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Biomechanical assessment of alternative hand trucks for transporting heavy loads up and down stairs

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ABSTRACT

Hand trucks are frequently used in delivery and moving occupations to move a variety of materials including appliances and beverages. Frequently these transport tasks involve ascending or descending stairs. This research assessed the efficacy of three commercially available alternative hand truck designs that could be used to deliver appliances. Nine experienced participants moved a 52.3 kg washing machine up and down a flight of stairs using a conventional two-wheeled hand truck, a multi-wheeled hand truck, and a two-speed powered hand truck. Electromyographic (EMG) data showed reduced right erector spinae, bilateral trapezius, and bilateral biceps 90th and 50th percentile normalized responses while ascending and descending the stairs when using the powered hand truck. The multi-wheel hand truck did not reduce EMG levels relative to the conventional hand truck. Participants, however, did express a potential concern regarding the ascent time with powered hand truck at the slower speed.

1. Introduction

Hand trucks are commonly used when transporting items such as appliances or beverage products. Often these material handling situations may include transporting items either up or down ramps and stairs. The delivery personnel who perform these tasks likely fall in the US Bureau of Labor Statistics' occupational classification as "Light Truck Drivers". As a group their rate of sprains, strains, and tears (110 per 10,000 workers) and injury rate due to overexertion and bodily reaction (108 per 10,000 workers) are over 4 times higher than the overall rate of sprains, strains, and tear across all occupations (27.4 per 10,000 workers) and the overall rate of injuries due to overexertion and bodily reaction (26.2 per 10,000 workers) (Bureau of Labor Statistics, 2020a, 2020b). Given their exposure to manual material handling tasks and vibration exposure, low back pain was found by Okunribido et al. (2006) to be prevalent in their sample of short-haul delivery personnel, with 50 percent of their sample indicating they had experienced back pain within the last 12 months. Injuries incurred can be also due to environmental factors such as slippery surfaces, ramps, and stairs (Chandler et al., 2017; Reiman et al., 2018). Reiman et al. (2014), reported that their participating delivery drivers identified the use of the hand truck as an origin of physical discomfort. Thus, tools such as hand trucks (sometimes referred to as dollies), need to be further investigated as design variations may have the potential to mitigate biomechanical exposures during delivery tasks and therefore reduce the potential for fatigue and musculoskeletal injury.

While earlier research has shown the benefits of braking mechanisms when descending ramps with hand trucks (Keyserling et al., 1999), prior research on use of hand trucks on stairs is limited. A review of the literature by Jung et al. (2005) identified only one publication on the topic. Young et al. (1997) compared several commercially available 2-wheel manual hand trucks and one tri-wheel hand truck to determine if there were differences in the pulling force required to move a load up stairs. Weights tested were 30 and 60 kg. Though differences were seen in average force and average-peak force among the hand trucks tested, no design element was identified as consistently predictive of increasing or lowering both average force and average-peak forces, though the average-peak force was significantly lower for the tri-wheel. However, no biomechanical or usability data were collected in that study. An earlier relevant study by Jäger et al. (1984) reported on patterns of activity (using electromyography) of muscles in the back, shoulders, arms, and thighs in an investigation of loads imposed on workers pulling 2-wheeled dustbins over curbs and up a set of stairs. There do not appear to be any papers published that have compared powered hand trucks

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Fig. 1. The three hand truck designs used in the study included a "conventional" (a) used for appliance delivery, the multi-wheel design (b), and the powered stair ascending/descending hand truck (c).

with conventional 2-wheel manual, or the multi-wheel alternative designs with respect to the potential biomechanical benefits or usability challenges when taking loads up and down stairs. Thus, the goal of this study was to determine the extent to which different types of hand trucks may provide biomechanical benefits to potential users when ascending or descending stairs with a heavy load. Specifically, this study compared muscle activation levels when using a conventional two-wheeled hand truck to the muscular effort required when using a multi-wheel hand truck, and to the muscular effort required when using a two-speed powered hand truck that provided mechanized assistance when going up and down stairs. The hypothesis was that these alternative hand truck designs (the powered hand truck and the mulit-wheel hand truck) would reduce the muscular effort required, as quantified via surface electromyography.

2. Methods

2.1. Research design

This study used a repeated measures design with one independent variable, the hand truck design (Fig. 1). There were four hand truck design conditions: (1) the conventional 2-wheel hand truck, (2) the multi-wheel hand truck, (3) the powered hand truck ascending at a slower speed (29 steps per minute), and (4) the powered hand truck ascending at the faster speed (48 steps per minute). Separate analyses were performed for the stair ascent and the stair descent tasks given that some delivery operations may perform more of one type than the other while the hand truck is loaded. It should be noted that the descent speed for the powered hand truck did not change with the speed selection (this only affect the ascent speed). Therefore, there were only 3 hand truck conditions studied during the descent (conventional, multi-wheel, and powered). The dependent measures were the electromyographic responses from the arm, trunk, and leg muscles, and the participants' usability ratings.

2.2. Participants

Nine males with professional delivery experience, including beverage and appliance delivery, were recruited to participate in this study. Participants ranged in age from 25 to 54 (mean = 43 years) and had between 10 and 26 years of moving experience (mean = 19 years). Mean height and weight were 1.76 m (range 1.65–1.82 m) and 94 kg (range 77–102 kg), respectively.

2.3. Equipment

The three hand trucks used in the study are shown in Fig. 1. The conventional appliance hand truck had a length of 1.52 m and weighed 16.8 kg. The multi-wheel hand truck (Mitchell Industrial Dolly Innovations-M3) had a length of 1.55 m and weighed 29.9 kg. The powered hand truck (Magliner – Model 110FNG4) had a length of 1.52 m and weighed 19.3 kg (with the battery). The washing machine used as load on the hand truck weighed 52 kg and had a height of 109 cm and a width of 68 cm. The washing machine was transported on each hand truck up and down a flight of 11 stairs where the step rise was 17.8 cm high and the tread depth was 29.2 cm.

Surface EMG data were obtained using a Delsys Trigno wireless EMG system that provided data at 2000 Hz to The Motion Monitor System (Innsport) used for data collection.

Fig. 2. The postures used for maximal isometric exertions for the latissimus dorsi (a), erector spinae (b), trapezius (c), biceps (d), and quadriceps (e). Arrows show the applied force direction.

2.4. Procedures

After participants reviewed and signed the Institutional Review Board (IRB) approved consent form, they were instrumented with Delsys Trigno wireless electrodes, which were placed bilaterally over the latissimus dorsi, erector spinae, trapezius, biceps, and quadriceps muscles. These muscles were selected based upon their likely involvement in either or both the stair ascent and descent tasks. Latissimus dorsi electrodes were placed on the thorax (approximately T9 level) over the belly of the muscle and oriented along a line between the axilla and the sacrum. The erector spinae electrodes were place at the L3 level approximately 3–4 cm lateral to the spinous process. The trapezius electrodes were placed 2 cm lateral to the midpoint of the acromion-C7 line (Jensen et al., 1993). The biceps electrodes were placed over the belly of the muscle when the elbow was flexed 90°. The quadriceps electrodes were placed half way along a line from anterior spina iliaca superior (ASIS) to the superior part of patella.

Participants then performed a series of isometric maximum voluntary contractions (MVCs) in postures approximating those that would be adopted while moving the hand trucks on the stairs (Fig. 2). A “resting” sample was also obtained in an upright standing posture. The data from these MVCs were used along with data from the resting trial in normalizing the EMG data collected when performing the stair ascent and descent tasks.

The participants then performed stair descent and stair ascent tasks. The sequence of hand truck conditions was randomized for each individual. For the powered hand truck, the slower speed was always used first to give the participants without powered hand truck experience more time to become familiar with the how this hand truck operated before exposure to the fast ascent speed condition. Within each hand truck condition, the participants were shown the hand truck they would be using, provided with instruction how to use it if they were unfamiliar with it, and given an opportunity to do a practice descent followed by a practice ascent. The practice period was followed by a series of three data collection trials that began with the descent of the flight of stairs. At the bottom of the stairs, the participants were given a 1 min rest period, which was then followed by a data collection trial as the participant ascended the stairs. This descent and ascent of the stairs with the hand truck and appliance was repeated two more times so that there were three replications for each hand truck condition. The EMG data collection was initiated prior to the movement and continued through the completion of each ascent or descent task.

After the data collection on the stairs was completed, the participant was asked to complete a questionnaire regarding their experience with each hand truck. Specifically, the questionnaire asked participants to rate their level of agreement with statements about the pace at which they could work both up and down the stairs with each hand truck, the ease of handling, the ease of learning to use each hand truck they were not previously familiar with, and relative to the conventional hand truck would each alternative truck make their work easier and leave them less fatigued at the end of the shift. Each item was evaluated using a 6 point Likert scale ranging from “disagree strongly” to “agree strongly”.

Table 1
Effect sizes (Eta Squared) calculated for both the 90th and 50th percentile analyses for the stair ascent and descent tasks.

Muscle	90th Percentile		50th Percentile	
	Stair Ascent	Stair Decent	Stair Ascent	Stair Decent
	Effect Size	Effect Size	Effect Size	Effect Size
LATL	0.31	0.39	0.36	0.49
LATR	0.47	0.62	0.60	0.57
ERSL	0.50	0.52	0.34	0.30
ERSR	0.62	0.30	0.53	0.61
BICL	0.54	0.52	0.48	0.53
BICR	0.61	0.85	0.56	0.78
TRPL	0.79	0.67	0.59	0.45
TRPR	0.64	0.39	0.49	0.33

2.5. Data analysis

The EMG data were normalized relative to the maximum and resting values obtained for each muscle using the equation below.

$$\text{Normalized EMG}(i,t) = \frac{\text{EMG value}(i,t) - \text{Resting EMG}(i)}{\text{Max EMG value}(i) - \text{Resting EMG}(i)} \tag{Eq. 1}$$

i = muscle 1–10; t = sample frame (time point).

The data from the right quadriceps muscle were removed from the analysis due to many artifacts in the signal, which occurred in many of the participants, likely caused by the hand, arm, or hand truck coming in contact with the electrode. While this task is relatively symmetric for the upper body, the same cannot be said for the lower body as one leg needs to lead the stair ascent or descent tasks. Typically, this was the right leg. This would often bring the hand truck in contact with the right leg and electrode, especially when descending the stairs. When this would occur, it could result in movement artifact or a minor displacement of the electrode that was often not detected and resulted in artifacts in subsequent samples.

The data from the stairs, as opposed to the initial or ending parts while on the landings, were extracted using the left quadriceps as an indicator given that this muscle showed spikes with each step while ascending and descending the stairs. Within this window on the stairs, the 90th and 50th percentile activity levels were obtained for each muscle. These 90th and 50th percentile values were then averaged across the three replications of each hand truck condition, with the exception of stair descent conditions using the powered hand truck. Given that the powered hand truck descended at the same speed under the slow and fast conditions, all 6 stair descents with powered hand truck were averaged together for each participant.

The data were analyzed with an ANOVA model, blocked on subjects, using the Proc GLM within the SAS software. An underlying assumption of the ANOVA model is that the data are normally distributed. This

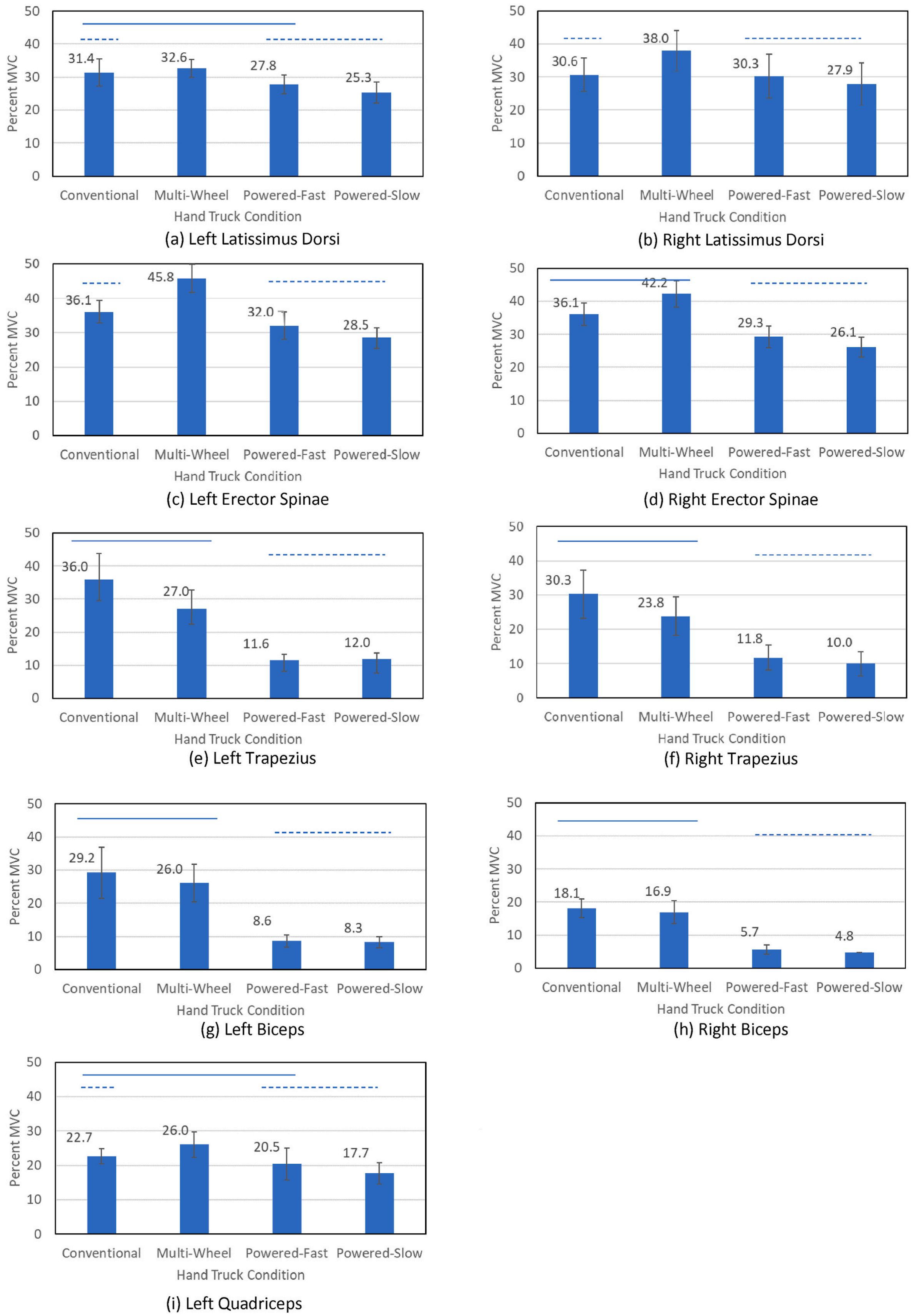

Fig. 3. Mean 90[th] percentile normalized EMG values results obtained during the stair ascent tasks. Bars connected by the same style of horizontal line are not significantly different ($p > .05$) in post-hoc tests.

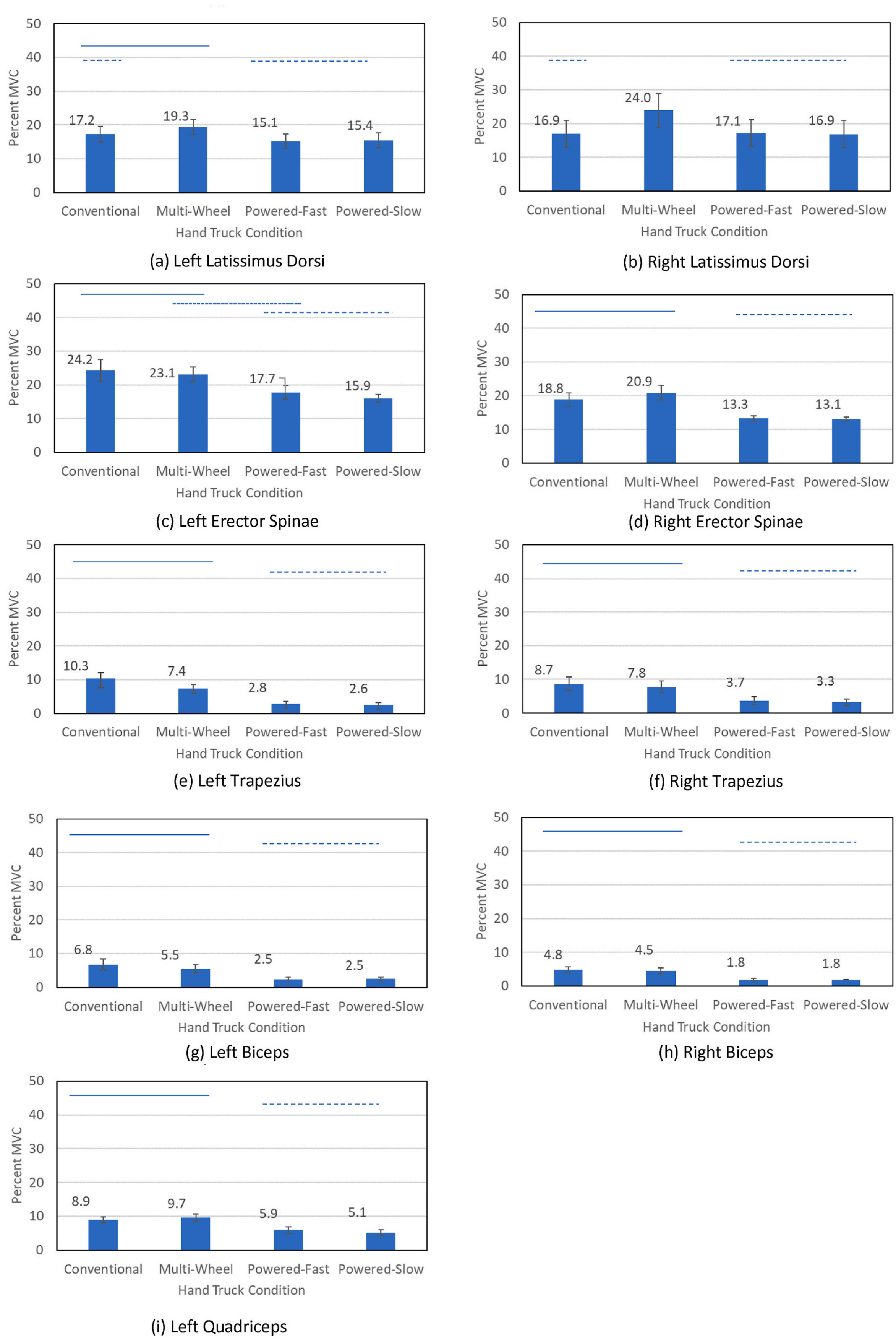

Fig. 4. Mean 50th percentile normalized EMG values obtained during the stair ascent tasks. Bars connected by the same style of horizontal line are not significantly different ($p > .05$) in post-hoc tests.

Table 2
ANOVA p-values for the stair ascent and descent tasks for the 90th percentile normalized EMG values.

Dependent Measure	Ascent	Decent
Left Latissimus Dorsi	0.028	0.020
Right Latissimus Dorsi	0.001	<0.001
Left Erector Spinae	<0.001	0.004
Right Erector Spinae	<0.001	0.058
Left Trapezius	<0.001	0.070
Right Trapezius	<0.001	0.007
Left Biceps	<0.001	0.003
Right Biceps	<0.001	<0.001
Left Quadriceps	0.067	0.001

Table 3
ANOVA p-values for the stair ascent and descent tasks for the 50th percentile normalized EMG values.

Dependent Measure	Ascent	Decent
Left Latissimus Dorsi	0.012	0.001
Right Latissimus Dorsi	<0.001	0.001
Left Erector Spinae	0.006	0.005
Right Erector Spinae	<0.001	<0.001
Left Trapezius	<0.001	0.008
Right Trapezius	0.001	0.123
Left Biceps	0.001	0.002
Right Biceps	<0.001	<0.001
Left Quadriceps	<0.001	0.001

assumption was verified using the Shapiro-Wilk test within the SAS Proc Univariate procedure. Significant ANOVA effects (alpha≤.05) were evaluated with post-hoc testing, using the REGWQ procedure within SAS that controls the experimental type I error rate, was used to assess pairwise comparisons between experimental conditions. For the ANOVA analysis, the overall effect sizes ranged from 0.30 to 0.85 (Table 1). The frequency of the Likert scale responses to the questionnaire were obtained and analyzed using Chi-Square analyses.

3. Results

3.1. Stair ascent

Figs. 3 and 4 show the mean 90th and 50th percentile normalized EMG values, averaged across subjects, while ascending the stairs. The ANOVA results for the 90th percentile values, except for the left latissimus dorsi and the left quadriceps, showed p-values of .001 or less (Table 2). The p-value for the left latissimus dorsi was 0.028 and the result for the left quadriceps was not significant across the hand truck conditions. For the 50th percentile values, all of the sampled muscles showed significant changes across hand truck conditions. Relative to the conventional hand truck, post-hoc tests showed that using the multi-wheel hand truck led to increased 90th percentile activation levels in the right latissimus dorsi and the left erector spinae muscles. A similar finding occurred for the 50th percentile right latissimus dorsi muscle. Relative to the conventional hand truck, the powered hand truck reduced the 90th and 50th percentile muscle activation level in the right erector spinae, bilaterally in the trapezius muscles, and bilaterally in the biceps muscles. The 50th percentile values were also reduced in the left quadriceps when using the powered hand truck. Relative to the slower speed setting on the powered hand truck, ascending the stairs at the faster speed led to no significant increases in the EMG activities in any of the sampled muscles.

3.2. Stair descent

Most of the 90th and 50th percentile muscle activity levels showed significant differences across the three hand truck conditions evaluated during the stair descent tasks (Table 3). The results of the post-hoc tests, shown in Fig. 5, for the 90th percentile values indicate that relative to the conventional hand truck, the powered hand truck reduced the muscle activity bilaterally in the biceps muscles and in the left quadriceps muscle. Similar trends were seen in the analysis of the 50th percentile values (Fig. 6), but with the additional effects found in the right erector spinae and the left trapezius muscles. The latissimus dorsi and erector spinae 90th percentile activation levels were not significantly different between the conventional and the powered hand truck conditions. However, the 50th percentile right erector spinae response was lower with the powered hand truck. Comparisons with the multi-wheel hand truck showed bilateral 90th percentile values for the latissimus dorsi and erector spinae response were higher with the multi-wheel hand truck during the stair descent tasks relative to the conventional and powered hand trucks. Similar results can be seen in the 50th percentile values for both latissimus dorsi muscles. The 90th percentile values from the right trapezius were also significantly lower when the powered hand truck was compared to multi-wheel hand truck.

3.3. Questionnaire analysis

Eight out of nine participants stated that the work they performed during the study was very similar to the work they typically encountered in a workday. The participants were asked to list the brand of hand truck they would typically use for work, and many used a Magliner hand truck, the same company that sells the powered hand truck used in this study. A Chi-square analysis showed borderline significance ($p = .056$) with regards to the question asking if the hand truck takes too long when descending the stairs. Six of the participants agreed to some extent with the statement for each of the powered hand truck conditions (Fig. 7a). A similar question about whether the hand truck takes too long when ascending the stairs showed a p-value of .01 in the Chi-Square analysis. This was primarily due to the powered hand truck when set for the slower ascent speed (Fig. 7b). Questions about the level of fatigue and ease of use relative to the conventional hand truck were not significantly different across the multi-wheel and the two powered hand truck conditions.

4. Discussion

Overall, the results suggest that using the tested powered hand truck when ascending stairs has the potential to significantly reduce the physical demands on selected muscles relative to the conventional hand truck. Similar responses were observed during the stair descent tasks, except for the bilateral 90th percentile bilateral response of the erector spinae and the 50th percentile response of the left erector spinae. And even for the muscles that did not show a significant change when using the powered hand truck, none of the mean responses were greater than those observed with the conventional hand truck. The same cannot be said about the multi-wheel hand truck. Relative to the conventional hand truck, there were significant increases in the 90th percentile activity levels in the right latissimus dorsi and left erector spinae muscles during the ascent tasks and bilaterally in latissimus dorsi and left erector spinae muscles during the descent tasks with the multi-wheel hand truck.

Young et al. (1997) determined the forces required to pull a hand truck up the stairs using an instrumented handle. These investigators found that the diameter of the wheels significantly affected the forces experienced by the user. The multi-wheel hand truck, by its design, essentially further increases wheel diameter, if one considers the 5 wheels rotating about a common axis as essentially one large wheel. In this case, smooth transition from one step to the next may have required more consistent muscle force to control the hand truck's more linear motion on the stairs.

Use of the powered hand truck significantly reduced select muscle activations in both the stair ascent and stair descent tasks relative to the

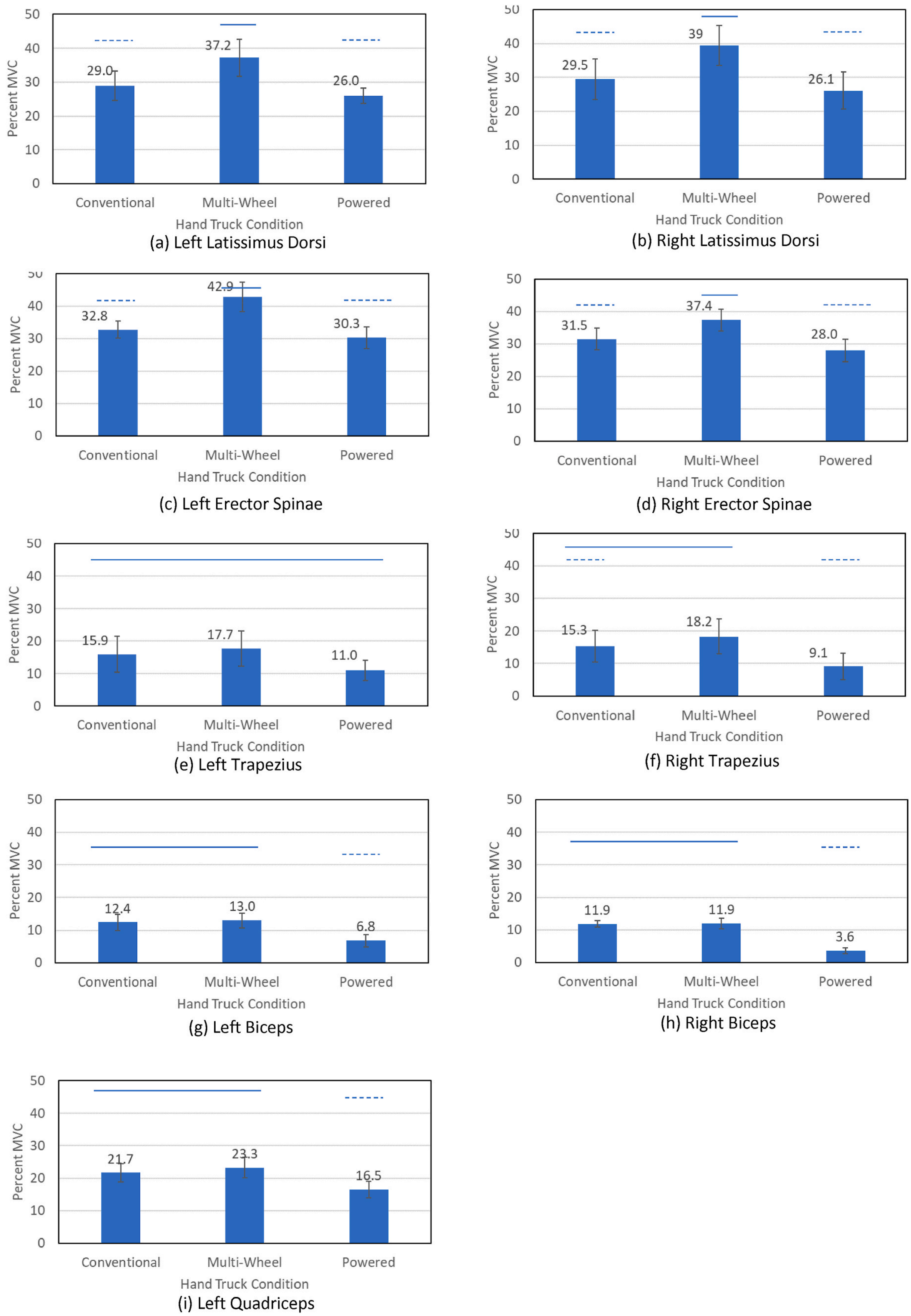

Fig. 5. Mean 90th percentile normalized EMG values obtained during the stair descent tasks. Bars connected by the same style of horizontal line are not significantly different ($p > .05$) in post-hoc tests.

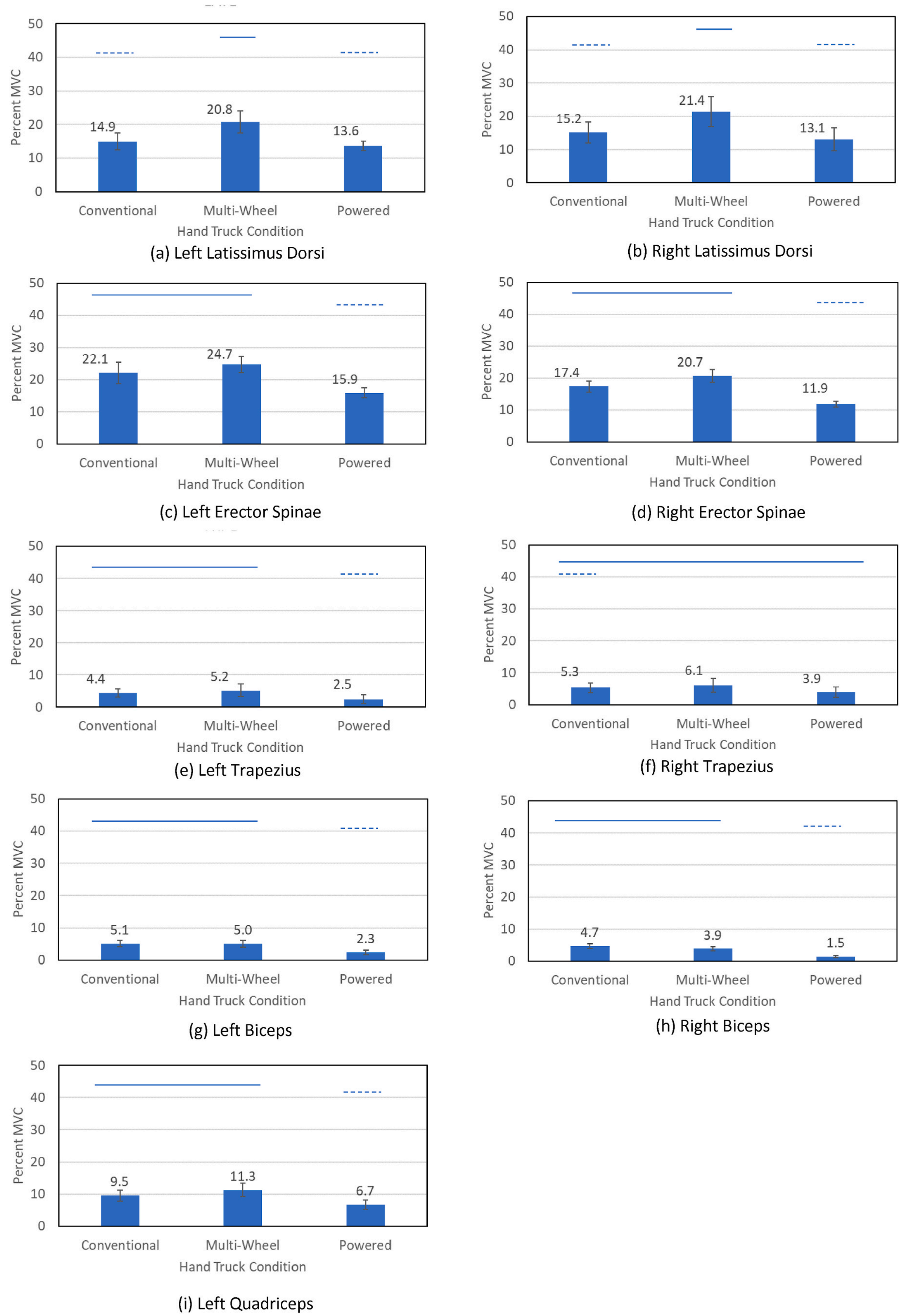

Fig. 6. Mean 50th percentile normalized EMG values obtained during the stair descent tasks. Bars connected by the same style of horizontal line are not significantly different (p > .05) in post-hoc tests.

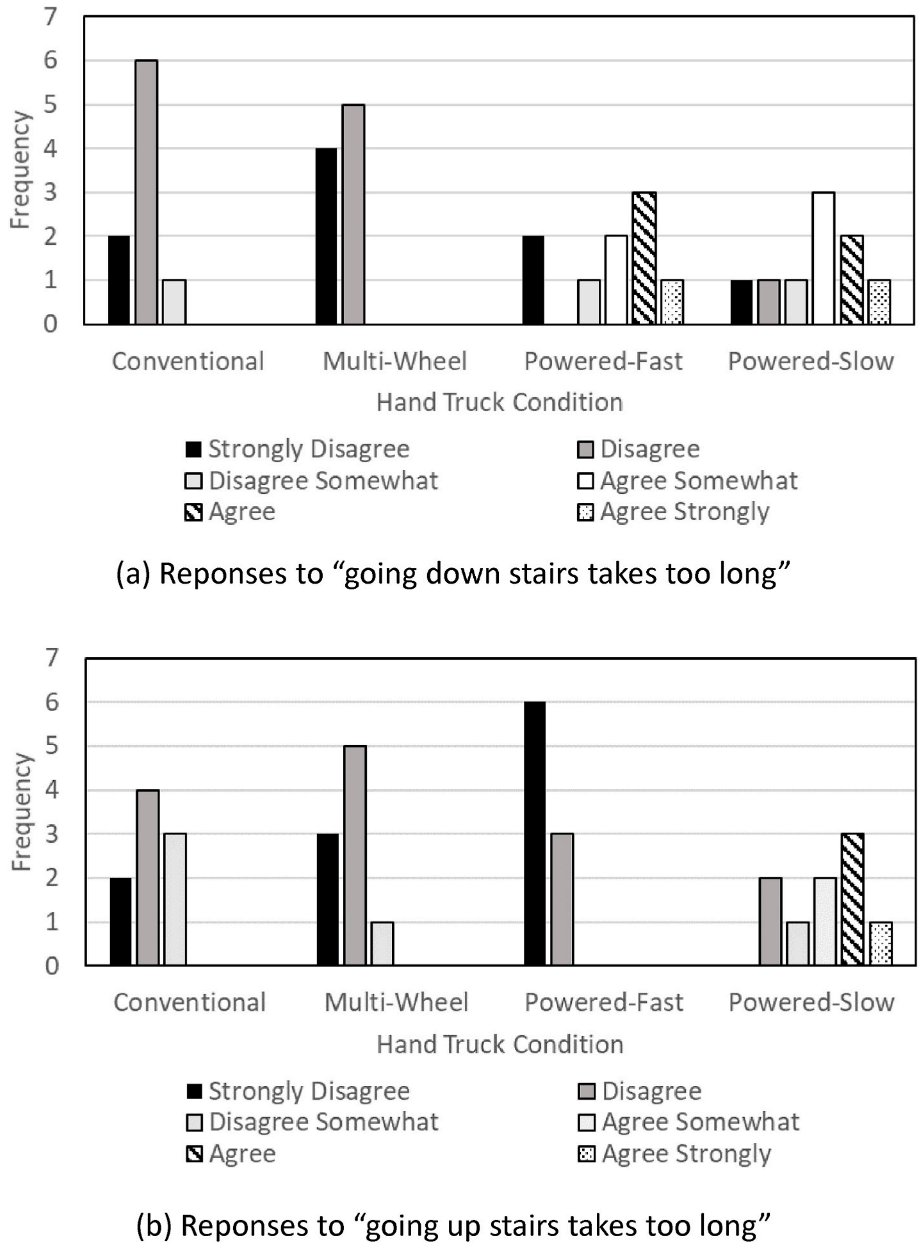

Fig. 7. Response distributions to follow-up survey questions about the perceived rate of descent (a) and ascent (b).

conventional hand truck. These changes were most pronounced in the trapezius and biceps muscles. Smaller changes were observed in the erector spinae muscles. Interestingly, there were no significant reductions in the latissimus dorsi, a muscle often recruited during pulling tasks. But the reductions in muscle activation levels that did occur suggest the powered hand trucks have the potential to decrease the overall level of fatigue experienced by delivery drivers. Second to not enough sleep, Hanowski et al.'s (1999) research participants reported that fatigue was driven by a hard or physical workday. Friswell and Williamson (2008), in their study of light and short haul drivers in Australia, found evidence that the physical workload experienced by the drivers can lead to fatigue, which in turn, can lead to driving-related incidents. Thus, the use of a powered hand truck may do more than just prevent musculoskeletal disorders.

Some participants expressed a sense that the weight shifted forwards when ascending the stairs using the powered hand truck. This is likely due to the mechanism used by the powered hand trucks for gripping the stair and pulling itself slightly out and then up to the level of the next stair. This mechanism would momentarily shift the supporting point of the system relative to its center of gravity, thus creating a momentary rotational force that needed to be controlled by the operator. While there are other mechanisms available for moving hand trucks up the stairs, we had not found one that had the ascent and descent speed of the magnitude tested in this study. As the qualitative data show, the speed at which the powered unit can climb stairs is a concern of professional operators. Hanowski et al. (1999) reported that the local and short haul drivers participating in their focus groups were very concerned about the time pressure they experienced. The comment “We are always working against the clock” by one of their participants emphasizes the need for powered hand trucks that can match the desired work pace of the delivery drivers. In short, powered hand trucks that are perceived to be too slow will likely not be adopted into daily work practices. Prior literature on adoption for ergonomic interventions has shown that the perceived ergonomics advantage is an important factor affecting adoption decisions (Weiler et al., 2013). This factor includes whether the device is easy to use, which could include reduced physical demands and the ability of the equipment to perform at the operator's desired pace.

4.1. Limitations

The participants in this study were experienced material handlers that have used hand trucks in their daily work activities, however, most worked in the delivery of beverages, rather than appliances. Nevertheless, they all indicated they frequently encountered stairs in their normal work activities. Most had limited experience with powered hand trucks and none had experience with the multi-wheel hand truck. It is possible that with more experience the latissimus dorsi, a primary muscle engaged in pulling activities, would show reduced activations with powered the hand truck as users become more comfortable with the hand truck's motion.

Only one load size and magnitude (a single washing machine) was used in this study. There could be performance differences with loads of different sizes and densities as variations along these dimensions could affect the load's center of gravity relative to the hand truck's axle and thus the hand truck orientation (angle relative to the vertical) when on the stairs.

This study investigated different commercially available hand trucks. It is likely that some of the increased biomechanical loading observed with the multi-wheel hand truck was due to it weighing more than the conventional and powered hand trucks, especially during the stair ascent tasks where the more notable differences occurred. This additional weight could have masked possible advantages of the multi-wheel mechanism. Further studies could be conducted where the combined total weights of the hand truck and load are made equivalent, thereby removing this initial load differential and allowing a more sensitive test of the multi-wheel mechanism.

Data for this study were only collected while descending and ascending a single flight of eleven stairs. There could also be variations in the handling of these different types of hand trucks as they are maneuvered through landings and positioned to begin travel on the next flight of stairs. This is an opportunity for further study.

5. Conclusion

Relative to the conventional hand truck, using the powered hand truck, when working at both the slow and fast speeds, led to statistically significant reductions in upper extremity and trunk muscle activity, which should reduce the potential for muscular fatigue and the potential development of musculoskeletal disorders. Conversely, using the multi-wheel hand truck elicited more muscle activity, particularly in the trunk muscles. Making powered hand trucks more available to those delivering heavier items where stairs are encountered should also aid in recruiting and retaining employees that would otherwise find performing tasks with a manual hand truck too physically demanding. Although concerns regarding the speed of the ascents with the powered hand truck in the slower speed mode should be addressed by those implementing this intervention as employees will likely be concerned how this may affect their overall work performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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