Effects of Different Surfaces on Biomechanical Loading of the Upper Extremities While Handling Wheelbarrows

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ABSTRACT

This study examines the effects of ground surfaces, gross weight loaded, and wheelbarrows on muscular activities, hand force, and subject-perceived exertions while pushing a construction trolley in a straight line on a horizontal surface. Twelve subjects pushed the trolleys on three different surfaces: asphalt pavement, paving gravel, and grass. Gross weight when loaded was 45, 75, and 105 kg, and two construction trolleys (a one-wheeled barrow and two-wheeled barrow) were used in this experiment. Experimental results show that gross weight loaded significantly affected muscular activities, hand force, and subject-perceived exertion while pushing construction trolleys. Additionally, different ground surfaces and wheelbarrow type also affected the muscular activities of the dominant hand; grass generated the highest muscle load and asphalt pavement generated the smallest muscle load. Muscular activity increased significantly in dominant hand with the one-wheeled barrow when compared with the two-wheeled barrow, suggesting that, in terms of muscle loads, the two-wheeled barrow is better than the one-wheeled barrow.

Keywords: Pushing task, construction trolleys, muscular activity

INTRODUCTION

Manual materials handling is common on construction sites, often involving lifting, carrying, and pulling or pushing heavy objects. Although lifting a load is generally considered hazardous and has been studied extensively, few data exist regarding the biomechanical load while pushing and pulling objects (Hoozemans *et al*., 2001; Laursen and Schibye, 2002; Herring and Hallbeck, 2007). Frequent pushing and pulling has been observed as construction workers performed manual materials handling tasks (Hoozemans *et al*., 2001). To minimize the load on the body during manual materials handling, construction trolleys have gradually replaced buckets, boxes, and other containers that were previously carried. Conventional construction trolleys are one-wheeled or two-wheeled barrows used to deliver masonry materials, such as cement, mortar, brick, and sand, to construct external and internal walls. On the other hand, working in the construction industry typically requires awkward postures, heavy lifting, and considerable exertion. Many workers performing such tasks complain of discomfort in their upper extremities and lower back over the course of a workday (Buchholz *et al*., 1996; Jeong, 1998; Hoozemans *et al*., 2001; Davis *et al*., 2010). Meerding *et al*. (2005) reported that 59% of construction workers had musculoskeletal complaints, and 41%

experienced low back pain in the preceding 6 months. Goldsheyder *et al*. (2002) identified a high prevalence of 82% for musculoskeletal disorders among stone masons. Construction trolleys are pushed and pulled on such surfaces as asphalt, flagstone, paving stone, gravel, grass, and occasionally soil. These surfaces have different resistances for cart movement. Significant differences in rolling resistance have been identified for trolleys pushed manually; soft surfaces have highest resistance (Al-Eisawi *et al*., 1999). Such differences in rolling resistance may result in different magnitudes and directions of pushing or pulling force, and differences in working posture. Operating a construction trolleys should be considered in terms of problems associated with manual materials handling and, in particular, pushing and pulling activities. To minimize operator discomfort and possible injury, one must evaluate construction trolleys operation from an ergonomic perspective. Besides, measuring hand exertion is a common approach when quantifying risk of upper-extremity work-related musculoskeletal disorders (Silverstein *et al*., 1987; Moore and Garg, 1994). Electromyography (EMG) has been applied to assess muscular exertion when specific muscle groups are activated. Load cells and force sensors mounted on handles can capture force signals, and have been adopted to measure muscular effort, especially that during pushing and pulling tasks. Furthermore, subjective ratings are also used to measure hand exertion indirectly. This approach is both cost-effective and easily administered, especially for large population studies (Hjelm *et al*., 1995; King and Finet, 2004; Bao and Silverstein, 2005; Bao *et al*., 2009). The primary objective of this study is to determine the task demands and loads on the shoulder and upper extremities under different task and ground surface combinations, and to associate these demands with the strength of subjects. This study will provide evidence that supports ergonomic recommendations to promote workplace health by alleviating pain or fatigue of the shoulder and upper extremities while pushing trolleys.

2. MATERIALS AND METHODS

2.1 Subjects

Twelve college students, 6 males and 6 females, were recruited and paid for their participation. Subject age range was 20–23 (mean, 21.9). Average height was 169.3±5.6 cm and average weight was 66.8±7.9 kg. All subjects were in good health and had no history of musculoskeletal and cardiovascular problems. All were right-handed and no subject had experience using construction trolleys. Before participation, subjects were informed of study objectives, and all chose to participate voluntarily.

2.2 Apparatus

Two construction trolleys, a one-wheeled barrow and a two-wheeled barrow, were used in this experiment (Fig. 1). The empty weight of the one-wheeled and two-wheeled barrows was 14 kg and 15 kg with the force-measuring equipment, respectively. The wheelbarrows were made of slightly profiled hard rubber with a diameter of 25 cm and width of 8 cm. Handle height was 67cm in the vertical position. The wheelbarrow was filled with 45kg, 75kg, and 105kg, and was pushed by subjects using both hands. A field study found that wheelbarrows are most commonly used for transporting bricks, sand, concrete, and other construction materials on construction sites. A surface EMG (sEMG) system was used to measure muscle activity via surface electrodes (Liu *et al*., 2006). Four sEMG sensors were positioned based on the specific muscle location recommendations of Cram *et al.* (1998). These bipolar surface electrodes were attached bilaterally over the right and left biceps and trapezius muscle groups of subjects to record muscular activities. The sampling rating was 1000Hz per channel and data were analyzed using Viewlog software (Liu *et al*., 2006). The subject's skin was abraded or shaved and cleaned with an alcohol pad when necessary. A ground electrode was placed over the lateral epicondyle. A series of calibrations were then performed to obtain individual baselines for maximal voluntary contraction (MVC) of each muscle group. The recorded sEMG data were subsequently utilized to normalize sEMG signals recorded during task performance by expressing these signals as a percentage of MVC (%MVC). All maximum contractions were performed three times, and the highest 1-s mean force was utilized. Hand force applied to the wheelbarrow during trials was measured using a three-dimensional force transducer load cell (Model MTA 400; FUTEK), making it possible to record both force magnitude and direction. Via tension and compression, the force transducer load cell measures the amount of force exerted during each pushing trial. The force transducer load cell, which had a sampling rate of 100 samples/sec, was mounted on the cart handle.

(a) (b)

Figure 1 Illustration of the trolley in this study, (a) one-wheeled barrow; (b) two-wheeled barrow.

2.3 Experimental design

The experiment had a three-factor design with repeated measures analysis of variance (ANOVA). Ground surfaces (three levels), construction trolley type (two levels), and gross weight loaded (three levels) were fixed factors. Subjects were the random factor. Three different ground surfaces were used: asphalt pavement (smooth surface); paving gravel (hard, bumpy surface); and, grass (soft surface). All surfaces were horizontal. The push trials were performed over a distance of approximately 60 m (*i.e.*, subjects pulled a cart backward for 30 m and pushed it forward for 30 m). Two wheelbarrows were tested, a one-wheeled barrow, and a two-wheeled barrow. The wheelbarrows were made of hard rubber and had a diameter of 25 cm. Gross weight loaded was 45, 75, and 105 kg. The experiments were performed on the three surfaces outside, and only push forces were measured. During the experiment, each subject performed 18 trials (three different ground surfaces with all three weight loads in the two construction wheelbarrows). Task order was randomized across subjects. To present experimental data clearly, Table 1 lists the 18 experimental tasks in a fixed order. Dependent variables were average hand force (kg) measured by the three-dimensional force transducer load cell, muscle activity (%MVC) measured from the sEMG for each of the four muscle groups, and subject-perceived exertion to quantify perceived muscular exertion for body segments. Subjective ratings of perceived exertion responses were on a six-point Likert scale, ranging from 0 for “very easy” to 5 for “extremely hard.”

Table 1 Eighteen experimental tasks used in this study

Experimental tasks	**Ground surface**	**Trolley type**	**Weight load (kg)**
Task 1	Grass	One-wheel	45
Task 2	Grass	Two-wheel	45
Task 3	Grass	One-wheel	75
Task 4	Grass	Two-wheel	75
Task 5	Grass	One-wheel	105
Task 6	Grass	Two-wheel	105
Task 7	Gravel	One-wheel	45
Task 8	Gravel	Two-wheel	45
Task 9	Gravel	One-wheel	75
Task 10	Gravel	Two-wheel	75
Task 11	Gravel	One-wheel	105
Task 12	Gravel	Two-wheel	105
Task 13	Asphalt	One-wheel	45
Task 14	Asphalt	Two-wheel	45
Task 15	Asphalt	One-wheel	75
Task 16	Asphalt	Two-wheel	75
Task 17	Asphalt	One-wheel	105
Task 18	Asphalt	Two-wheel	105

2.4 Experimental procedure

Prior to the experimental sessions, all subjects were informed of the study's purpose, procedures, and physical risks and informed consent forms were voluntarily signed. Experimentally significant anthropometric data were obtained, including body height, weight, and elbow height. After anthropometric measurements were taken, the sEMG sensors were attached using double-sided tape collars. The sensors were then zeroed while a subject was in a relaxed standing position. Resting and set muscular activity measures were then recorded, such that sEMG data could be normalized during analysis. The EMG electrodes were placed on the forearm and upper back while a subject was in a pushing posture. As mentioned, each subject participated in 18 experimental sessions. The experimental task was to push a construction wheelbarrow in a realistic work situation. Subjects adopted a natural and comfortable stance to perform pushing tasks and were allowed to work at their own pace. Each session lasted approximately 10 min, and each subject performed no more than three trials on the same day. All hand push forces were measured with wheelbarrows with hard rubber wheels 25 cm in diameter on smooth asphalt, hard gravel and grass. Subjects were given a 5-min break at minimum between trials to minimize muscle fatigue. This break was measured using a stopwatch. After each pushing trial was completed, subjects then filled out a subjective rating of perceived exertion questionnaire. No subject practiced before the experiment. The order in which each subject performed each of the 18 trials was randomized.

2.5 Data analysis

All analyses used SPSS v 11.5.0 (SPSS, Inc., 2002). First, descriptive statistical analysis was conducted for all variables. Next, repeated-measures ANOVA was applied to each dependent variable to test whether it significantly affected any measure. *Post hoc* multiple-range tests were conducted to compare variable values when a factor was statistically significant at the $\alpha=0.05$ level.

3. RESULTS

Table 2 presents means of %MVC under all treatment conditions. Exertion force (%MVC) of the right trapezius (44.3 % MVC) and left trapezius (38.4 % MVC) was significantly higher than that of the right bicep (10.8% MVC) and left bicep (13.4% MVC). Average hand force was 7.6 kg. Each subject rated perceived exertion of five body segments at the end of each trial. Table 3 presents perceived exertion ratings under the 18 conditions on a scale of 0–5, with 5 indicating "extremely hard." Subject-perceived exertion of all five body parts increased over time from 1.00 to 4.38. The trapezius muscle (2.88) had the greatest average subject-perceived exertion after the test period, while the back (2.35) and waist (2.35) had the lowest subject-perceived exertion. To identify factors impacting hand force and muscle loads, muscle activation levels of the four muscles were subjected to a three-factor design with repeated measures ANOVA (Table 4). The ANOVA results of sEMG measurements demonstrate that the main effects of the ground surface, weight load, and trolley type on the right trapezius and right biceps were significant ($p<0.05$). Ground surface had a significant effect on left trapezius exertion ($F_{2,198} = 3.66$, $p=0.027$). Weight load had a significant effect on muscle activities of the left trapezius ($F_{2,198} = 37.88$, $p<0.01$) and left bicep ($F_{2,198} = 20.98$, $p<0.01$), and hand force ($F_{2,198} = 22.07$, $p<0.01$). The interactive effect between ground surface and weight load significantly influenced muscle activities of the right trapezius ($F_{4,198} = 4.54$, $p<0.01$), left trapezius ($F_{4,198} = 7.22$, $p<0.01$), right bicep ($F_{4,198} = 10.03$, $p<0.01$), and left bicep ($F_{4,198} = 8.94$, $p<0.01$), but not hand force. The interactive effect between the ground surface and trolley type significantly impacted the left trapezius ($F_{2,198} = 3.17$, $p<0.05$), while no interactive effects existed between weight load and trolley type.

Furthermore, variations in subject-perceived exertion were analyzed by ANOVA with ground surface, weight load, and trolley type as independent factors (Table 4). The effects of ground surface on subject-perceived bicep exertion ($F_{2,198} = 7.15$, $p<0.01$) and neck exertion ($F_{2,198} = 3.42$, $p<0.05$) were significant, and weight load significantly affected subject-perceived trapezius, bicep, neck, back, and waist exertion, and interactions between ground surface and trolley type significantly affected the change in subject-perceived trapezius, bicep, neck, back and waist exertion. Multiple-range tests using LSD show that the mean subject-perceived exertion of the biceps and back muscle groups for a weight load of 105 kg was significantly greater than that under cart loads of 75 kg and 45 kg. The increase in mean subject-perceived exertion was significant in the biceps and neck muscle groups on grass, but was not significantly different between the paving gravel or asphalt pavement.

Table 2 Mean of Relative EMG signal activity (%MVC) and hand force exerted (kg) in experimental tasks.

Experimental tasks	Right trapezius	Left trapezius	Right biceps	Left biceps	Hand force
Task 1	38	36	9	11	5.7
Task 2	44	36	11	14	6.5
Task 3	50	39	16	19	8.1
Task 4	52	38	12	16	8.2
Task 5	54	48	21	20	9.2
Task 6	54	40	25	29	9.1
Task 7	42	36	7	7	5.8
Task 8	38	32	7	11	6.3
Task 9	51	41	11	14	7.2
Task 10	45	35	8	11	7.7
Task 11	48	48	14	17	8.5
Task 12	51	40	8	10	8.0
Task 13	38	36	9	11	5.7
Task 14	28	31	5	8	6.1
Task 15	39	37	5	9	8.4
Task 16	37	35	5	8	8.2
Task 17	49	53	12	14	9.1
Task 18	39	31	10	13	8.6
Average	44.3	38.4	10.8	13.4	7.6

Table 3 Mean and standard deviations of subjective rating of perceived exertion responses in experimental tasks.

Experimental tasks	Trapezius	Biceps	Neck	Back	Waist
Task 1	2.13(1.13)	2.38(1.19)	2.25(0.71)	1.25(1.04)	1.63(0.92)
Task 2	2.88(1.36)	3.00(1.07)	3.25(0.89)	2.38(1.30)	2.38(1.51)
Task 3	2.88(1.25)	2.88(1.55)	2.75(1.49)	2.13(1.46)	1.88(1.36)
Task 4	3.75(0.89)	4.13(0.83)	3.25(1.49)	3.00(1.31)	3.25(1.49)
Task 5	3.25(1.39)	3.25(1.49)	3.00(1.31)	3.00(1.60)	2.88(1.36)
Task 6	4.25(1.04)	4.38(0.92)	3.75(1.75)	4.13(1.73)	4.00(1.69)
Task 7	2.50(0.93)	2.25(0.71)	2.38(1.06)	1.75(1.16)	2.00(1.31)
Task 8	1.63(1.06)	1.88(1.36)	1.63(1.30)	1.25(0.89)	0.88(0.83)
Task 9	3.25(1.28)	3.25(0.89)	3.00(0.93)	2.50(1.20)	2.88(1.55)
Task 10	2.50(0.76)	1.75(1.16)	2.00(1.20)	1.75(1.16)	1.88(0.99)
Task 11	3.50(1.07)	4.00(1.07)	3.38(0.92)	2.63(1.30)	2.50(1.31)
Task 12	3.25(0.71)	2.38(1.31)	2.13(0.99)	2.75(0.71)	2.63(1.41)
Task 13	2.38(1.30)	2.13(0.83)	2.50(1.41)	2.38(0.92)	2.25(1.16)
Task 14	1.63(1.06)	1.63(0.92)	1.63(1.06)	1.00(1.07)	1.00(0.93)
Task 15	3.25(0.71)	2.88(1.55)	3.00(1.19)	3.13(0.83)	3.00(0.76)
Task 16	2.63(1.19)	2.25(1.16)	2.25(1.04)	1.38(1.30)	1.63(1.30)

Task 17	3.50(1.51)	3.75(1.28)	3.50(1.77)	3.38(1.30)	3.25(1.67)
Task 18	2.75(0.89)	2.50(1.31)	2.63(0.52)	2.50(1.41)	1.67(1.31)
Average	2.88(1.24)	2.81(1.37)	2.68(1.29)	2.35(1.42)	2.35(1.45)

Table 4 ANOVA of relative EMG, hand force and subjective ratings of perceived exertion.

Performance measures	Ground surface	Weight load	Trolley type	Ground surface x Weight	Ground surface x Trolley	Weight load x Trolley
EMG						
Right trapezius	8.66**	32.55**	4.81*	4.54**	1.33	1.55
Left trapezius	3.66*	37.88**	1.75	7.22**	3.17*	2.12
Right biceps	3.95*	31.99**	7.97**	10.03**	2.16	1.51
Left biceps	2.75	20.98**	3.66	8.94**	1.84	1.07
Hand force	1.25	22.07**	0.08	0.27	0.16	0.44
Subjective rating of perceived exertion						
Trapezius	2.81	15.52**	0.68	0.09	7.76**	0.21
Biceps	7.15**	11.95**	2.68	0.15	11.73**	0.55
Neck	3.42*	5.13**	3.19	0.13	7.61**	0.15
Back	2.39	15.41**	1.17	0.27	11.27**	0.88
Waist	2.27	11.13**	1.32	0.29	9.85**	0.82

*p<0.05, **p<0.01.

4. DISCUSSION

Although the hand and shoulder discomfort mechanisms remain unclear, forceful exertion, repetition, and static muscle load are significant risk factors for cumulative trauma disorders. Silverstein *et al*., (1987) identified a correlation between repetitive tasks using high hand force and risk of hand tendonitis. In a study by Fennigkoh *et al*. (1999), a job requiring high force was defined as that requiring with >30% MVC, whereas a job requiring low force was defined as that requiring <10% MVC. In this study, muscular activity (*i.e*., %MVC) increased over time from 5% MVC to 54% MVC during testing periods, ranging from an average of 10.8% MVC for the right bicep to44.3% MVC for the right trapezius (Table 2); thus, pushing a construction cart was categorized as low to high force. However, as the experiment task involved lifting plus holding a cart handle, and pushing a construction cart over a distance of approximately 60 m, this may have generated a highly static muscle load, resulting in fatigue, regardless of whether a subject's muscular activity was <10% MVC. Furthermore, the muscular activity of trapezius was higher than that of the biceps muscle when pushing the cart (Table 2). Increased trapezius activity while pushing is in agreement with psychophysical ratings (Table 3), indicating that subjects believed the shoulder was the body part stressed most while pushing. The consistent findings in objective and subjective response parameters suggest that a future study is required to describe accurately the work performed and ways of measuring these parameters while pushing a cart.

A significant finding for all response variables in this study is the strong relationship between the load pushed and cart weight (Table 4). This significant difference existed for all four muscular activities (%MVC), hand force, and subject-perceived trapezius, bicep, neck, back, and waist exertion. Furthermore, variations in the ground surface as well as cart type caused differences in hand force magnitudes, muscular loads, and subject-perceived exertion of the biceps and neck. Thus, the largest loads were in the initial phase while pushing the heaviest cart on grass. This is agreement with findings obtained by Laursen and Schibye (2002), who demonstrated that the largest force existed in the initial phase while pushing the heaviest containers on grass. Muscular activity increased in the dominant hand, right trapezius, and right bicep when the cart was a one-wheeled cart. This is likely because pushing a one-wheeled construction cart, as in this study, requires a subject to maintain cart balance, generating additional restrictions on the magnitude and direction of right-hand muscular activity on the cart as well as body posture. However, stability requirements did not generate a particular load on the hand or subject-perceived exertion for the trapezius, bicep, neck, back, and waist. This study did not measure the coefficients of rolling friction for hard rubber wheels on different surfaces. Thus, resistance between rolling wheels and the surfaces was not measured. Future study is necessary, as noted by Al-Eisawi *et al*. (1999), to establish a database of coefficients of rolling friction for various wheel materials, tires, and surfaces that exist in industry. However, as expected, a hard surface required less pushing force that a soft surface (Al-Eisawi *et al*., 1999). Among the three surfaces tested, cart pushing forces were lowest for asphalt pavement, followed by those for paving gravel, and grass. Laursen and Schibye (2002) also obtained a similar relationship between the forces needed to push vehicles on grass.

5. CONCLUSIONS

This demonstrates that weight load affects muscular activities, hand force, and subject-perceived exertion while pushing construction wheelbarrows. Additionally, different ground surfaces and trolley type also affected dominant-hand muscular activities—grass generated the highest muscle load and asphalt pavement the smallest. The highest muscle loads were in the initial phase while pushing a cart for males. These muscle loads may increase risk for musculoskeletal disorders. The significant increase in muscular activity in the dominant hand while pushing a one-wheeled barrow suggests that, in terms of muscle activities, the two-wheeled barrow is better than the one-wheeled barrow.

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