A thorough investigation on pushing activities in industry: The impact of the variation in the speed of motion and load conditions on initial and sustained forces

Published Version:

Botti, L., Galizia, F.G., Mora, C., Zecchi, G. (2020). A thorough investigation on pushing activities in industry: The impact of the variation in the speed of motion and load conditions on initial and sustained forces. APPLIED ERGONOMICS, 85, 1-8 [10.1016/j.apergo.2020.103080].

Availability:

This version is available at: https://hdl.handle.net/11585/735248 since: 2020-03-01

Published:

DOI: http://doi.org/10.1016/j.apergo.2020.103080

A thorough investigation on pushing activities in industry: the impact of the variation in the speed of motion and load conditions on initial and sustained forces

Abstract

Pushing and pulling wheeled objects represent a significant part of manual material handling activities in industry. Medical investigations and epidemiological studies proved the correlation between such activities and the occurrence of lumbago, low back pain and adverse effects on the shoulders. The ISO 11228-2:2007 provides the recommended limits for pushing and pulling. Such values are the results of psychophysical studies realized under prescribed speed conditions referring to a slow walk. However, observation of real industrial and service sector environments reveals that workers are required to perform pushing activities at higher speed of motion.

The aim of this study was to investigate the impact of the variation in the speed of motion and load conditions on push forces. 96 subjects performed a total of 2,592 trials consisting of pushing an industrial trolley for warehouse applications, at different speed values and load conditions. Results confirm the presence of correlation between the increasing speed of motion and push forces. The findings have practical value for researchers, occupational physicians and ergonomics practitioners.

Keywords: Push force; initial force; sustained force; speed of motion; industrial trolley.

1. Introduction

The pressure to meet the market requests and the customers' needs, the shortage of human resources and technical skills, and the chronical lack of technical aids that characterize current manufacturing systems lead to strenuous working conditions (Botti, Mora, Zecchi, & Baruffaldi, 2019). Epidemiological studies and medical investigations performed by researchers and occupational physicians identified a strong relationship between musculoskeletal disorders (MSDs) and work practices in industry (Cole, Van Eerd, Bigelow, & Rivilis, 2006; National Research Council, 2001). Biomechanical factors (movement frequency and intensity, task duration, assumed posture, vibration, etc.), psycho-social factors (stress, decision-making control, psychological demand, motivation, monotony, etc.), and organizational factors (work organization, relationship with the colleagues, etc.) contribute to the development of these pathologies (Caroly, Coutarel, Landry, & Mary-Cheray, 2010; HSE, 2018; Michie, 2002). Such risk factors are the result of workers exposure to the characteristics of the current dynamic market, which requires high product customization and short delivery times. Conventional working conditions in manual picking tasks and logistics operations are not able to satisfy the market requirements because of the high presence of manual material handling (MMH) activities. MMH is considered a complementary and non-indispensable service that is expected to be accomplished in a short time and with high performances. These characteristics require the adoption of efficient solutions that reduce the overall costs of logistics, at the expenses of an effective reduction of the protection against the risks arising from MMH.

This paper investigates the ergonomics of MMH in industry, focusing on the activity of two-handed pushing. The aim was to enlarge the previous research from Botti et al. (2019) providing a thorough investigation about the correlation between the variation in the speed of motion and the push forces.

Push and pull activities characterize a significant part of MMH tasks in industry (Argubi-Wollesen, Wollesen, Leitner, & Mattes, 2017; Garg, Moore, & Kapellusch, 2016; Seo, Armstrong, & Young, 2010).

Previous studies showed that redesign interventions in industry often call for replacing lifting, lowering, and carrying tasks with pushing (Garg, Waters, Kapellusch, & Karwowski, 2014; Laursen & Schibye, 2002). Research has not yet proven whether pushing or pulling should be favoured (Garg et al., 2014). However, a properly designed industrial trolley allows the replacement of heavy lifting tasks with acceptable push forces for a high percentage of population (Vincent M. Ciriello, McGorry, Martin, Bezverkh Ny, & Bezverkhny, 1999).

Despite the ergonomic benefit compared with lifting and lowering, many studies revealed multiple factors for musculoskeletal strain and low back pain originating from pushing and pulling (Argubi-Wollesen et al., 2017; Damkot, Pope, Lord, & Frymoyer, 1984; Frymoyer et al., 1983; M. J. M. Hoozemans, Van der Beek, Frings-Dresen, Van der Woude, & Van Dijk, 2002; M. J. Hoozemans, van der Beek, Frings-Dresen, van Dijk, & van der Woude, 1998; Kelsey, 1975; J. Lee, Nussbaum, & Kyung, 2014; Plouvier, Renahy, Chastang, Bonenfant, & Leclerc, 2008).

Past and recent studies revealed that the frequency of the push/pull exertions is a relevant factor impacting on push and pull forces (Argubi-Wollesen et al., 2017; V. M. Ciriello & Snook, 1983; Vincent M. Ciriello, Dempsey, Maikala, & O'Brien, 2007; Garg et al., 2014; M. J. M. Hoozemans et al., 2002; J. Lee et al., 2014; Marras, Knapik, & Ferguson, 2009). Few studies investigated the impact of the speed of push, i.e. the speed of the pushing action performed by the user's arms with the hands on an object, during pushing and pulling tasks (Garg & Beller, 1990; Garg et al., 2014; Marras et al., 2009). Marras et al. (2009) investigated the influence of different physical factors as the load magnitude, the handle height and the speed of push during pushing tasks. The results show that increasing speed of push has a dramatic impact on initial forces and on the anterior/posterior shear force magnitudes. Specifically, *Initial force (IF)* is the force required to move an object, while s*ustained force (SF)* is the force required to keep the object moving (V. M. Ciriello & Snook, 1983; Vincent M. Ciriello et al., 1999). The study from Marras et al. (2009) revealed that an increase in the speed of push from 0.7 m/s to 1 m/s causes a 30% increase of the initial force. More recently, Garg et al. (2014) revealed that the speed of push/pull impacts as well as the size and type of trolley wheels on the required horizontal force needed to move an object. Neither research study investigated the variation in the speed of motion, i.e. the speed related to time required to walk a specific distance with the legs, during pushing activities and the impact on push forces. However, current practice shows that high frequency of push/pull exertions is often associated with high speed of motion.

The regulations on Occupational Health and Safety (OHS) marginally cover the relationship between speed of motion and push/pull forces during pushing/pulling tasks. However, the international standards on the machinery design consider the movement speed as a health risk factor to include in the risk evaluation of the intended use of machinery, i.e. the maximum force capacity decreases during performance of fast and contractive movements (European Committee for Standardization, 2008). Actions demanding high accelerations involve significant tissue forces and, thus, an increased risk for disorders and injuries (European Committee for Standardization, 2008). Furthermore, the International Standard Organization (ISO) requires consideration of high-accelerated motions and high speed movements (over 1.2 m/s) among the health risk factors for task evaluation (International Standard Organization, 2007).

The ISO Standard 11228-2 (International Standard Organization, 2007) and the ISO Technical Report (TR) 12295 (International Standard Organization, 2014) describe a commonly adopted methodology for the identification of acceptable pushing and pulling conditions at work, providing the directions for the ergonomic redesign of pushing and pulling tasks. Based on the approach developed by Snook and Ciriello (V. M. Ciriello & Snook, 1983; Vincent M. Ciriello et al., 1999; S. H. Snook, 1971; S H Snook, 1978; Stover H. Snook & Ciriello, 1991), such methodology requires the comparison between the actual forces applied during the pushing/pulling task and a set of recommended force limit values. Actual force values should not exceed the recommended force values in the ISO Standard. The ISO approach for measuring push/pull forces suggests to use a force gauge to take measurements. Mechanical and digital force gauges equipped with handles in conformity with the ISO Standard are commercially available for force measurements. Both IF and SF are recorded during pushing and pulling. The limit values in the ISO 11228-2 (International Standard Organization, 2007) and in the ISO TR 12295 (International Standard Organization, 2014) are from the Snook and Ciriello's empirical studies. The authors employed a psychophysical approach to determine maximum acceptable push and pull forces. The suggested methodology for measuring push and pull force requires to move the object adopting a slow walk, i.e. 0.1 m/s for IF and 0.3 m/s for SF (Botti et al., 2019; International Standard Organization, 2007).

Current practice shows that this requirement is not respected in many industries, e.g. manufacturing, service and health-care sectors. Work organization and job schedules impose high pace and short takt times, aiming to achieve the planned productivity levels (Mattos, Ariente Neto, Merino, & Forcellini, 2019). Workers choose the appropriate speed of motion under different work conditions, ranging from 0.25 m/s to 1.5 m/s (Jung, Haight, & Freivalds, 2005; K. S. Lee, Chaffin, & Parks, 1992; Resnick & Chaffin, 1995). Furthermore, warehouse carts and industrial trolleys are not usually suitable for the task and the context for which they are adopted, e.g. the wheels are inadequate and the maintenance is poor. The adoption of inadequate equipment determines difficult work conditions and a negative impact on human factors, as physical and mental stress, biomechanical overload and fatigue. These factors, together with the disregard for human anthropometrics and workers' suitability for performing the work activity, are the cause of unsafe behaviors and health and safety issues (HSE, 2018; Michie, 2002; Rocha, Mollo, & Daniellou, 2015).

The findings of a preliminary study from Botti et al. (2019) on MMH activities in industry revealed some correlation between speed variation and push forces. Specifically, an industrial trolley was pushed at different speed values to investigate the increase in push force in four load conditions, i.e. 0 kg (empty cart), 24 kg, 48 kg and 72 kg on the trolley. Three multi-year career occupational safety and health professionals performed twenty-six pushing trials. Maximum initial and sustained push forces were measured for each trial with an electronic force gauge. Results suggested that increasing the speed of motion and the load condition leads to increased push forces.

Following the empirical approach in Botti et al. (2019), this paper extended the preliminary study providing a thorough investigation of such correlation. 96 subjects performed a total of 2,592 trials consisting of pushing an industrial trolley for warehouse applications, at different speed values and load conditions. The findings of this research do not aim to question Snook and Ciriello's psychophysical approach (Stover H. Snook & Ciriello, 1991) nor the effectiveness of the risk assessment methodology introduced in the ISO 11228-2 standard (International Standard Organization, 2007). The aim was to investigate the variation of push forces when the speed of motion and the pushed weight increase.

2. Materials and method

2.1. Approach

This study was intended to examine how the speed of motion influences the push forces that workers apply during pushing tasks in industry. The correlation between push forces and load, handle height and movement frequency has been previously examined in several studies. In this study, a thorough investigation of the impact of speed variation and load on IF and SF was performed. Specifically, an empirical approach was adopted to investigate a push task that varied according to the speed of motion and to the load on an industrial trolley. A digital force gauge was employed to measure the push forces during the study. Data were recorded and analyzed with a digital support.

2.2. Subjects

Ninety-six individuals (68 males and 28 females) volunteered as subjects for this study. The size of the panel was determined considering the sample size formula based on the normal approximation to the binomial proposed by Fosgate (2009). The subjects were university students, full time researchers, professors, and other university staff members, e.g. laboratory technicians, administrative employees and bar tenders. Subjects were included if they were in good health condition, capable of providing informed consent and of understanding the testing procedure. None of the subjects were experiencing low back pain or other musculoskeletal disorders prior to or during the study. Subjects with cardiac or pulmonary problems, and pregnant women or elite athletes were excluded from the study. Subjects demographic data were recorded prior to each trial. Specifically, each subject filled in a questionnaire (see Appendix A) reporting personal data and anthropometric measures, such as age, weight, stature, elbow height, i.e. vertical distance from the floor to the lowest bony point of the bent elbow (International Standard Organization, 2017), physical activity and previous experiences in MMH activities. Finally, the informed consent of each subject participating in the study was obtained and documented prior to each trial.

2.3. Experimental design

A digital force gauge equipped with two handles (IMADA ZTA-500N, sample rate 2000 data/s, accuracy +/- 0.2% Full Scale +/- 1digit, Handle dimensions h:191 x 75 x 34 mm) was employed to measure individuals Maximum Voluntary Isometric Contraction (MVIC) before each trial. Each subject performed five MVIC trials. Subjects were asked to maximally push against the gauge until the investigator saw a peak in the contraction on the computer screen (Meldrum, Cahalane, Conroy, Fitzgerald, & Hardiman, 2007). A rest of 3–5 seconds was given between each MVIC trial. Both the maximum and the mean of five values were recorded for the purposes of statistical analysis. Consistency was ensured by discarding measurements that differed from each other by more than 15%. The investigator provided each subject with verbal instruction and encouragement during testing. Subjects received no visual feedback nor were they provided with knowledge of their results (Meldrum et al., 2007).

Testing took place at the Department of Industrial Engineering of the University of Bologna (Italy). The experimental design consisted of 3 x 3 x 3 x 96 pushing trials. Each trial required the subjects to push an industrial trolley in a straight ahead position, on an industrial flat surface for 7.1 m. Three consecutive sections of 7.1 m defined the pushing distance during the trials. Three load conditions (24 kg, 48 kg and 72 kg on the trolley) and three speed conditions (low, medium and high) were defined. The load conditions were realized by positioning multiple baskets of bottled water on the trolley surface until the target load was reached. The speed values were not prescribed. Each subject pushed the trolley to reach the slow, medium and fast speed conditions. Discretion was allowed to permit the subjects in deciding how to meet the speed demands, aiming to increase the decision latitude and to reduce the mental strain (Karasek, 1979). Specifically, low speed is associated to a slow walk. Medium speed refers to the speed adopted during a normal walk. High speed refers to a walk at a fast pace. The reference speed values for each range are in Table 1 (Jung et al., 2005; K. S. Lee et al., 1992; Resnick & Chaffin, 1995).

Table 1. Speed ranges adopted in the study (Jung et al., 2005; K. S. Lee et al., 1992; Resnick & Chaffin, 1995).

Speed range	*Description*
0.4 – 0.9 [m/s]	Low, slow walk
0.9 – 1.3 [m/s]	Medium, normal walk
1.3 – 1.5 [m/s]	High, fast walk
1.5 – 1.7 [m/s]	Very high, very fast walk
>1.7 [m/s]	Almost running or running

Each subject repeated the trials until three consistent measurements were recorded for each load and speed condition (International Standard Organization, 2007). The results of the preliminary study suggested that high speed conditions are difficult to reach when the load on the trolley is heavier than 72 kg (Botti et al., 2019). Users reported difficulties in handling the trolley in such load condition. Furthermore, the European Standard EN 1005-3 recommends to let force limits for professional users correspond to the 15th percentile of the whole adult population, i.e. males and females between 20 years and 65 years of age (European Committee for Standardization, 2008). For example, the maximum isometric force for professional female users between 20 and 30 years old for whole body pushing in standing posture is 200 N (European Committee for Standardization, 2008). For domestic users, the maximum isometric force is 119 N. Given the results of the preliminary study and the requirements from the European Standard, the maximum load condition on the trolley in this study was set to 72 kg.

The digital force gauge used for MVIC measurements was adopted for push force measurements. Figure 1-A shows the industrial trolley adopted during the study. The trolley dimensions were 100 cm (width) and 79.5 cm (length). The trolley was equipped with four fixed casters. The handle of the trolley was at 95 cm from the floor (International Standard Organization, 2007). A flat adaptor was applied on the handle to allow the stable positioning of the gauge (see the red board in Figure 1-B). The subjects positioned the gauge on the central point of the flat adaptor in Figure 1-B then pushed the cart by means of the gauge handles (Figures 1-C).

Figure 1-A, 1-B and 1-C. Industrial trolley adopted in the study (A), flat adaptor on the trolley handle (B) and force gauge in position (C).

2.4. The protocol

An experimental protocol was developed to address the investigator and the subjects during the study (see Appendix B). Each subject followed the directions of the investigator. The investigator positioned the industrial trolley behind the starting line on the floor at the beginning of each trial. The load was firmly placed on the central part of the trolley surface, with the center of mass on the motion trajectory. When the investigator called the start of the first trial, the subject placed the force gauge on the trolley handle and pushed the trolley at low and constant speed over the end of the first section. Speed and force measurements were recorded until the anterior casters of the trolley moved within the section. The negative force applied to stop the trolley was not considered in this study. Then, the investigator placed the trolley behind the line of the first section and called the start of the second trial. Three consistent measurements were recorded for each subject, load and speed condition (International Standard Organization, 2007).

The MVIC test and the pushing trials for the experimental study required about 30 minutes for each user.

Data were managed and analyzed using a customized application built in MATLAB and Microsoft Excel Version 16.16.15. Specifically, the MATLAB application transferred the data generated by digital force gauge into an Excel worksheet. Excel functions were adopted for the statistical analysis.

3. Results

The anthropometric measurements and the results of the MVIC describe the characteristics of the subjects involved in this study. Table 2 contains the mean values and the standard deviations (SD) of age and anthropometric measurements. The results of the MVIC test are in Table 3 and Figure 2.

Table 2. Subjects demographic data.

	Males and females			**Males**			**Females**		
Subjects	96			68 (71%)			28 (29%)		
	Mean (SD)	*Min*	*Max*	*Mean (SD)*	*Min*	*Max*	*Mean (SD)*	*Min*	*Max*
Age [years]	27.8 (8.8)	20	58	29.0 (9.9)	20	58	25.1 (4.6)	22	41
Weight [kg]	69.7 (12.0)	47	102	74.8 (10.1)	58	102	57.9 (6.2)	47	67
Stature [cm]	175.2 (7.8)	156	194	177.8 (6.3)	160	194	168.9 (7.5)	156	184
Elbow height [cm]	108.7 (5.3)	98	119	110.4 (5.0)	101	119	104.5 (3.9)	98	115
Sport practitioners [%]	68.0%			77.1%			46.7%		
Experience in MMH [%]	28.0%			37.1%			6.7%		

Table 3. MVIC test results.

	Males and females			**Males**			**Females**		
	Mean (SD)	*Min*	*Max*	*Mean (SD)*	*Min*	*Max*	*Mean (SD)*	*Min*	*Max*
MVIC [N]	241.6 (75.3)	132	456	260.0 (76.0)	143	456	198.8 (54.8)	132	318

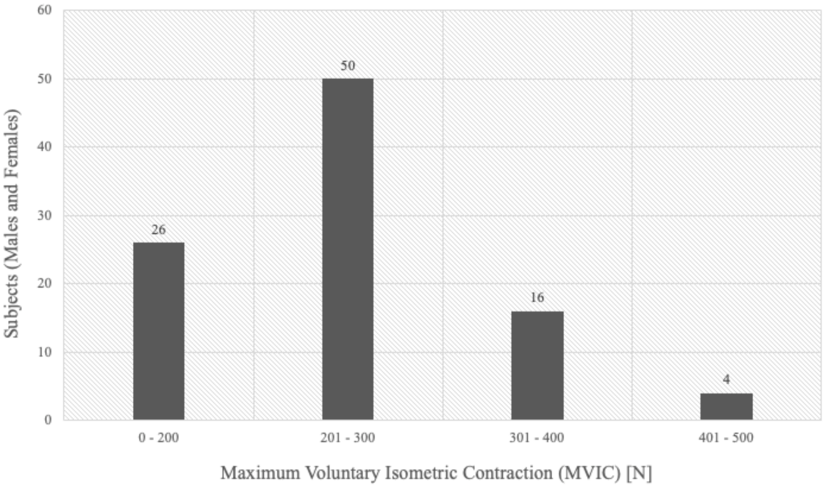

Figure 2. MVIC mean values of the subjects involved in the study.

Table 4 shows the minimum and the maximum recorded values for the speed of motion and for the push forces in the three investigated load conditions. The speed value is the result of the ratio between the distance of motion (7.1 m) and the travel time. Force measurements within the 5th – 95th percentile range were included in the statistical analysis.

Table 4. Minimum, maximum and mean (SD) recorded values for speed of motion and push forces.

	Load conditions		
Load condition	*Condition 1*	*Condition 2*	*Condition 3*
Load on the trolley [kg]	24	48	72
Number of trials	864	864	864
Speed of motion			
Minimum speed [m/s]	0.41	0.52	0.53
Maximum speed [m/s]	1.92	1.83	1.83
Mean (SD) [m/s]	1.05 (0.30)	1.05 (0.28)	1.05 (0.27)
Speed increase [%]	368%	252%	245%
Initial force IF			
Minimum IF [N]	53.50	83.26	109.23
Maximum IF [N]	141.63	172.77	228.03
Mean (SD) [N]	87.09 (21.49)	121.07 (22.35)	152.96 (25.52)
IF increase [%]	165%	107%	109%
Sustained force SF			
Minimum SF [N]	27.42	37.37	47.59
Maximum SF [N]	41.46	56.26	73.35
Mean (SD) [N]	32.36 (2.44)	45.13 (3.53)	59.31 (4.66)
SF increase [%]	51%	51%	54%

Percentage values for speed, IF and SF in Table 4 refer to the increase from the minimum to the maximum values in the study. The subject variability may affect the percentage values. Though, these results show that increasing the load on the trolley and the speed of motion leads to increased initial and sustained forces (see Table 4). Such trend is visible in each load condition.

Specifically, Figure 3 and Figure 4 describe the increase of IF and SF due to the increasing speed of motion in Condition 1 (24 kg on the trolley). The vertical dotted line shows the speed of motion equal to 1.5 m/s (5.4 km/h), which is the upper limit for the speed range of a fast walk (see Table 1).

Similar results were obtained for Condition 2, when the load on the trolley was 48 kg (Figure 5 and Figure 6). Condition 3 (72 kg on the trolley) is in the following Figure 7 and Figure 8.

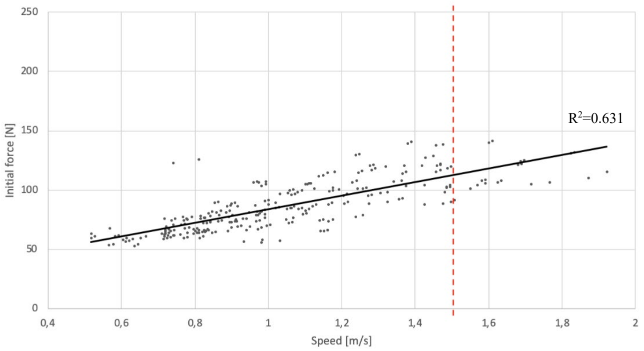

Figure 3. Initial force 24 kg (Regression equation: y = 57.5x + 26.5).

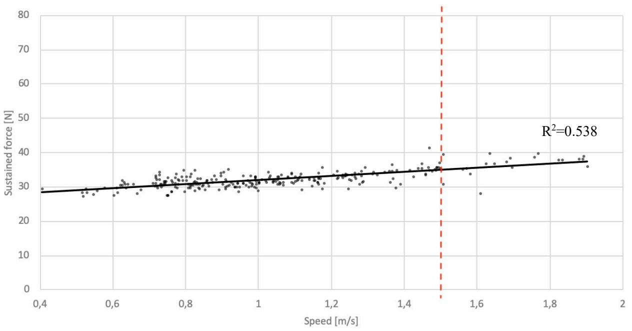

Figure 4. Sustained force 24 kg (Regression equation: y = 5.9x + 26.2)

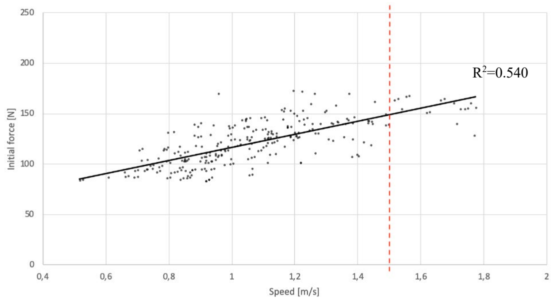

Figure 5. Initial force 48 kg (Regression equation: y = 64.8x + 51.9).

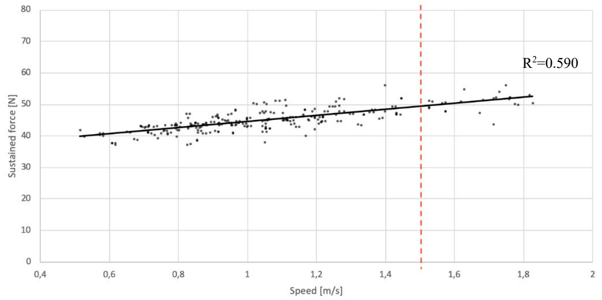

Figure 6. Sustained force 48 kg (Regression equation: y = 9.7x + 35.0)

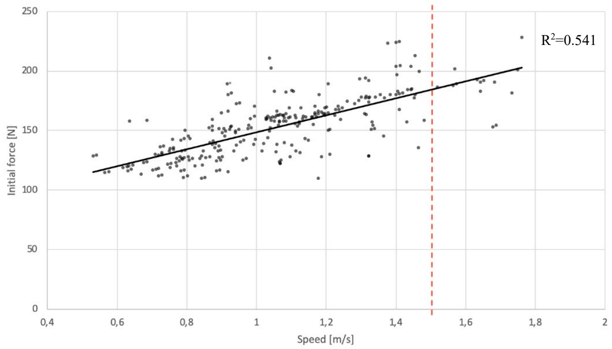

Figure 7. Initial force 72 kg (Regression equation: y = 71.4x + 77.2).

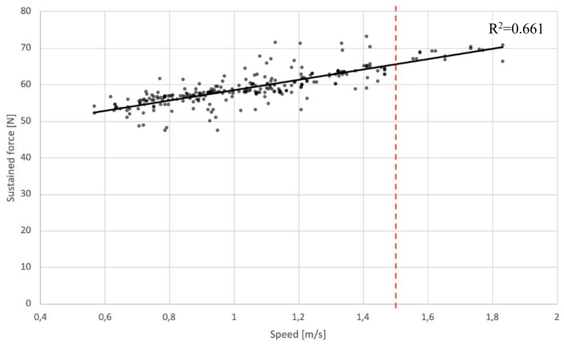

Figure 8. Sustained force 72 kg (Regression equation: y = 14.2x + 44.5).

The correlation between the variation in the speed of motion and push forces for the different load conditions was investigated by creating the correlation matrix with the data obtained from the pushing trials. The resulting coefficients of determination (R^2) for force measurements and speed of motion are in the following Table 5.

Table 5. Coefficient of determination R^2 for the speed of motion and force measurements in each load condition.

	Load conditions		
Load condition	*Condition 1*	*Condition 2*	*Condition 3*
Load on the trolley [kg]	24	48	72

IF Coefficient of determination R^2	0.631	0.540	0.541
SF Coefficient of determination R^2	0.538	0.590	0.661

4. Discussion

The results in previous Section 3 confirm that increasing the speed of motion during pushing tasks leads to increased push forces. Such trend is strongly marked for the IF (see Table 4). Table 4 and Table 5 confirm the trends introduced in the preliminary study from Botti et al. (2019). The minimum speed values reflect a slow walk in both the studies. Some discrepancy was found for the maximum speed values, push forces and standard deviations. The maximum speed value reached in this study was 1.92 m/s (6.92 km/h), which was higher than the highest speed value in the preliminary study (Botti et al., 2019), and higher than the transition speed from walking to running (1.81 m/s - 6.50 km/h) (Nüesch, Overberg, Schwameder, Pagenstert, & Mündermann, 2018; Shih, Chen, Lee, Chan, & Shiang, 2016). SD values in this study were higher than the values in the preliminary study. Such difference may derive from the different anthropometric characteristics and level of experience in MMH and occupational safety of the subjects involved in the present study. Three safety professionals with multiple years of experience in occupational health and safety performed the trials in the preliminary study. This research involved an heterogeneous sample of subjects with different levels and years of experience. Such heterogeneities are present in industry, where education and training programs marginally cover the topics of optimal two-handed pushing and pulling. Furthermore, the subjects in the present study autonomously decided the speed of motion adopted during the trials. No specific values for low, medium and high speed of motion were defined. This choice allowed the creation of a more realistic industrial context, at the expense of higher SD values. Subjects were not required to follow a specific speed sequence, e.g. decreasing, increasing or randomized speed of motion. All the subjects chose to gradually increase the speed of motion during the trials. This may be due to the fact that the speed values were not prescribed and the gradual increment allowed an easier adoption of the proper speed range.

Table 6 shows the distribution of the trials within different speed ranges in each condition. Similar percentage values in the speed of motion ranges are visible for the same load conditions, regardless the type of the investigated push force, i.e. IF or SF. Specifically, different percentage values for IF and SF are due to the cut-off of force measurements outside the 5th - 95th percentile range.

Table 6. Percentage distribution of the trials within different speed ranges in each load condition.

	IF			*SF*		
Load condition	*Condition 1*	*Condition 2*	*Condition 3*	*Condition 1*	*Condition 2*	*Condition 3*
Load on the trolley [kg]	24	48	72	24	48	72
Speed of motion [m/s]	*Trials [%]*			*Trials [%]*		
0.4 – 0.9	37%	27%	32%	37%	32%	34%
0.9 – 1.3	42%	55%	47%	45%	51%	47%
1.3 – 1.5	13%	11%	16%	11%	8%	14%
1.5 – 1.7	5%	3%	4 %	4%	5%	3%
> 1.7	2%	3%	1%	3%	4%	2%
Total	100%	100%	100%	100%	100%	100%

These findings confirm the consistency of results. Specifically, a significant part of the subjects involved in this study were able to adopt a fast walk when they were required to accomplish a pushing task in a short time. High speed values were difficult to reach when the load on the trolley was heavy. However, a very fast walk should not be adopted in the workplace during pushing and pulling tasks, where potential obstacles and interferences with other work activities may result in accidents and injuries. Then, the vertical dotted lines at 1.5 m/s in Figures from 3 to 8 show a theoretical upper limit value for the speed of motion during pushing and pulling tasks in the workplace.

Table 7 and Table 8 show the minimum, the maximum and the mean values for initial and sustained forces, and for each speed range and load condition. These results confirm that given a specific load condition, the adopted speed of motion impacts on the resulting push forces. Hence, the speed of motion is a critical factor that should be investigated during the risk assessment of pushing activities.

Table 7. Initial forces for each speed range and load condition.

IF	*Condition 1*				*Condition 2*				*Condition 3*			
Speed of motion [m/s]	*Min [N]*	*Max [N]*	*Mean (SD) [N]*	*Increase [%]*	*Min [N]*	*Max [N]*	*Mean (SD) [N]*	*Increase [%]*	*Min [N]*	*Max [N]*	*Mean (SD) [N]*	*Increase [%]*
0.4 – 0.9	53.50	126.13	69.58 (11.61)	136%	83.73	139.40	101.07 (13.45)	66%	109.23	159.23	128.56 (12.20)	46%
0.9 – 1.3	56.50	130.77	88.81 (13.36)	131%	83.27	172.77	123.37 (19.09)	107%	109.57	210.40	155.96 (17.61)	92%
1.3 – 1.5	88.07	140.80	112.41 (15.26)	60%	107.00	169.63	137.18 (15.42)	59%	128.10	224.63	178.13 (23.07)	75%
1.5 – 1.7	90.77	141.63	113.20 (15.17)	56%	139.33	167.53	158.51 (9.19)	20%	152.97	201.20	183.48 (15.54)	32%
> 1.7	105.63	132.07	118.18 (11.31)	25%	128.20	160.20	151.03 (11.13)	25%	181.57	228.03	203.54 (23.33)	26%

Table 8. Sustained forces for each speed range and load condition.

SF	*Condition 1*				*Condition 2*				*Condition 3*			
Speed of motion [m/s]	*Min [N]*	*Max [N]*	*Mean (SD) [N]*	*Increase [%]*	*Min [N]*	*Max [N]*	*Mean (SD) [N]*	*Increase [%]*	*Min [N]*	*Max [N]*	*Mean (SD) [N]*	*Increase [%]*
0.4 – 0.9	27.42	34.99	30.97 (1.69)	28%	37.37	47.13	42.13 (2.08)	26%	47.70	61.80	55.64 (2.46)	30%
0.9 – 1.3	28.90	35.70	32.14 (1.45)	24%	38.03	52.12	45.60 (2.58)	37%	47.59	71.63	59.28 (3.46)	51%
1.3 – 1.5	29.83	41.46	34.77 (2.12)	39%	43.50	56.17	48.00 (2.83)	29%	59.11	73.35	64.14 (2.89)	24%
1.5 – 1.7	28.18	39.91	35.72 (3.44)	42%	47.53	54.89	50.22 (2.07)	15%	67.05	69.47	68.31 (1.02)	4%
> 1.7	35.89	39.88	38.05 (1.31)	11%	43.75	56.26	51.55 (3.01)	29%	66.50	71.00	69.60 (1.59)	7%

Specifically, given a load condition on the trolley, both IF and SF vary depending on the adopted speed of motion. For example, pushing an industrial trolley with 24 kg on its surface at 1.3 m/s (4.7 km/h) will require an additional 131% of initial force and a further 24% of sustained force, compared with the force required to push the same cart at 0.9 m/s (3.2 km/h). The increase of IF (Table 7) and SF (Table 8) reduces with the increasing load on the trolley. This trend may be due to the difficulty of the subjects in handling the trolley with an heavy load. Furthermore, the maximum push forces associated with the speed values in this study are higher than the maximum forces registered in the preliminary study. Such discrepancies may be due to the different level of experience of the subjects involved in the two studies, i.e. the subjects in the preliminary study were safety professionals with multiple years of experience in MMH and OHS. Limitations of this study include the heterogeneity of the sample involved in this research. University students, full time researchers, professors, and other university staff members, e.g. laboratory technicians, administrative employees and bar tenders, participated in the study. The 28% of the subjects had previous experience with pushing activities. However, their main occupation at the time of the study did not involve pushing tasks. Furthermore, the adoption of a random order of testing speed conditions may affect the results. Specifically, higher variance of measurements may appear adopting a random order of testing speed conditions.

Finally, personal data were collected anonymously. User gender and age information related to each trial were not recorded for privacy reasons. The authors are aware that the anthropometric and gender differences among the subjects involved in the study might influence the results. However, the working population involved in two-handed pushing in industry may present similar heterogeneities.

5. Conclusions

This paper investigated the correlation between the speed of motion and load conditions during pushing wheeled objects in the workplace and the applied push forces. An empirical study involved 96 subjects who pushed an industrial trolley for warehouse applications, in different speed and load conditions. A total of 2,592 trials were performed aiming to measure the speed of motion in different load conditions, and the resulting push forces. The interest in the correlation between the speed of motion and the push forces in the workplace started after the observation of the actual speed conditions with which the workers push wheeled objects in industry. Such conditions differ from the speed values adopted in the studies from Snook and Ciriello (V. M. Ciriello & Snook, 1983; Stover H. Snook & Ciriello, 1991) based on which the International Standard on pushing and pulling activities in the workplace was released (International Standard Organization, 2007). The methodology proposed in the ISO 11228-2 (International Standard Organization, 2007) requires to adopt a speed of motion between 0.1 and 0.3 m/s during the risk assessment of pushing and pulling tasks. This speed equates to a slow walk. Previous studies and experimental researches showed that workers select appropriate speeds under different conditions, ranging from 0.25 to 1.5 m/s (Jung et al., 2005). Such conditions include the features of the workplace (e.g. equipment), the characteristics of the working population (e.g. skills and strength) and the organizational requirements (e.g. the available time for the pushing/pulling task) (K. S. Lee et al., 1992; Resnick & Chaffin, 1995). The results of the previous studies investigating pushing and pulling tasks in the workplace (Botti et al., 2019; Marras et al., 2009) encouraged the present research.

Three load conditions on an industrial trolley were investigated, i.e. 24 kg, 48 kg and 72 kg. The results confirmed the presence of high correlation between the increasing push forces and the speed of motion. The adoption of an higher load on the trolley may produce dissimilar results. However, the subjects have difficulties in handling the trolley in Condition 3 (72 kg), i.e. an high speed of motion may be difficult with an heavier trolley.

The findings of this study confirmed that increasing the speed of motion during pushing tasks requires higher push forces. These results suggest a deeper investigation of the potential correlation of such phenomenon with an increased risk for workers' health and safety, and the appearance of occupational injuries, diseases and disorders.

The recommendations from the ISO 11228-2 (International Standard Organization, 2007) and the results of previous studies on recommended forces during pushing tasks (Vincent M. Ciriello et al., 1999; Stover H. Snook & Ciriello, 1991) are a valid and useful reference for both ergonomics researchers and practitioners. However, this study revealed that the speed of motion adopted during two-handed pushing impacts on the resulting push forces. The findings of this study suggest that the speed requirements defined in the ISO 11228-2 (International Standard Organization, 2007) may differ from the actual working conditions adopted in industry. Consequently, when the workers are required to exceed the speed requirements in the ISO 11228-2 (International Standard Organization, 2007), the comparison with the maximum acceptable initial and sustained forces in the ISO risk assessment method may underestimate the potential hazards and risks associated with pushing. The preventive purposes of the ISO Standard are still adequate when pushing activities are performed at low speed.

This study has some limitations due to the heterogeneity of the experimental sample. The subjects involved in this study were mainly academics and other workers from the university personnel, e.g. administrative staff and bar tenders. However, nearly one third of the subjects had previous experience with pushing activities. Furthermore, personal information, e.g.

anthropometric, gender and age data related to each trial were not recorded for privacy reasons. Future developments of this work may include the participation of industrial workers and the investigation of further factors that may impact on push forces, e.g. anthropometric, age and gender differences or the geometry of the handles.

Acknowledgments

The data used in this study were recorded at the Department of Industrial Engineering of the University of Bologna, Bologna (IT). Lorenzo De Santis, Eng., former graduated student from the School of Engineering of the University of Bologna, supported part of the experimental research. The authors are grateful for this support.

References

Argubi-Wollesen, A., Wollesen, B., Leitner, M., & Mattes, K. (2017). Human Body Mechanics of Pushing and Pulling: Analyzing the Factors of Task-related Strain on the Musculoskeletal System. *Safety and Health at Work*, *8*, 11–18. https://doi.org/10.1016/j.shaw.2016.07.003

Botti, L., Mora, C., Zecchi, G., & Baruffaldi, G. (2019). The Effect of Speed Variation on Initial and Sustained Forces During Pushing and Pulling Activities: A Preliminary Study. In *Advances in Intelligent Systems and Computing*. https://doi.org/10.1007/978-3-319-94196-7_16

Caroly, S., Coutarel, F., Landry, A., & Mary-Cheray, I. (2010). Sustainable MSD prevention: Management for continuous improvement between prevention and production. Ergonomic intervention in two assembly line companies. *Applied Ergonomics*. https://doi.org/10.1016/j.apergo.2009.12.016

Ciriello, V. M., & Snook, S. H. (1983). A study of size, distance, height, and frequency effects on manual handling tasks. *Human Factors*. https://doi.org/10.1177/001872088302500502

Ciriello, Vincent M., Dempsey, P. G., Maikala, R. V., & O'Brien, N. V. (2007). Revisited: Comparison of two techniques to establish maximum acceptable forces of dynamic pushing for male industrial workers. *International Journal of Industrial Ergonomics*, *37*(11–12), 877–882. https://doi.org/10.1016/J.ERGON.2007.07.003

Ciriello, Vincent M., McGorry, R. W., Martin, S. E., Bezverkh Ny, I. B., & Bezverkhny, I. B. (1999). Maximum acceptable forces of dynamic pushing: comparison of two techniques. *Ergonomics*, *42*(1), 32–39. https://doi.org/10.1080/001401399185784

Cole, D. C., Van Eerd, D., Bigelow, P., & Rivilis, I. (2006). Integrative interventions for MSDs: Nature, evidence, challenges & directions. *Journal of Occupational Rehabilitation*. https://doi.org/10.1007/s10926-006-9032-5

Damkot, D. K., Pope, M. H., Lord, J., & Frymoyer, J. W. (1984). The relationship between work history, work environment and low-back pain in men. *Spine*, *9*(4), 395–399. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6236564

European Committee for Standardization. (2008). EN 1005-3:2002+A1:2008. Safety of machinery - Human physical performance - Part 3: Recommended force limits for machinery operation.

Fosgate, G. T. (2009). Practical sample size calculations for surveillance and diagnostic investigations. *Journal of Veterinary Diagnostic Investigation*. https://doi.org/10.1177/104063870902100102

Frymoyer, J. W., Pope, M. H., Clements, J. H., Wilder, D. G., MacPherson, B., & Ashikaga, T. (1983). Risk factors in low-back pain. An epidemiological survey. *The Journal of Bone and Joint Surgery. American Volume*, *65*(2), 213–218. https://doi.org/10.1007/978-1-4471-5451-8

Garg, A., & Beller, D. (1990). One-handed dynamic pulling strength with special reference to speed, handle height and angles of pulling. *International Journal of Industrial Ergonomics*, *6*, 231–240. https://doi.org/10.1016/0169-8141(90)90037-3

Garg, A., Moore, J. S., & Kapellusch, J. M. (2016). The Revised Strain Index: an improved upper extremity exposure assessment model. *Ergonomics*, *60*(7), 912–922. https://doi.org/10.1080/00140139.2016.1237678

Garg, A., Waters, T., Kapellusch, J., & Karwowski, W. (2014). Psychophysical basis for maximum pushing and pulling forces: A review and recommendations. *International Journal of Industrial Ergonomics*, *44*, 281–291. https://doi.org/10.1016/j.ergon.2012.09.005

Hoozemans, M. J. M., Van der Beek, A. J., Frings-Dresen, M. H. W., Van der Woude, L. H. V., & Van Dijk, F. J. H. (2002). Pushing and pulling in association with low back and shoulder complaints. *Occupational and Environmental Medicine*, *59*(10), 696–702. https://doi.org/10.1136/oem.59.10.696

Hoozemans, M. J., van der Beek, a J., Frings-Dresen, M. H., van Dijk, F. J., & van der Woude, L. H. (1998). Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors. *Ergonomics*, *41*(6), 757–781. https://doi.org/10.1080/001401398186621

HSE. (2018). Human factors/ergonomics – Introduction to human factors. Retrieved February 28, 2018, from http://www.hse.gov.uk/humanfactors/introduction.htm

International Standard Organization. (2007). ISO 11228-2:2007. Ergonomics — Manual handling — Part 2: Pushing and pulling.

International Standard Organization. (2014). Ergonomics. Application document for International Stamdards on manual handling (ISO 11228-1, ISO 11228-2 and ISO 11228-3) and evaluation of static working postures (ISO 11226). Technical Report.

International Standard Organization. (2017). ISO 7250-1:2017 Basic human body measurements for technological design. Part 1: Body measurement definitions and landmarks. International Standard Organization (ISO).

Jung, M.-C., Haight, J. M., & Freivalds, A. (2005). Pushing and pulling carts and two-wheeled hand trucks. *International Journal of Industrial Ergonomics*, *35*, 79–89. https://doi.org/10.1016/j.ergon.2004.08.006

Karasek, R. A. (1979). Job Demands, Job Decision Latitude, and Mental Strain: Implications for Job Redesign. *Administrative Science Quarterly*. https://doi.org/10.2307/2392498

Kelsey, J. L. (1975). An epidemiological study of the relationship between occupations and acute herniated lumbar intervertebral discs. *Int J Epidemiol*, *4*(3), 197–205. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=1184269

Laursen, B., & Schibye, B. (2002). The effect of different surfaces on biomechanical loading of shoulder and lumbar spine during pushing and pulling of two-wheeled containers. *Applied Ergonomics*, *33*, 167–174. Retrieved from https://ac.els-cdn.com/S0003687001000540/1-s2.0-S0003687001000540-main.pdf?_tid=bbcdce80-d42d-11e7-b116-00000aacb35e&acdnat=1511868035_aa63b11da8deddf5f82b0b82a4f8f4e6

Lee, J., Nussbaum, M. A., & Kyung, G. (2014). Effects of work experience on work methods during dynamic pushing and pulling. *International Journal of Industrial Ergonomics*, *44*(5), 647–653. https://doi.org/10.1016/J.ERGON.2014.07.007

Lee, K. S., Chaffin, D. B., & Parks, C. (1992). A study of slip potential during cart pushing and pulling. *IIE Transactions*, *24*(5), 139–146. https://doi.org/10.1080/07408179208964254

Marras, W. S., Knapik, G. G., & Ferguson, S. (2009). Loading along the lumbar spine as influence by speed, control, load magnitude, and handle height during pushing. *Clinical Biomechanics*, *24*(2), 155–163. https://doi.org/10.1016/J.CLINBIOMECH.2008.10.007

Mattos, D. L. de, Ariente Neto, R., Merino, E. A. D., & Forcellini, F. A. (2019). Simulating the influence of physical overload on assembly line performance: A case study in an automotive electrical component plant. *Applied Ergonomics*. https://doi.org/10.1016/j.apergo.2018.08.001

Meldrum, D., Cahalane, E., Conroy, R., Fitzgerald, D., & Hardiman, O. (2007). Maximum voluntary isometric contraction: Reference values and clinical application. *Amyotrophic Lateral Sclerosis*. https://doi.org/10.1080/17482960601012491

Michie, S. (2002). Causes and management of stress at work. *Occupational and Environmental Medicine*, *59*(1), 67–72. https://doi.org/10.1136/OEM.59.1.67

National Research Council. (2001). *Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities*. *Musculoskeletal Disorders and the Workplace*. https://doi.org/10.17226/10032

Nüesch, C., Overberg, J. A., Schwameder, H., Pagenstert, G., & Mündermann, A. (2018). Repeatability of spatiotemporal, plantar pressure and force parameters during treadmill walking and running. *Gait and Posture*. https://doi.org/10.1016/j.gaitpost.2018.03.017

Plouvier, S., Renahy, E., Chastang, J. F., Bonenfant, S., & Leclerc, A. (2008). Biomechanical strains and low back disorders: Quantifying the effects of the number of years of exposure on various types of pain. *Occupational and Environmental Medicine*, *65*(4), 268–274. https://doi.org/10.1136/oem.2007.036095

Resnick, M. L., & Chaffin, D. B. (1995). An ergonomic evaluation of handle height and load in maximal and submaximal cart pushing. *Applied Ergonomics*, *26*(3), 173–178. https://doi.org/10.1016/0003-6870(95)00014-4

Rocha, R., Mollo, V., & Daniellou, F. (2015). Work debate spaces: A tool for developing a participatory safety management. *Applied Ergonomics*. https://doi.org/10.1016/j.apergo.2014.07.012

Seo, N. J., Armstrong, T. J., & Young, J. G. (2010). Effects of handle orientation, gloves, handle friction and elbow posture on maximum horizontal pull and push forces. *Ergonomics*, *53*(1), 92–101. https://doi.org/10.1080/00140130903389035

Shih, Y., Chen, Y. C., Lee, Y. S., Chan, M. S., & Shiang, T. Y. (2016). Walking beyond preferred transition speed increases muscle activations with a shift from inverted pendulum to spring mass model in lower extremity. *Gait and Posture*. https://doi.org/10.1016/j.gaitpost.2016.01.003

Snook, S. H. (1971). The Effects of Age and Physique on Continuous-Work Capacity. *Human Factors: The Journal of Human Factors and Ergonomics Society*, *13*(5), 467–479. https://doi.org/10.1177/001872087101300509

Snook, S H. (1978). The ergonomics society. The society's lecture 1978. The design of manual handling tasks. *Ergonomics*, *21*(12), 963. https://doi.org/10.1080/00140137808931804

Snook, Stover H., & Ciriello, V. M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics*, *34*(9), 1197–1213. https://doi.org/10.1080/00140139108964855

Appendix A. The questionnaire

Date:

__/__/____

Subject ID:

____ / 96

Personal data:

Name:
Surname:
Gender: [M] [F]
Age:
Height:
  Total body [cm]:
  Elbow from the ground [cm]:

Weight [kg]:
Previous experience with pushing tasks: [Y] [N]
Physical activity: [Y] [N]

Appendix B. The protocol

MVIC test (Maximum Voluntary Isometric Contraction)

The subject keeps the elbow at 90° (elbow flexion) and pushes the gauge for 2 s.

MVIC [N]	1	2	3	4	5

MVIC result [N]: _______ (mean value of 5 trials)

Speed – force test

Before each trial, reset the gauge and position the trolley at the marker on the floor.
Force measurements are automatically recorded on the gauge.

	Low speed	*Medium speed*	*High speed*
Condition 1	**24 kg**		
Trials 1-2-3	Travel time [s]	Travel time [s]	Travel time [s]
1-24			
2-24			
3-24			
Condition 2	**48 kg**		
Trials 1-2-3	Travel time [s]	Travel time [s]	Travel time [s]
1-48			
2-48			
3-48			
Condition 3	**72 kg**		
Trials 1-2-3	Travel time [s]	Travel time [s]	Travel time [s]
1-72			
2-72			
3-72			