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Investigating gripping force during lifting tasks using a pressure sensing glove system

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ABSTRACT

Lifting tasks remain one of the leading causes of musculoskeletal disorders (MSDs), primarily in the low back region. Lifting analysis tools are, therefore, designed for assessing the risk of low back pain. Shoulder musculoskeletal problems have emerged as common MSDs associated with manual handling tasks. It is hypothesized that gripping force is related to lifting conditions and may be used as a supplementary risk metric for MSDs in the shoulder and low back regions, because it measures additional hand exertions for coupling the lifted object during lifting. We assessed the capability tactile gloves for measuring the gripping force during lifting as a means for assessing different task conditions (lifting weight, lifting height, lifting direction, body rotation, and handle). Thirty participants wore the tactile gloves and performed simulated lifting tasks. Regression models were used to analyze the effects of the task variables on estimating the measured gripping force. Results demonstrated that 58% and 70% of the lifting weight variance were explained by the measured gripping force without and with considering the individual difference, respectively. In addition to the lifting risk measures commonly used by practitioners, this study suggests a potential for using gripping force as a supplementary or additional risk metric for MSDs.

1. Introduction

Lifting tasks are common contributors to workplace musculoskeletal disorders (MSDs) and present a significant burden to society in terms of productivity, financial costs, and worker health and safety. The U.S. Bureau of Labor Statistics has recently reported that overexertion associated with lifting tasks caused 86,740 injuries in the workplace, accounting for around 10% of all workplace injuries (U.S. Bureau of Labor Statistics, 2019). According to the Liberty Mutual report (Liberty Mutual Workplace Safety Index, 2021), overexertion (i.e., handling objects) costs businesses $13.3 billion in direct costs and accounts for 23% of overall national worker compensation cost.

Hand force exertion has been considered an important factor for lifting risks (Greenland et al., 2013; Lu et al., 2014; Merryweather et al., 2009). These previous studies investigated the hand forces required for lifting a weight and demonstrated a correlation between lifting weight and the risk of low back disorders (Greenland et al., 2013; Lu et al., 2014; Merryweather et al., 2009). Among the lifting risk assessments tools, the Revised NIOSH Lifting Equation (RNLE) (Waters et al., 1994) and the Liberty Mutual Manual Material Handling Tables (MMH Tables) (Potvin et al., 2021) are widely used by ergonomics practitioners. Specifically, the RNLE (Waters et al., 1994) calculates the recommended weight limit (RWL) for each lifting task based on six task variables (horizontal and vertical distances of the loaded hands relative to the feet during lifting; trunk asymmetry angle; hand coupling for the load at the origin and destination of each lift; the displacement of load for each lifting task; and the frequency of performing each lifting task). The RNLE compares RWL with the actual weight to determine a lifting index (LI) as an injury risk for each lifting task. These lifting risk assessment methods, however, showed different risk magnitudes for low back pain (Marras et al., 1999; Potvin & Bent, 1997; Waters et al., 1998). The discrepancies were attributed to different methodologies such as biomechanics vs. psychophysics (Marras et al., 1999; Waters et al., 1998) and static vs. dynamic biomechanical models (Waters et al., 1998).

Lifting risk assessment methods were often not designed to protect workers from MSDs other than low back disorders, except the MMH Table. The MMH table was developed based on the psychophysical method taking into account subjects' willingness to lift a weight in different lifting conditions (Snook et al., 1970). Theoretically, if the studied subjects were not capable of lifting the weights in different

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conditions, their shoulder strengths might have been considered to minimize the risk of shoulder injuries. However, the relationship between shoulder disorders and the lifting weights recommended by the MMH table has not been investigated.

Biomechanically, the gripping force is used to couple the object for whole body movements during lifting. The gripping effort is thought to depend on the weight of a lifted object, the dynamics and directions of body movements during lifting, and the handles available for lifting. The current biomechanical models for estimating the spinal loads or moments do not consider the gripping force for lifting. Therefore, the effect of gripping force on body joint loading is unclear. Because the gripping force is exerted by the muscles in the arms, shoulders, and upper body, we think that the gripping force may be linked to muscular or joint strain in the shoulder region. We also hypothesis that there is a relationship between the gripping force for lifting and the lifting conditions.

With the current force gauge technologies, measuring all the objective hand forces for manual handling tasks in the field is difficult (Bao et al., 2009). Gold standard technologies include hand force transducers, typically used for measuring required hand forces for manual tasks in three orthogonal directions (i.e., three axes of force direction). However, these three axis force transducers are large and not suited for instrumentation at the worker's hand-tool interface for continuous measurements. Measurement of the gripping force do not require such tethered, bulky sensors, and thus, may be more suitable for field measurements.

Tactile gloves are gloves embedded with pressure sensors across every region of the hands. These embedded pressure sensors can measure the compressive or contact hand force (i.e., force vertically exerted on sensors). The gripping force can then be estimated by summing these measured compressive forces. Compared to traditional techniques of measuring the gripping force using the hand dynamometers (Bao and Silverstein, 2005), the tactile gloves have a major advantage in that they can be used without interfering with the workers. Thus, the tactile gloves have been widely used by researchers and developers for real-time and dynamic measuring tasks. A recent systematic review (Caeiro-Rodríguez et al., 2021) illustrated that smart gloves equipped with sensors (e.g., IMU and pressure) have been successfully utilized in different application areas, such as measuring the hand mobility of stroke patients for rehabilitation, estimating the hand posture and motion for enhancing the interaction between human and computer, and training novices in professions involving hand-activities (e.g., surgeons and musicians). Ergonomics researchers have also used the tactile gloves to measure motor bikers' hand forces to ensure their safety in real-time (Ye et al., 2015), to evaluate and optimize the design of handles (Kong and Lowe, 2005), and to measure hand forces required for pipetting (Lu et al., 2008).

The gripping force has yet to be used for lifting risk assessments. The notion that the gripping force can be a potential metric for indicating some important lifting risk factors is based on the following motivations. First, many lifting injuries occurred not only in the low back regions but also in the upper extremities (e.g., shoulders, hands, and wrists). A few studies have illustrated that excessive force while gripping objects was linked to worker stress, fatigue, muscle strain, and hand or wrist-related musculoskeletal disorders (Bao and Silverstein, 2005; Barr et al., 2004; Thomsen et al., 2007). Second, the gripping force is the actual and total force exerted by workers' hands to complete the lifting tasks; thus, it can potentially reflect the lifting weight and the inertial forces. Theoretically, the gripping force (i.e., force vertically acting on the pressure sensor) should be highly associated with the lifting weight and inertial forces against the gravity pull for lifting. A study for precision gripping tasks has suggested that people tend to grasp the object harder when the object is heavier (Hiramatsu et al., 2015). With the evidence from the literature, we hypothesize that the required gripping force for a lifting task is a function of different lifting task variables.

To test this hypothesis, this study aimed to investigate the effect of various lifting risk factors on the gripping force measured by the tactile gloves. This investigation may help ergonomics researchers and practitioners gain some an initial understanding of the gripping force required for lifting tasks and help determine if the gripping force measured by the tactile gloves is suitable for lifting risk assessments.

The two research objects of this study are summarized below:

- (Primary) Investigate the association between the lifting weight and measured gripping force
- (Secondary) Investigate how different lifting risk factors (lifting height, lifting direction, body rotation, and handle factors) affect the measured gripping force

2. Method

2.1. Study participants

Thirty-one participants consented and completed the experiment; 39% of the participants were female, and 81% of the participants were right-handed. One participant's data was removed from the study due to disconnection of the glove device. The participants were recruited from a university population without professional experience in workplace lifting tasks and without musculoskeletal physical pain or discomfort at the time of the experiment. The study protocol was reviewed and approved by the university's institutional review board. All participants provided signed consent prior to experiments.

2.2. Study device – tactile gloves

The tactile gloves utilized in this study were developed by the PPS, Inc. (Hawthorne, CA). Each glove had 65 embedded pressure sensors for estimating the pressure exerted on the palmar side of the hand (Fig. 1). According to the manufacturer's manual, each sensor's full-scale range and minimum sensitivity was 80 psi ($55N/cm^2$) and 0.04 N, respectively. The tactile gloves were designed to scan at a rate of 25–40 Hz and was connected to a computer via Bluetooth. The area of each sensor was provided by the manufacturer and was used to convert the measured pressure to the compressive force exerted on each sensor.

2.3. Experiment design and procedure

2.3.1. Task conditions

The study was conducted in a laboratory environment. The participants were instructed to move a box with different assigned loads between a chair, a height-adjustable platform, and the floor (Fig. 2). The participants performed a sequence of six tasks lifting and lowering as described below:

- Task 1: Lift the box from the chair (location 1) to the platform (location 2) with a counterclockwise 90° body rotation
- Task 2: Lower the box from the platform to the floor (location 3) with 0° body rotation
- Task 3: Lift the box back to the platform from the ground with 0° body rotation
- Task 4: Lower the box to the floor (location 4) with a counterclockwise 90° body rotation
- Task 5: Lift the box back to the platform from the floor with a clockwise 90° body rotation
- Task 6: Lower the box back to the chair from the platform with a clockwise 90° body rotation

The platform's height (location 2) was systematically adjusted to have three different levels (high [1.1 m], middle [0.9 m], low [0.7 m]). Each task was performed on every height level.

To capture some of the variabilities in box types observed in workplaces, the boxes lifted by the participants were four commonly used containers: one commercial moving box, one crate, and two storage bin boxes. Their handles were considered good according to the RNLE but

Fig. 1. The PPS tactile glove system utilized in this study.

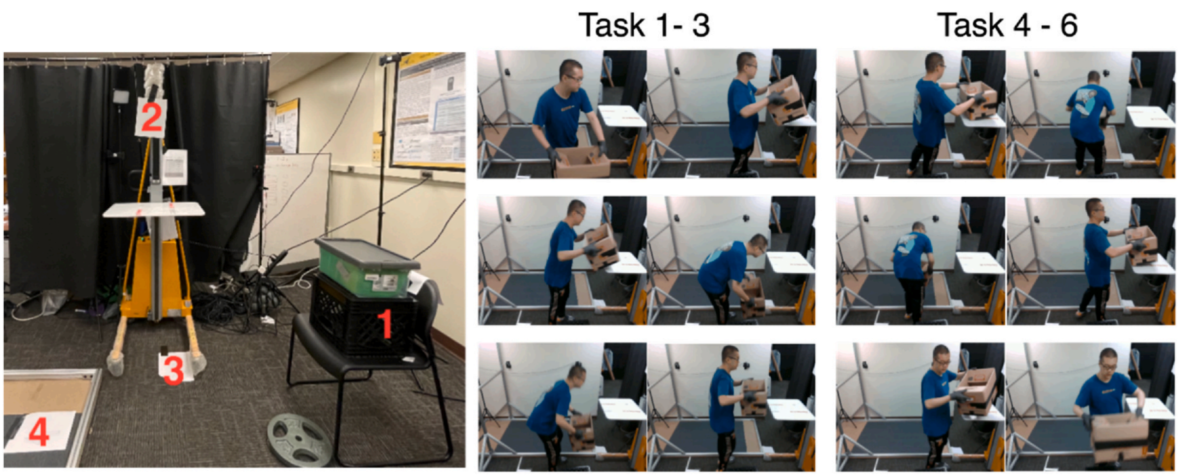

Fig. 2. The layout of the experiment environment and demonstration of each task. The location 2 had three different height levels during the experiment: low, middle, and high.

were different in terms of the shape and contact area. For the data analysis, we categorized the required handles into two categories: type 1 and type 2. The type 1 grip was a square edge (Fig. 3a), while the type 2 grip was a complete cut-out (Fig. 3b). In this study, 60% of the participants (n = 18) performed the lifts with the type 1 handle, while 40% (n = 12) performed the lifts with the type 2 handle.

2.3.2. *Lifting weight*

Our experimental setup defined six different tasks and three different height levels (Section 2.3.1). To determine the weights for each lift, we used the RNLE. For each task, we determined its RWL using the RNLE and assigned the weight. The LI, which is equal to the ratio of the actual weight to the RWL (LI = actual weight/RWL), was utilized to control the participants' risk during the experiment. Specifically, a distribution of weights was selected and grouped according to three LI ranges ($LI < 1$, $1 < LI < 2$, and $2 < LI < 3$). To guide our experimental design exploring task conditions and lifting pattern, weight levels in this experiment were categorize by their associated LI range (i.e., Light [$LI < 1$], Medium [$1 < LI < 2$], Heavy [$2 < LI < 3$]). Table 1 details every weight that had being assigned to the participants during the experiment under different weight and height level combinations. Since an LI larger than 3 indicates high injury risk, weights within this range were not included in the experiment.

Table 1
The weight assigned in the experiment (units: kg).

Weight Level	Height Level		
	Low	Middle	High
Light	3.4, 4.5	2.3, 3.4	1.1, 2.3
Medium	10.2, 11.3, 12.5	9.1, 10.2, 11.3, 12.5	7.9, 9.1, 10.2
Heavy	13.6, 14.7, 15.9, 17.0	13.6, 14.7, 15.9	13.6, 14.7

2.3.3. *Lifting pattern*

To standardize the experiment procedure, tasks 1–6 were considered as an action set. There were three different height levels of the platform and three different weight levels (Table 1). The participants were required to complete the action set for each height and weight level combination in a controlled pattern shown in Fig. 4. Throughout the experiment, a study team member would randomly pick a weight from

Fig. 3. The two types of handles utilized in the experiment.

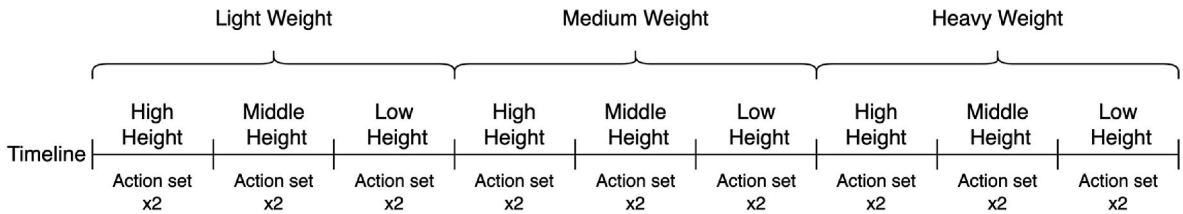

Fig. 4. The lifting pattern or task order in the experiment.

Table 1 for each weight and height level combination and assigned it to the participant.

All participants were required to perform the action set twice for each combination of the weight and height level. Rest time was given to the participants to reduce the fatigue effect during the experiment. Specifically, a 10-s rest occurred after the participants finished each task; a 2- minute rest was provided after the participants finished each action set; and a 10- minute rest was provided after the participants finished all required tasks for each risk level.

2.4. Data analysis

2.4.1. Data cleaning

The tactile glove has 130 embedded pressure sensors (65 from the left glove + 65 from the right glove) for measuring the hand pressure at different hand regions. We observed that the recorded pressure of a few sensors was out of the measurable limit of 80 psi (provided by the manufacturer) in approximately 3.96% of the total data collection. To ensure the robustness of the data, we removed the lifts with readings larger than the instrumentation limit of 80 psi.

2.4.2. Action detection algorithm

After sensor data cleaning, the exact period of each lifting event was located with traditional signal processing techniques. Specifically, a Gaussian + peak detection method was utilized. First, the total force exerted by both hands at each recorded timestamp was calculated by summing up the force observed by each sensor. This step produced a 1D time series sequence. Second, a 1D Gaussian filter was applied to denoise the data from step 1. The 1D Gaussian filter could flatten relatively short-lived forces from non-lifting actions. Third, a peak detection algorithm was utilized to locate the peaks on the filtered data by comparing neighboring values. Lastly, we utilized the gradients around each peak to locate the start and end of each task. Specifically, we calculated all gradients 2 s before and 2 s after each peak. Then, we sorted these gradients and selected the largest five before the peak and the largest five after the peak. Among these selected gradients, the one with the lowest force before the peak was set as the start, and the one with the lowest force after the peak was set as the end. Fig. 5 demonstrates the proposed method on an untrimmed recording.

2.4.3. Data conversion and feature extraction

Each sensor's raw pressure reading (in psi) was converted to initial compressive force estimations using the surface area of each sensor. The action detection section mentioned previously located all timestamps for each lift. With these timestamps, we calculated the aggregated compressive force (i.e., the gripping force) exerted on hands by summing the compressive force exerted on each sensor. Then, we determined the mean and the peak of the gripping force across the located timestamps for each lift. As shown in Fig. 5, the action detection module would start accepting data for a lifting task when the force increase occurred and would stop accepting data when the force fell back to nearly zero. Finally, the units of the gripping force and the actual lifting weight were both converted to Newton (N) in the results.

2.4.4. Linear regression analyses

This study utilized statistical models to investigate how much variance in the measured gripping force can be explained by the assigned lifting weight. In addition, we also utilized progressive statistical models including the individual difference (subject ID) and the task conditions (height level, body rotation level, handle type, and moving direction) to investigate how these conditions affected the measured gripping force.

First, two simple regression models were fitted to investigate the correlation between the gripping force and the assigned lifting weight. The fitted models were presented as follows:

$$Model\ 1:\ Mean\ Gripping\ Force \sim Weight$$

$$Model\ 2:\ Peak\ Gripping\ Force \sim Weight$$

Second, we fitted two linear mixed-effect models including the gripping force as a fixed effect term and the subject ID as a random effect term to investigate the effect of individual differences on the gripping force. We determined the Nakagawa's R-squared value (conditional) of each model to indicate the effect of the individual differences on the model result. The fitted models were presented as follows:

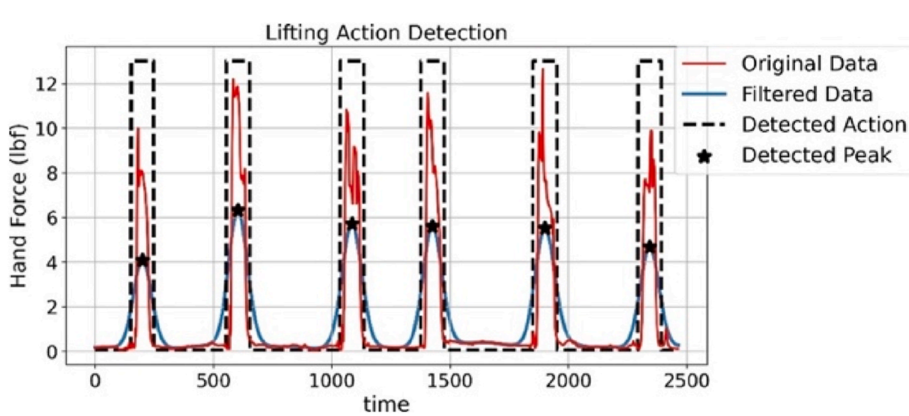

Fig. 5. The effect of the 1D Gaussian + peak detection method for locating the lifting actions from an untrimmed recording. The black dotted lines depict the period of each lift.

$$Model\ 3: Mean\ Gripping\ Force \sim Weight + (1|Subject_{ID})$$

$$Model\ 4: Peak\ Gripping\ Force \sim Weight + (1|Subject_{ID})$$

Lastly, we fitted two linear mixed-effect models including the measured gripping force and task conditions as fixed effect terms and the subject ID as a random effect term. Specifically, the task conditions included the three height levels (low, middle, high), three body rotation degrees (−90, 0, 90), two moving directions (lifting, lowering), and two different handles (type 1, type 2). The fitted models were presented as follows:

$$Model\ 5: Mean\ Gripping\ Force \sim Weight + Height + Rotation + Direction + Grip + (1|Subject_{ID})$$

$$Model\ 6: Peak\ Gripping\ Force \sim Weight + Height + Rotation + Direction + Grip + (1|Subject_{ID})$$

To fulfill the normality and equal variance assumptions of the linear regression model, all dependent variables were transformed through the Box-Cox transformation. The scatter plot and the quantile-quantile plot of the residuals were generated and presented for each model to illustrate the robustness of our results.

3. Result

3.1. Visualization of the measured gripping force

Results from models 1 (mean) and 2 (peak) gripping force are shown in Fig. 6. A 1:1 matching line, whose slope equal to 1 and intercept equal to 0, was added in each plot to further demonstrate how does each point (i.e., value of the measured gripping force) correlated with the actual weight (underestimation/overestimation). The plots demonstrate that when the actual weights were heavier, the measured gripping forces, especially the mean gripping forces, were smaller than the actual weight. On the other hand, when the actual weights were lighter, the measured gripping force, especially the peak gripping forces, were larger than the actual weight.

3.2. Regression models without the task conditions (model 1–4)

The model 1 and model 2 achieved an R-squared of 0.581 ($p < 0.001$) and 0.574 ($p < 0.001$), respectively. The scatter plot and the quantile-quantile plot of the residuals are presented in Appendix 1-2. These residual plots demonstrate that the normality and equal variance assumptions were not violated.

Adding the subject ID as a random effect term into the regression model increased both models' performance. The performance of the mixed-effect model utilized the mean gripping force as the independent variable achieved a conditional R-squared of 0.711 ($p < 0.001$); the performance of the mixed-effect model utilized the peak gripping force as the independent variable achieved a conditional R-squared of 0.724 ($p < 0.001$). The scatter plot and the quantile-quantile plot of the residuals are presented in Appendix 3-4. These residual plots demonstrate that the normality and equal variance assumptions were not violated, thus the results of the model 3 and model 4 were robust. Each model's summary, which include the coefficient and t-value of each term in the model, was presented in Table 2 and Table 3.

3.3. Regression models with the task conditions (model 5–6)

The results of the model 5 utilizing the mean gripping force as a dependent variable is shown in Table 4. Increases in the lifting weight increased the mean gripping force ($p < 0.001$). Compared with the middle height, lifts to the low height level required less ($p = 0.010$) gripping force on average. In contrast, compared with the middle height, the high height level required more ($p = 0.009$) gripping force. Compared with the lowering direction, the lifting direction increased ($p < 0.001$) the mean gripping force. The handle factor also had a significant effect on the mean gripping force ($p < 0.001$). Specifically, the type 2 handle required less gripping force than the type 1 handle on average. The body rotation factor had no effect on the mean gripping force ($p = 0.822$ for -90° rotation, $p = 0.170$ for $+90^\circ$ rotation).

The summary of the peak gripping force model was presented in Table 5. Increases in the lifting weight increased the peak gripping force ($p < 0.001$). Compared with the middle height, the low height level induced less ($p < 0.001$) peak gripping force. In contrast, compared with the middle height, the high height increased ($p < 0.001$) the peak gripping force. Compared with the lowering direction, the lifting direction increased ($p < 0.001$) the peak gripping force. The body rotation ($p = 0.829$ for -90° rotation, $p = 0.778$ for $+90^\circ$ rotation) and grip factors ($p = 0.774$ for handle type 2) had no effect on the peak gripping force.

The scatter plot and the quantile-quantile plot of the residuals of the models 5 and 6 are presented in Appendix 5-6. These residual plots illustrates that the normality and equal variance assumptions were not violated, thus the results of the models 5 and 6 were robust.

4. Discussion

This study was based on the notion that the gripping force can provide a new variable for real-time monitoring of lifting tasks, and if feasible, may contribute metrics for modeling muscular strain in the upper body segments, potentially leading to MSDs in these body regions. We investigated the relationship between the required gripping force for

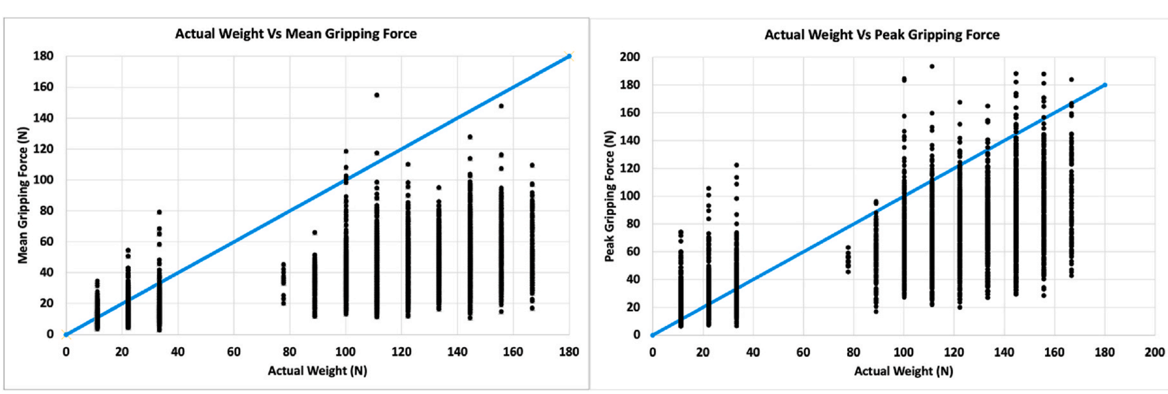

Fig. 6. The scatter plots for visualizing the measured gripping force across each assigned weight. The blue line represents the 1:1 matching line for demonstrating the correlation between the measured gripping force and actual weight. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
(Model 1 and model 3) dependent variable: Mean gripping force.

	Simple Regression			Mixed effect with Subject ID		
	R-squared: 0.581			R-squared: 0.711		
	Coefficient	t-value	p-value	Coefficient	t-value	p-value
(Intercept)	1.56	295.69	<0.001[a]	1.56	295.69	<0.001[a]
Weight	0.0030	65.98	<0.001[a]	0.0033	65.98	<0.001[a]

[a] $p < 0.05$ = statistically significant term.

Table 3
(Model 2 and model 4) dependent variable: Peak gripping force.

	Simple Regression			Mixed effect with Subject ID		
	R-squared: 0.574			R-squared: 0.724		
	Coefficient	t-value	p-value	Coefficient	t-value	p-value
(Intercept)	2.28	214.22	<0.001[a]	2.28	214.22	<0.001[a]
Weight	0.0070	65.10	<0.001[a]	0.0065	65.10	<0.001[a]

[a] $p < 0.05$ = statistically significant term.

Table 4
(Model 5) dependent variable: Mean gripping force.

Summary of the Linear-Mixed Effect Model R-squared = 0.717			
	Coefficient	t-value	p-value
Intercept	1.55	197.01	<0.001[a]
Assigned Weight			
Weight	0.0033	66.57	<0.001[a]
Task Conditions			
Height Level (middle)	Reference		
Height Level (low)	−0.016	−2.57	0.010[a]
Height Level (High)	0.017	2.63	0.009[a]
Body Rotation (0°)	Reference		
Body Rotation (−90°)	0.0014	0.23	0.822
Body Rotation (+90°)	0.0086	1.37	0.170
Lifting Direction (Lowering)	Reference		
Lifting Direction (Lifting)	0.021	4.10	<0.001[a]
Handle Type 1	Reference		
Handle Type 2	−0.019	−3.43	<0.001[a]

[a] $p < 0.05$ = statistically significant term.

Table 5
(Model 6) dependent variable: Peak gripping force.

Summary of the Linear-Mixed Effect Model R-squared = 0.735			
	Coefficient	t-value	p-value
Intercept	2.25	142.58	<0.001[a]
Assigned Weight			
Weight	0.0066	66.23	<0.001[a]
Task Conditions			
Height Level (middle)	Reference		
Height Level (low)	−0.052	−4.20	<0.001[a]
Height Level (High)	0.049	3.91	<0.001[a]
Body Rotation (0°)	Reference		
Body Rotation (−90°)	0.0027	0.22	0.829
Body Rotation (+90°)	−0.0035	−0.28	0.778
Lifting Direction (Lowering)	Reference		
Lifting Direction (Lifting)	0.034	3.31	<0.001[a]
Handle Type 1	Reference		
Handle Type 2	−0.0031	−0.29	0.774

[a] $p < 0.05$ = statistically significant term.

lifting and many lifting task variables as the first step to gain insight into the utility of using the tactile gloves for performing field measurements of lifting tasks. We used the tactile gloves for estimating the gripping force in relation to different lifting weights, lifting heights, lifting direction, body rotations, and handle types.

Results demonstrated that four lifting risk factors (i.e., lifting weight, lifting height, moving direction, and handle type) significantly affected the measured gripping force. These task variables explained approximately 70% of the variance of the measured gripping force. In the following sections, we discuss the correlations between the measured gripping force and the selected lifting risk factors. Then, we discussed the limitations and potential future work of utilizing the tactile gloves for risk assessments in the workplace.

4.1. Measured gripping force and lifting weight

The result of our best simple regression model (i.e., the peak gripping force) demonstrated that 58.1% of the variance of the peak gripping force could be explained by the variance of the lifting weight. Comparing between the mean and peak gripping force, the peak gripping force is a better indicator of the lifting weight than the mean gripping force, i.e., the models' R-squared values indicated that more variance of the peak gripping force could be explained by the lifting weight. One potential reason is that the mean gripping force accounted for both the starting and the ending stage (as shown in Fig. 5) where the force measurements at these two stages can be significantly different from the actual weight.

Comparing the results between the simple regression models and the mixed-effect regression models that accounted for the subject effects, we showed that the subject differences contributed to the variability in the measured gripping force. Although intuition may suggest a strong physical relationship between the lifting weight and measured gripping force that is robust to individual factors, the R-squared values increased by 0.13–0.15 when subject factors are taken into account. This may be partially due to the complexity of lifting. Lifting tasks are highly dynamic, and different participants may have different hand sizes, force exertion patterns, or lifting techniques that influence the amount of force exerted (Abdoli-Eramaki et al., 2019; Authier et al., 1996). Although further work may be needed to confirm how subject factors influence the gripping force in lifting tasks, a practical implication of the current findings suggests that individual calibration may be needed for improving the prediction of lifting weight. For example, workers may need to perform a standardized set of lifts prior to beginning their shifts with the gloves.

4.2. Measured gripping force and task variables

Comparison of the task factor levels showed that some, but not all the task factors influenced the measured gripping force. For example, the low height level required a lower gripping force than the middle height level, and the height level of lifting height required a larger gripping force than the middle height level. This result may be interpreted as a positive relationship between the initial lifting height and the required gripping force for lifting. Other studies have also observed impact of height on population-based strength capability (Yu et al., 2018).

The vertical moving direction significantly affected the measured gripping force as well, i.e., lifting required a larger gripping force than lowering when other task conditions were identical. From a biomechanics perspective, lifting an object may require the participants to exert a vertical force beyond the object's weight to counter the inertia (e.g., gravity) to accomplish the desired motion, while lowering an object may not require as much effort to counter these effects.

Our findings demonstrated that the body rotation factor had no significant effect on the measured gripping force. This may imply that other lifting factors influence our models more than rotation. However, this study only considered two body rotation levels (90-degree or 0-degree), which limited the generalization of the regression model. Assessments of multiple body rotation levels are needed.

Lastly, this study illustrated that the handle factor had a significant effect on the mean gripping force, meaning that different handle types require different amount of gripping force. This finding aligned with previous works introducing that the hand pressure measured by tactile gloves can be used to evaluate the quality of hand grip (Bao and Silverstein, 2005). Although the two different types of hand grip assigned in this study were both considered as good handles, they were different in that the first handle had a square edge while the second handle was a complete cut-out. This study implies that the tactile gloves can be used to reflect the handles' minor difference in shape; however, we note that handle factor was not significant in the peak force model. Thus, if handle is not of interest to the practitioner, a peak force model may be appropriate.

4.3. Limitations

The tactile gloves utilized in this study exhibit some limitations worth mentioning.

First, the pressure sensors embedded in the tactile glove have a measurable range (0–55N/cm^2) that may not be applicable for measuring gripping force for heavy weights.

Second, the exact contact area of each sensor is difficult to measure accurately in real-time. We assumed that each sensor's actual contact area was equal to its total surface area to convert the pressure to force, meaning that the weight was equally distributed and loaded on each sensor's surface area. This assumption likely led to underestimation of the gripping force observed in this study (Fig. 6) because some weights could be loaded on a small region only. In addition, as mentioned previously, the averaging process of calculating the mean gripping force considered the incremental and decremental stages, which could potentially cause the underestimation issue, as the measured gripping force in these two stages could be smaller than the lifting weight.

Third, although the gloves contained many sensors, there were also many sensor gaps; these spaces were dead spaces that were unable to detect pressure. The gaps reduce the gloves' capability of measuring the exact gripping force if some contact forces were generated in the dead spaces, which may be a cause for the underestimation of the lifting weight. Embedding more pressure sensors to fill in these dead spaces may improve the reliability of the measurements but will significantly increase the cost and flexibility of the glove. Another solution is to implement advanced non-linear modelling techniques (e.g., deep neural network) to either compensate or penalize the measurements of the gloves.

Forth, the mixed effect regression model used for testing for the effects of the task variables on the gripping force was based on the experimental design where only the lifting weight were randomly assigned to the participants, while other task variables were assigned to the participants in a fixed order. The mixed effect model may have a comprised statistical power for detecting a significant effect.

Finally, the primary object of this study was to investigate the feasibility of utilizing the gripping force measurements as a means for assessing different task conditions. The assumption that the gripping force can be used as a risk metric for MSDs in upper body regions need to be tested with injury date from the field in future research.

4.4. Future work

Despite the potential for utilizing the gripping force measured by the tactile glove for evaluating lifting risks is demonstrated in this study, MSD rates in upper body regions resulting from manual lifting tasks in the field should be collected and used as hypothesis testing metrics. Specifically, we recommend four areas of future work for researchers and developers to focus on for implementing the tactile gloves for real-world lifting risk assessments.

First, future studies should consider developing machine learning and deep learning models for predicting the lifting weight or hand force exertions for lifting using the measured gripping force. Individual and task difference should be considered when developing the prediction models for improving the prediction accuracy and reliability because the mixed-effect models demonstrated the individual difference and task conditions improved the R-squared values.

Second, additional lifting experiments covering move levels of lifting task variables should be conducted to expand on our dataset to thoroughly investigate the gloves' capability of analyzing lifting risks in many lifting conditions.

Third, other types of sensors (e.g., motion or vision/camera sensors) can be integrated with the tactile glove sensors to develop a comprehensive lifting risk assessment tool (Kratzke et al., 2022; Zhou et al., 2022). The combined usage of other sensors provides additional lifting risk information, such as dynamic body motion that has been independently associated with the risk of MSDs. This step will be very critical to future workplace implementation. Specifically, lifting conditions may vary greatly during a typical workday, and the computer vision techniques can provide real-time measurements of these changes to input in our gripping force model.

Lastly, to account for training effect and work experience, researchers may consider conducting lifting experiments using actual or experienced workers who perform lifting as part of their daily jobs. The experiment conducted in this study involved college students who might have different lifting techniques and styles from actual workers.

5. Conclusions

This study proposed utilizing the tactile gloves to measure the gripping force for lifting tasks and investigated the effects of different lifting risk factors on the measured gripping force. Several findings could be drawn from this study. First, through the simple linear regression analyses without considering the individual difference, we illustrated that the lifting weight explained 58.1% and 57.4% of the variance of the mean and peak gripping force, respectively. By adding the individual difference as a random effect term into the regression models, the lifting weight explained 71.1% and 72.4% of the variance of the mean and peak gripping force, respectively. The individual difference, which was potentially induced by factors such as the personal strength, affected the measured gripping force significantly. In addition, through the linear mixed-effect models, this study illustrated that the measured gripping force can also be explained by other lifting risk factors. The measured gripping force was significantly affected by the lifting height, handle type, and moving direction factors. In summary, this study demonstrated the feasibility of utilizing the gripping force measured by the tactile gloves for indicating some important lifting risk indicators, such as the lifting weight and height. In addition to the lifting risk measures commonly used by practitioners, this study suggests a potential for using gripping force as a supplementary or additional risk metric for MSDs in the upper body regions.

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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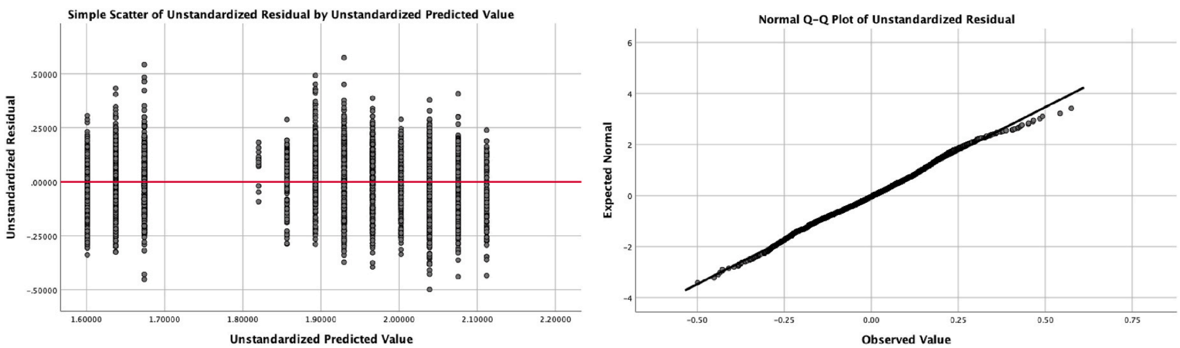
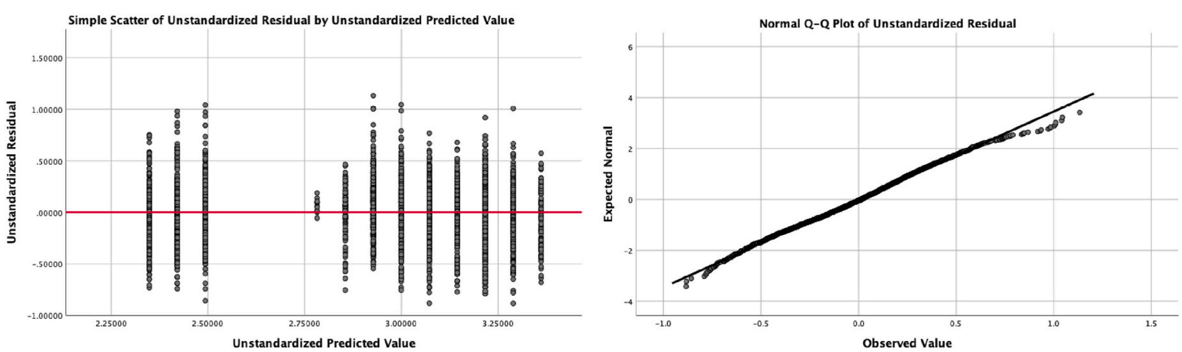
Findings and conclusions in this report are those of the authors and do not necessarily represent the official positions of National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH, CDC.

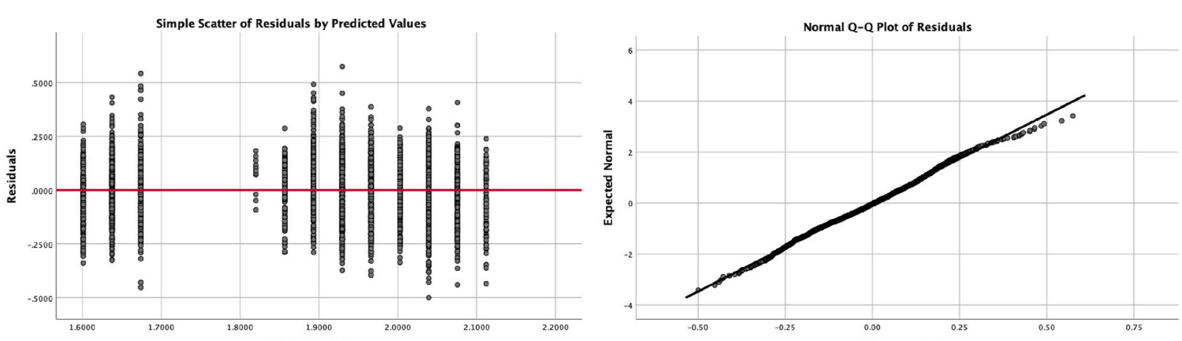
Appendix



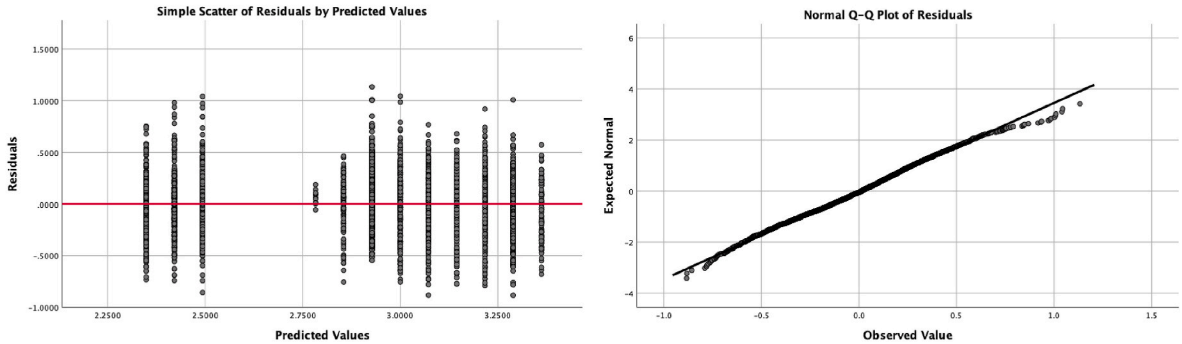
A1. Residual Plots for Model 1



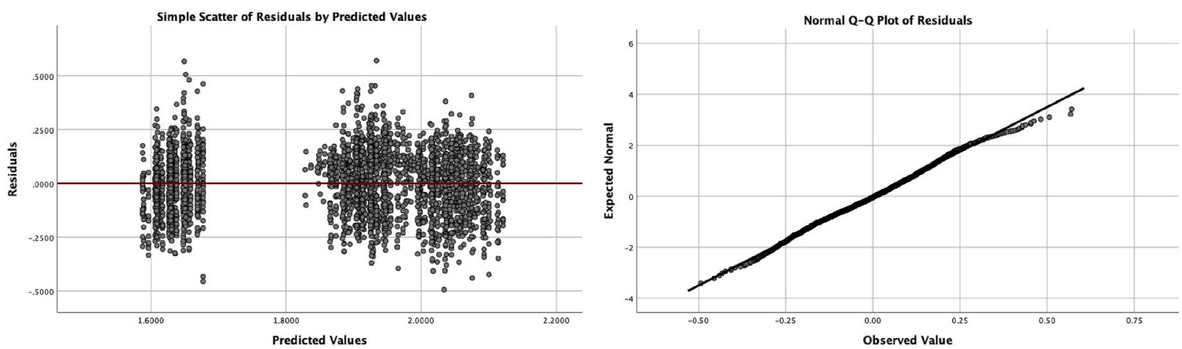
A2. Residual Plots for Model 2



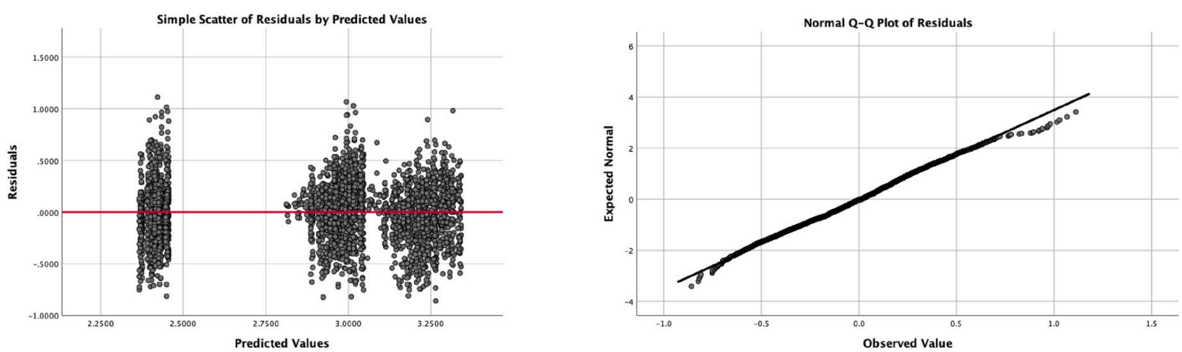
A3. Residual Plots for Model 3



A4. Residual Plots for Model 4



A5. Residual Plots for Model 5



A6. Residual Plots for Model 6

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