this experiment was 464 kg, similar to the average load selected in our previous study (482 kg) (Ciriello et al., 1999b). Jobs that are redesigned from higher risk lifting, lowering, and carrying activities to pushing or pulling activities benefit from horizontal forces of pushing and pulling that are acceptable to most industrial workers. The challenge still remains in loading the carts with specialized rollers and conveyors to eliminate the lifting, lowering and carrying. Our recent review of industrial pushing indicates that most pushing activities now are acceptable to high percentages of male and female population (Ciriello and Snook, 1999). Therefore, this redesign strategy has a sound basis.

5. Conclusions

It is concluded by the results of this study that maximum acceptable initial and sustained forces chosen by male industrial workers while pushing a high inertia cart were significantly greater than the pushing forces chosen on a MPB treadmill. These results were countered by a decrease in acceptable forces for the criterion MPB treadmill task. With the above considerations, the existing pushing data (Snook and Ciriello, 1991) still provides an accurate estimate of maximal acceptable forces for the industrial work force.

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Appendix. Instructions for adjusting workload

We want you to imagine that you are on piece work, getting paid for the amount of work that you do, but working a normal 8-h shift that allows you to go home without feeling bushed.

In other words, we want you to work as hard as you can without straining yourself, or *without becoming unusually tired, weakened, overheated, or out of breath.*

YOU WILL ADJUST YOUR OWN WORKLOAD. You will work only when you hear the beep. *Your job will be to adjust the load*; that is, to adjust the weight of the pushcart or the force of push on the treadmill.

Adjusting your own workload is not an easy task. Only *you* know how you feel.

IF YOU FEEL YOU ARE WORKING TOO HARD, reduce the load by depressing the less button for the pushcart or turn the knob to decrease for the treadmill.

WE DON'T WANT YOU LOAFING EITHER. If you feel that you can work harder, as you might on piece work, depress the more button for the pushcart and turn the knob toward increase for the treadmill.

DON'T BE AFRAID TO MAKE ADJUSTMENTS. You have to make enough adjustments so that you get a good feeling for what is too heavy and what is too light. You can never make too many adjustments—but you can make too few.

REMEMBER …

THIS IS NOT A CONTEST.

EVERYONE IS NOT EXPECTED TO DO THE SAME AMOUNT OF WORK.

WE WANT YOUR JUDGMENT ON HOW HARD YOU CAN WORK WITHOUT BECOMING UNUSUALLY TIRED.

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