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The effects of load and gradient on hand force responses during dynamic pushing and pulling tasks

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Abstract

The limited attention afforded to push/pull activities and the motion phases (initial, sustained and ending) characteristic of these tasks has prompted a research focus in this area. The present study examined biomechanical responses in the form of hand forces during dynamic submaximal trolley pushing and pulling. Participants pushed/pulled loads of 100, 200 and 300 kg on the level (determining impact of load) or pushed 100 kg along a 12^{o} ramp (uphill and downhill- determining impact of gradient).

During level exertions significant differences ($p<0.05$) in hand forces occurred between loads of 100 and 200 kg, and 100 and 300 kg for initial and sustained forces but not ending forces. Values were similar for pushing and pulling at respective loads and motion phases. Strong correlations indicate that initial forces can be used to accurately estimate sustained and ending forces. Importantly, correct technique is essential in force reduction.

Forces were highest during uphill initial and sustained phases and the downhill sustained phase. For the initial phase, the forces were highest during uphill pushing (86.5 ± 25.73 N); for the sustained phase, there was no difference between uphill and downhill forces but level forces were significantly lower (18.19 ± 8.09 N) than either of the other two conditions; for the ending phase, the highest forces were produced during downhill pushing (-53.34 ± 13.65N). As sustained forces equaled or exceeded initial forces for uphill and downhill efforts, consideration of sustained forces may be appropriate in determining the inherent potential risk of graded pushing.

Keywords: Pushing, pulling, load, gradient, motion phases

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1 Introduction

Due to the physical nature of manual materials handling (MMH), workers are frequently exposed to excessive task demands, resulting in strain on the cardiovascular and musculoskeletal systems, specifically when the worker is unable to meet the job requirements (Dempsey, 1998). Consequently worker safety and ultimately quality and quantity of productivity are compromised (Dempsey, 1998). While lifting and carrying have historically dominated MMH tasks, cognisance of the risk associated with these activities has led to their decreased usage, and the concurrent rise in pushing and pulling (Baril-Gingras and Lortie, 1995; Resnick and Chaffin, 1995; Hoozemans et al., 1998). Although this may allow for the movement of heavy loads (van der Beek et al., 1999) the hazards associated with pushing and pulling are not well known. Introduction of push/pull activities infers that the nature of the risk is changed rather than eliminated as a host of new demands are introduced (Resnick and Chaffin, 1995). As force exertion is a requisite, a relationship between pushing and pulling and musculoskeletal disorders such as lower back pain, shoulder stiffness and upper extremity complaints exists (Hoozemans et al., 1998; van der Beek et al., 1999; Hoozemans et al., 2004). Application of current push/pull guidelines is problematic as many are based on maximal static push/pull research (Lee et al., 1991; Resnick and Chaffin, 1995) while push/pull tasks in industry are predominately submaximal and dynamic (Todd, 2005). Furthermore Snook and Ciriello (1991), whose dynamic movement based guidelines are widely used in industry, have suggested that even their own guidelines require more investigation to improve accuracy and applicability.

Load mass is of concern during pushing/pulling due to the strong linear relationship between minimum cart push/pull forces and cart load mass (Al-Eisawi et al., 1999; van der Beek et al., 1999). Regardless of the type of vehicle it is agreed that load weight should be kept within an acceptable range to avoid overtaxing the worker (Resnick and Chaffin, 1995; van der Beek et al., 2000). General load limits must be used with caution as acceptable forces will vary with a complex range of worker, task, design and environmental factors in each situation (Mack et al., 1995; Jung et al., 2005). The presence of variable incline ramps in industry further complicates the situation by increasing the task demands and additional effort must be exerted to overcome the downward effect of gravity and the inertia of the object. Although horizontal floors are optimal, it has been suggested that slopes of less than 2% are preferable over stairs or curbs (Hansson, 1968). Limited research is available regarding pushing/pulling along ramps, despite the frequency with which such tasks occur. Furthermore past studies have failed to quantify the changes in the biomechanical demands associated with uphill and downhill push/pull exertions.

Three motion phases have been identified as occurring during a push/pull movement, these being the initial, sustained and ending phases (Snook, 1978). Initial forces are required to overcome inertia and accelerate the object; sustained forces maintain movement and ending forces decelerate the object in order to bring it to a standstill (van der Beek et al., 1999). However, literature concerning the motion phases is scant. Additionally, the lack of standardised methodologies within this area hinders comparison between those studies that do exist (Daams, 1993).

The current study acknowledged that it is important not only to understand the mechanisms involved in pushing/pulling, but also to be able to apply this knowledge *in situ*. Therefore the twofold objectives were to determine the separate effects of load and gradient on the hand forces required during submaximal dynamic pushing and pulling. Moreover, the initial, sustained and ending phases were analyzed to gain a more rigorous and comprehensive understanding of the potential problem areas associated with pushing and pulling in terms of hand forces.

2 Methodology

2.1 General experimental information

2.1.1 Procedures

Two experiments were performed: (a) experiment one (laboratory study) investigating the effects of load on hand force exertion and (b) experiment two (*in situ*) being concerned with the effects of gradient on hand force exertion. Two independent sample groups of healthy, active male participants (N=12 for experiment one and N=10 for experiment two) were drawn from a student population at Rhodes University, Grahamstown. In both studies participants were required to attend an introductory session which took place in the Human Kinetics and Ergonomics Department at Rhodes University. The primary aims were to provide detailed explanations of the objectives of the study, clarify procedures and use of equipment, habituate subjects to instrumentation and address any concerns that subjects may have had. Information sheets were distributed to participants and then informed consent was obtained. Basic anthropometric (stature, mass, radiale and acromiale heights) and demographic details (age) were recorded. Radiale and acromiale heights were used to ensure that the trolley handle was positioned between these anatomical points for all subjects, ensuring that participants adopted standardized postures and excluding posture as an extraneous variable. For investigating the effects of load the participants were required to attend two testing sessions while for investigating the effects of gradient a separate sample of participants was required to attend one testing session.

2.1.2 Equipment

A standard, locally made four-wheeled flatbed trolley was utilized as it represented those commonly used in local businesses, with a handle height of 1140 mm, rubber wheels with a diameter of 120 mm and a width of 27 mm, all orientated in the direction of motion. Hand forces in the horizontal plane (one dimensional) were collected using the Chatillon^{TM} FCE Series100 digital dynamometer attached to the trolley handle, allowing the collection of real time data and the quantification of the three motion phases. It was appropriate for both compressive and tensile forces, capable of measuring up to a maximum of 1100 kg. A two handed symmetrical technique was adopted for both pushing and pulling to reduce the likelihood of slip, trip or falls during experimentation. Foot placement was standardised across subjects, with each required to adopt a staggered starting position. Subjects performed three trials for each condition and conditions were randomised to prevent order effects. Participants were required to bring the trolley to a stop within clearly demarcated areas in an attempt to control the smoothness of motion, however subjects were allowed to choose the method of stopping.

The Statistica (Version 6.1) software programme was used for data analysis, with statistical responses being tested at a 95% confidence level ($p<0.05$). Kruskall-Wallis ANOVAs were used to assess significance and determine statistically significant differences between results. Significance was tested between loads and between pushing/pulling (experiment one) and gradients (experiment two). Due to differences in experimental conditions, significance was not investigated between results from experiments one and two.

2.2 Experiment one: Load mass

2.2.1 Participants

Twelve males, with a mean age of 21.7 (± 1.7) years, a mean stature of 1824 (± 34.2)mm and a mean body mass of 79.9 (± 10.0) kg participated in the study.

2.2.2 Experimental procedures

Three loads of 100, 200 and 300 kg were used in a laboratory environment, on a wooden walkway of 13 m, a movement distance considered to be representative of conditions within industry. This also allowed for clear demarcation of the initial, sustained and ending phases during the push/pull. The flooring consisted of plywood boards similar to those used by Ciriello et al. (2001), which ensured a sufficient coefficient of friction to avoid slipping, but a reasonable rolling friction to avoid excessive hand force requirements (Figure 1). In addition, the coefficient of friction was similar to that evidenced in industry. Walking speed was controlled at 3.6 $km.h^{-1}$, considered a normal average walking speed, as hand forces are likely to be influenced by velocity.

Figure 1. Photograph of the experimental condition and Chatillon^{TM} FCE Series100 digital dynamometer

2.3 Experiment two: Gradient

2.3.1 Participants

Ten males, with a mean age of 21.0 (±1.3) years, a mean stature of 1817 (± 56) mm and a mean body mass of 80.49 (± 7.84) kg participated in the study.

2.3.2 Experimental procedures

Experimentation for the three conditions (level, uphill and downhill pushing) took place *in situ* on the Rhodes University campus. Each participant was required to push the trolley with a 100 kg load, up and down a slope of 12^o, and on level ground, over a distance of 18.39 m (measured distance of ramp). The floor surfaces were concrete, which afforded a sufficient shoe/floor friction to prevent slipping.

3 Results

3.1 Introduction

Throughout the current paper it must be noted that positive and negative values shown in the results indicate a change in direction, thus during pulling the positive ending force illustrates a push force required to stop the moving trolley. Therefore positive values depict push forces and negative values depict pull forces. This is shown in Figure 2 which is a graphical representation of a pull trial from the present study. Important to notice are the negative initial and sustained ending forces (pulling), and positive (pushing) ending forces. Initial forces began at the first deviation from 0 N, including the peak and to the lowest point thereafter. From this point forces were categorised as being in the sustained phase. The ending phase was taken from when these forces became opposite (tension to compression or compression to tension) and then returned to 0 N, thus terminating the push/pull.

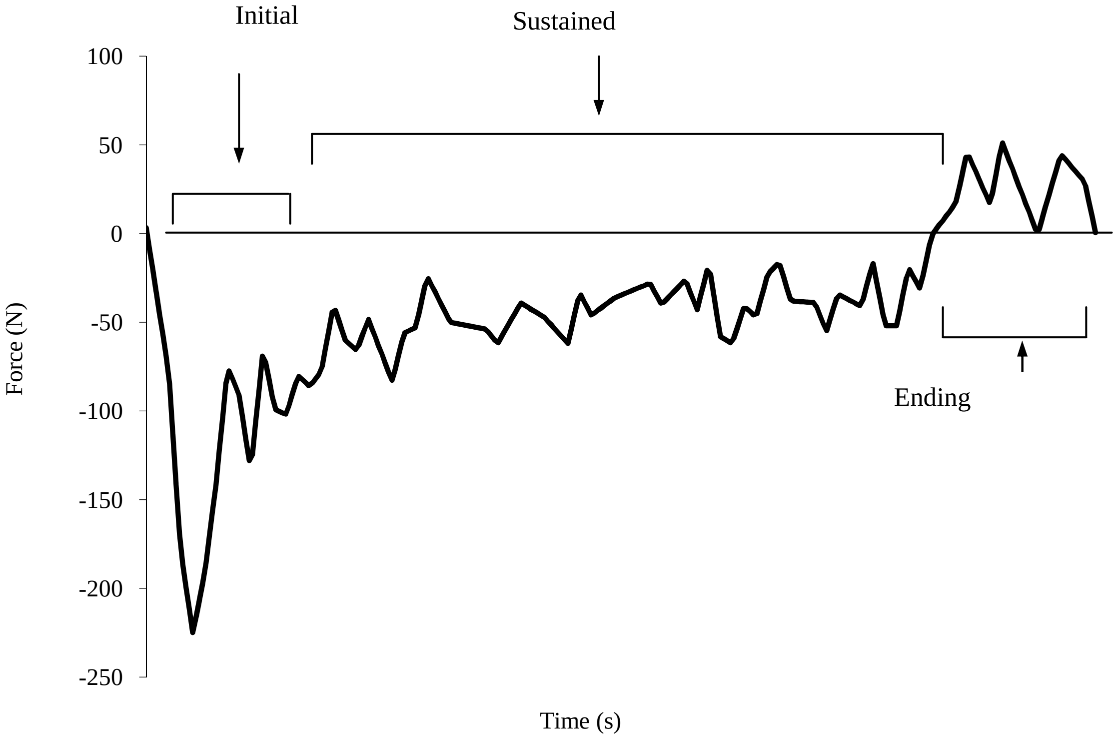

Figure 2. Forces exhibited during the dynamic pulling motion phases.

3.2 Experiment one: Load mass

3.2.1 Hand forces and motion phases

Operators in industry are often required to push and pull a variety of loads with little cognisance of what loads are appropriate to avoid worker overexertion. The current experiment thus examined the effect of load changes on the required hand forces, with specific reference to the separate motion phases. Table 1 presents the results of the mean hand forces for both pushing and pulling at the three motion phases.

Table 1. Mean hand forces (N) (standard deviations shown in brackets).

	Pushing		
	Initial	**Sustained**	**Ending**
100 kg	49.92 (7.63)	16.64 (4.49)	-20.42 (6.51)
200 kg	76.97 (6.29)	27.32 (4.81)	-26.39 (9.47)
300 kg	99.70 (16.35)	40.53 (7.10)	-32.84 (12.42)
	Pulling		
100 kg	-55.73 (4.78)	-15.40 (4.79)	19.78(9.22)
200 kg	-70.19 (8.17)	-25.74 (5.45)	25.36 (12.74)
300 kg	-98.31 (13.77)	-38.99 (4.84)	35.24 (18.30)

] Denotes statistically significant difference between conditions

Pushing: During pushing there were significant differences found between the initial forces at all three loads, with a 49% increase in hand forces from 100 to 300 kg. Similar significant differences were observed between the sustained forces at the three load conditions with a 60% increase in force requirement from 100 to 300 kg. However the ending phases only showed a significant difference between loads of 100 and 300 kg (forces of -20.42 N and -32.84 N respectively), a 61% increase.

Pulling: In contrast, Table 1 shows that during pulling significant differences were only observed between loads of 100 and 200 kg and 100 and 300 kg for both initial and sustained forces and not between 200 and 300 kg. A 43% increase from 100 to 300 kg during the initial phase is slightly lower than the increase of 49% occurring in the respective pushing conditions, while there was a similar increase as seen during sustained pushing. Ending forces revealed differences between 100 and 300 kg for pushing, but no statistical differences during pulling. The absence of statistical significance may not rule out the effect of the practical significance of the increasing loads. Increase in ending hand forces requires a concurrent increase in worker hand force generation, which may still lead to increased risk of injury.

3.2.2 Load and initial force

On comparing the motion phases, for both pushing and pulling on level ground, the initial forces were significantly greater than both sustained and ending forces with no further differences between phases (Table 1). This finding supports previous literature that has identified initial forces as those most likely to result in overexertion due to their high magnitude (Donders et al. 1997; Shoaf et al. 1997; van der Beek et al., 2000; Jansen et al., 2002; Laursen and Schibye, 2002; Hoozemans et al., 2004). This necessitated a more comprehensive examination of the relationship between load and initial forces.

Figure 3 below details this relationship, demonstrating a strong correlation between increasing load and hand forces with R^2 values of 0.9 for both pushing and pulling. This allows for prediction of hand forces at higher loads by extrapolation. Figure 3 shows that the extrapolated hand forces expected at 500 kg, for example, would be 150 N and -139 N.

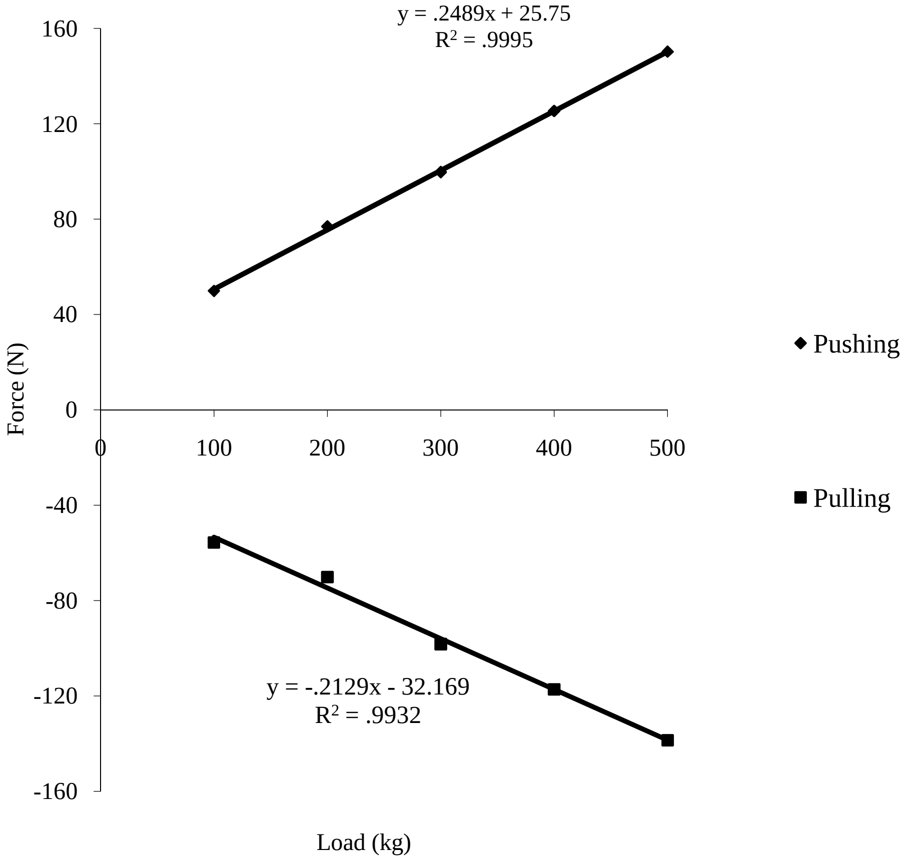

Figure 3. Extrapolation of initial hand forces.

This prediction would only be valid assuming the relationship remains linear, hence caution must always be used in these extrapolations. However Cripwell (2006) showed a linear relationship between load and hand force similar to these results for loads as high as 500 kg, and this would suggest that the current extrapolations are appropriate and applicable to industry.

3.3 Experiment two: Gradient

3.3.1 Hand forces and motion phases

In order to determine the difference between level, uphill and downhill conditions, pushing forces were separated into mean and peak forces, with significant differences being similar between conditions (Table 2). Regardless of the differences between mean and peak values, it is always more appropriate to employ the forces of lower magnitude when making recommendations for ceiling limits to prevent workers from being overtaxed. Peak uphill forces were between 31 and 40% higher than peak level and downhill forces, while mean uphill forces were 58 and 67% higher than mean level and downhill forces respectively for the initial phase. Contrastingly, during the sustained phase, peak level forces were 68 and 55% lower than peak uphill and downhill efforts respectively, while mean level forces were between 80 and 85% lower than mean uphill and downhill efforts. For the ending phase, peak downhill forces were approximately 55% higher than peak level or uphill forces, while mean downhill forces were between 70 and 80% higher than mean level and uphill forces.

Table 2. Peak and mean forces for initial, sustained and ending phases for all conditions (standard deviations shown in brackets)

	Force output (N)		**Force output (N)**		**Force output (N)**	
	Peak	**Mean**	**Peak**	**Mean**	**Peak**	**Mean**
	Initial		**Sustained**		**Ending**	
Level	92.97 (30.53)	36.05 (16.60)	51.8 (16.41)	18.19 (8.09)	-44.20 (18.80)	-15.17 (11.31)
Uphill	150.30 (35.78)	86.50 (25.73)	163.80 (16.08)	118.49 (7.43)	-39.48 (28.99)	-12.11 (12.33)
Downhill	102.99 (31.30)	28.18 (13.19)	-116.00 (91.77)	-95.80 (8.48)	-91.56 (18.36)	-53.43 (13.65)

┐ Denotes statistically significant difference between conditions (p<.05)

3.3.2 Gradient and initial versus sustained force

Importantly, findings suggested that the forces evidenced in the initial phase of uphill and downhill pushing do not always surpass those of the sustained phase (Figure 4) and although this may hold true for level pushing, the current study demonstrated that this is not necessarily the case for graded exertions.

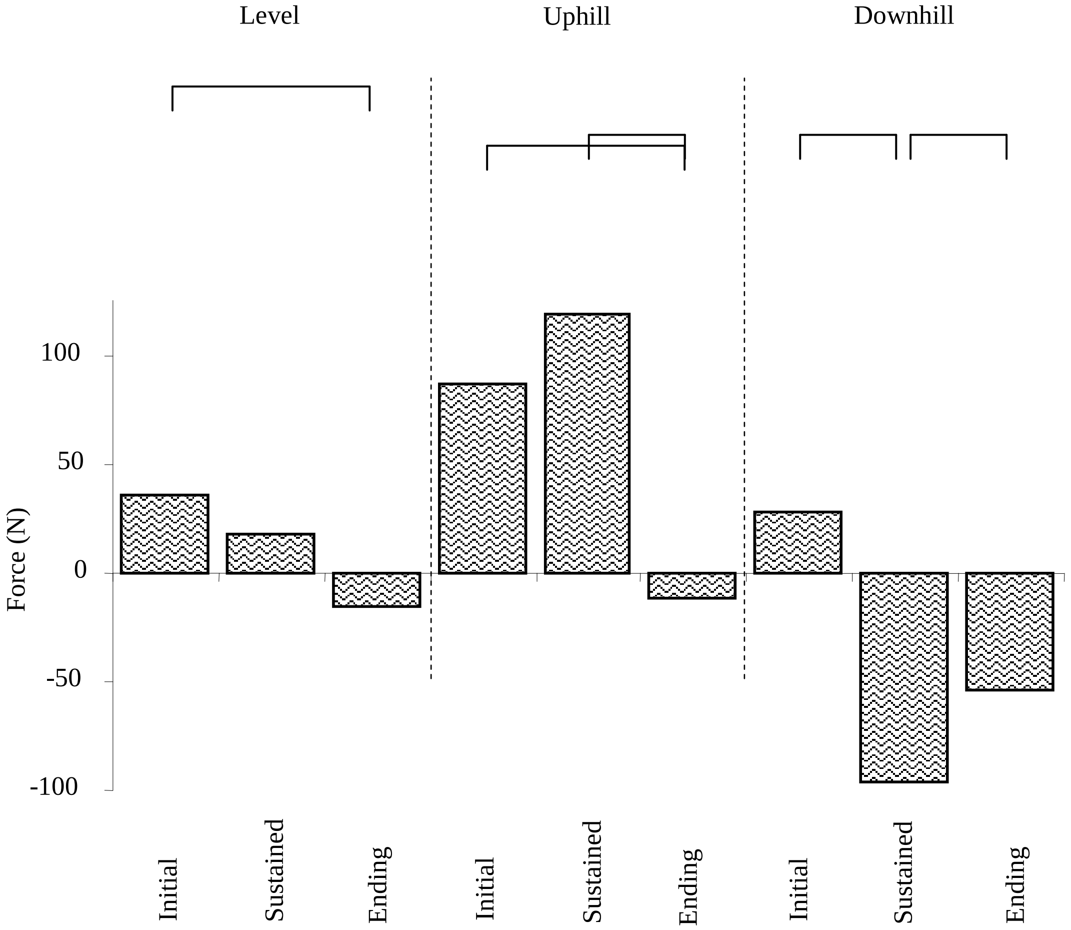

Figure 4. Mean hand forces for motion phases for all conditions

⊓ Denotes statistically significant difference between conditions (p<0.05)

Considering uphill pushing, there were no significant differences between the forces produced in the initial (86.5 ± 25.73 N) or sustained (118.49 ± 7.43 N) phases, while, for downhill pushing, the forces exhibited in the sustained phase (-95.8 ± 8.48 N for mean efforts) were significantly higher than the forces produced during the initial phase (28.18 ± 13.19 N for mean forces). Since no difference existed between the forces in the initial and sustained phases for uphill pushing, these forces may be equally taxing on the operator.

4 Discussion

Results from the current study highlighted the importance of technique in the reduction of hand forces. The high standards deviations evidenced in Table 1 during level pushing/pulling indicated high variability, particularly in the ending forces. This could be partly explained by the variety of techniques used to bring the trolley to a stop. Participants were requested to stop the trolley gradually in a demarcated distance, but were free to choose the method of stopping. It was observed that stopping the trolley gradually resulted in lower hand forces as opposed to the high (peak and mean) forces occurring during sudden termination of the movement. This has important practical implications within industry as it suggests that worker education is paramount in reducing hand forces and thus potentially the overall forces experienced by the worker. A slow, gradual start and stop during the push/pull would arguably reduce the hand forces experienced by the worker and consequently lower chances of injury. Further research is necessary to determine the most effective technique and optimal posture to place the employee at minimal risk.

When investigating load effects on hand forces, it was found that there existed a linear relationship between the two, with higher loads eliciting associated higher hand forces, particularly initial forces. This may be of use in industrial situations where force measures at lower loads can be used to establish a specific regression equation (as this relationship is dependent on the relationship between the trolley wheels and the floor) and thus determine the hand forces required at heavier loads without imposing undue stress on the worker. Results from Cripwell (2006) suggest that this may be true for loads up to 500 kg, however higher loads warrant further investigation before specific conclusions are drawn. Furthermore it must be acknowledged that this relationship is also specific to the situation due to the complex interaction of factors acting within the push/pull scenario (Mack et al. 1995).

The current experiment was conducted under ‘ideal’ conditions where rolling friction was low, the surface was flat and free of obstacles and the cart was in good working order. The hand forces are likely to increase as conditions deteriorate (poor trolley maintenance, presence of ramps/curbs, inappropriate handle height) and so acceptable load mass would decrease. This research would therefore advocate the use of acceptable hand force limits rather than load limits to be more applicable to a wide range of industrial situations. Further research should consider the effects of load on muscle activation, joint loading and posture in an attempt to quantify the risk of injury placed on workers who push/pull variable loads during their working shifts.

The investigation of pushing along graded ramps indicated that for all motion phases, forces exhibited during uphill and/or downhill efforts were significantly greater than those elicited during level pushing. Specifically, uphill pushing was the most taxing during the initial phase, while downhill pushing imposed the greatest stress on the musculoskeletal system during the ending phase; for the sustained phase, hand forces for both graded conditions were higher compared to level pushing. The general trend indicated that level pushing is less physically taxing than the other two conditions, hence it is recommended that level pushing is preferable over graded pushing. This can be explained by the external forces acting on the load; during level pushing only the weight of the trolley provided resistance to motion; contrastingly when pushing uphill or downhill, additional effort was required to overcome the downward effect of gravity. In essence, more effort was exerted by participants to control the load during uphill and downhill pushing. However, results were inconclusive in determining which of uphill or downhill pushing elicits the highest hand forces, and potentially the highest strain; rather findings demonstrated that depending on the phase of motion, one or the other will have a larger detrimental impact.

The finding that forces produced during the sustained phase of graded exertions may be equivalent to, or higher than, those demonstrated during the initial phase has important implications for task design. Results dictate that the lower initial forces as opposed to the higher sustained forces may be more suitable to infer upper limits for force exertion. On the other hand, to determine the risk associated with graded pushing, consideration of higher sustained forces and the associated posture may be appropriate. Although Ferreira et al. (2004) argued that ending forces may surpass those of the initial phase during level pushing, this was not the case for any of the conditions. In fact, for level and uphill conditions, forces in the initial phase were significantly higher than those in the ending phase. Contrastingly for downhill pushing, there were no significant differences between forces in these two phases.

5 Conclusion & Recommendations

To set suitable limits for push/pull activities, biomechanical responses to a variety of loads and gradients must be considered, while acknowledging the broader range of factors associated with load movement. The current study showed that as load increased, so did the hand forces exerted, with a linear relationship existing between the two. This allowed for the extrapolation of hand forces once the relationship was known, and thus one may calculate the hand forces required at heavier loads to establish acceptability. The initial phases during level pushing/pulling required the highest hand forces and are arguably most important to monitor in relation to potential overexertion.

Although results were indeterminate in identifying which of uphill or downhill pushing is favourable, level pushing is preferable. However, if graded slopes are a requisite, they should be kept as close as possible to the horizontal. The commonness of ramps in industrial settings together with the present findings infers that recommendations should not be based solely on level exertions. Following this there is a need to investigate a wider range of gradients to corroborate these results. Additionally, sustained forces were found to equal or exceed initial forces during uphill as well as downhill exertions, implying consideration of sustained forces is necessary when recommending ceiling limits and identifying excessive forces to prevent the worker from being overtaxed. Future studies should investigate the combined effect of load and gradient on hand forces. Finally, workers should ideally be educated as to the benefits of adopting a slow controlled technique as a practical means of reducing the risk of push/pull activities.

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