

Comparison of push/pull force estimates using a single-axis gauge versus a three-dimensional hand transducer

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ABSTRACT

This study investigated the effects of using a single-axis force gauge for push/pull force measurement on kinetic/kinematic measures associated with the exertion and assessed agreement between forces recorded from two technologies (single-axis gauge, three-dimensional hand transducer) and various test conditions via intraclass correlations. Independent measures included exertion type (push, pull, turn), test condition (natural/cart alone, using force gauge at fast/slow/self-selected paces), and cart weight (light, heavy). Dependent measures included mean angles of force application, peak forces recorded from both technologies, and cart velocity. Excellent agreement was observed between technologies (ICC = 0.998). Likewise, peak forces using the single-axis gauge at the fast pace agreed best with the natural test condition (ICC = 0.631). Forces should be measured using a faster initial acceleration and sustained velocity than is prescribed by the current standard if they are to accurately approximate forces relative to existing push/pull guidelines. Future work should also develop recommendations for measuring turning forces.

1. Introduction

Low back disorders (LBDs) are strongly associated with occupational exposures related to manual materials handling (NRC, 2001). As employers have recognized the risks to the low back associated with lifting, manual materials handling work has shifted towards pushing and pulling activities (de Looze et al., 2000). Unfortunately, pushing and pulling exposures may also lead to LBDs. It has been estimated that 9–20% of all occupationally-related LBDs may be attributable to pushing and pulling (Klein et al., 1984; Kumar, 1995; Schibye et al., 2001). More recent data suggests that in Ohio, approximately 10% of LBD costs are associated with pushing and pulling (Weston et al., 2018).

During lifting exertions, the forces required to maneuver an object are easy to determine, given that workers must simply oppose the gravitational forces from the weight of the object being lifted and that this gravitational force typically acts in the vertical direction. However, during pushing and pulling, the weight of the object that is to be displaced gives limited information about the actual forces required to push or pull the object (Hoozemans et al., 2001). Thus, practitioners must assess the forces that need to be exerted to move the object during ergonomics assessments. These assessments are most frequently

performed using a single-axis force gauge, where peak forces are recorded from the gauge and compared to associated risk limits for the given task, derived via either psychophysical methods (Snook and Ciriello, 1991) or biomechanical methods (Weston et al., 2018).

However, while using a single-axis force gauge is ideal for portable measurements, the hand forces recorded by practitioners using this tool may be imprecise or inaccurate. Practitioners are most often asked to apply push/pull forces horizontally against the cart handle(s) via the single-axis gauge, but the accuracy and consistency of the push/pull force measurement is affected by conditions including the angle of the applied push/pull force on the cart handle, gradients in the terrain, and more (Cerbai and Placci, 2019). Hoozemans et al. (2001) compared forces derived from a single-axis force gauge to a more accurate measuring frame during push/pull activities in construction and found that peak forces assessed with a single-axis force gauge can be slightly underestimated relative to those assessed with the frame, particularly during pushing. This potential underestimation of peak push/pull forces with a single-axis gauge relative to a three-dimensional “gold standard” measuring tool could cause practitioners to underestimate low back injury risk, deeming certain pushing and pulling activities as acceptable when in fact that job task exposes workers to a higher risk of an

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occupationally-related LBD.

Moreover, in addition to potential inaccuracy or imprecision in the magnitude of the applied push/pull force coming from using a single-axis force gauge as opposed to a higher-end force measurement modality, push/pull force readings are also likely to be influenced by the testing procedure itself. As the magnitude of push/pull force measurements are most affected by the acceleration of the cart, current best practices for push/pull force testing (including recommendations for cart acceleration and more) have been specified previously in ISO 11228-2 (Standards, 2007). Conceivably, alignment with these standards should allow for the derivation of precise, repeatable push/pull force measurements. It should be noted, however, that companies often use their own standardized methods to test push/pull forces, sometimes in misalignment with these standards. Moreover, it is also likely that the recommended acceleration of a cart laid out by the current ISO standard is misaligned to actual work context, where workers may push/pull more quickly and subsequently expose themselves to higher peak push/pull forces.

As the overarching goals of push/pull force testing are to assess the biomechanical risk for injury associated with a task and to redesign those job tasks that are associated with a higher biomechanical risk for injury, the potential sources of imprecise or inaccurate force measurements mentioned above could also lead to an inaccurate estimation of biomechanical risk when applying the previously mentioned push/pull guidelines. Thus, the objectives of this study were 1) to investigate how using a single-axis force gauge to record push/pull force measurements affects kinetic and kinematic measures associated with the exertions and 2) to determine the level of agreement between forces recorded from various technologies (single-axis gauge versus three-dimensional hand transducer) and test conditions (natural/cart alone versus those using single-axis gauge at multiple paces).

2. Methods

2.1. Approach

A laboratory study was conducted to provide recommendations for push/pull testing that improve hand force estimates derived with a single-axis force gauge. In every trial, subjects pushed, pulled, or turned a manual materials handling cart outfitted with a six-axis (i.e., three-dimensional) hand transducer. Subjects started each session by pushing, pulling, and turning directly on the three-dimensional hand transducer in order to record hand forces for a “natural” test condition. Then, subjects performed these same exertion types with the single-axis force gauge. The dependent measures of interest included the magnitude and direction (i.e., angle) of pushing/pulling forces applied onto the cart and measures of the cart velocity. Ultimately, the agreement between the peak forces recorded from both technologies (single-axis gauge vs. three-dimensional hand transducer) and the agreement between peak forces recorded for each of the test conditions (the natural test condition performed first without the single-axis gauge vs. the single-axis force gauge test conditions) were investigated.

2.2. Subjects

Ten participants (6 male, 4 female, age 25.6 ± 6.2 years (SD)) were recruited as participants for this study. This population size was deemed appropriate to detect a small effect size (Cohen $d = 0.1$) in the dependent variables of interest with a power of 0.80 and a significance level $\alpha = 0.05$ prior to beginning the study, consistent with the first objective for the study. Two of the ten participants reported that they were familiar with the push/pull testing procedure, but none of the subjects reported having significant prior experience using a single-axis gauge to record push/pull forces. All subjects provided informed consent to the research protocol as approved by the University's Institutional Review Board.

2.3. Experimental design

A mixed model design was implemented for this study to assess the effects of 1) exertion type (3 levels), 2) test condition (4 levels), 3) cart weight (2 levels), and 4) their interactions on the dependent measures of interest. Three repetitions of each experimental condition were collected.

2.3.1. Independent variables

Exertion types included straight two-handed pushing, straight two-handed pulling, or cart turning. Test condition described whether or not the single-axis force gauge was used to record push/pull forces for the given trial, and if so, the prescribed pace to move the cart during the testing procedure. One level of the test condition variable included natural/cart alone trials, which were performed at a self-selected pace without the single-axis force gauge. The other three levels of this variable were trials performed with the single-axis force gauge at self-selected, fast, and slow paces. The slow condition required subjects to push or pull the cart 1 m in 5 s and every meter thereafter in 3 s (0.33 m/s sustained velocity). Likewise, the fast condition required subjects to push or pull the cart 1 m in 3 s and every meter thereafter in 2 s (0.5 m/s sustained velocity). However, it should be noted that the fast and slow paces were excluded during cart turning; only a self-selected pace was tested for this exertion type. Finally, cart weights were either light (680 kg, or 1500 lbs.) or heavy (907 kg, or 2000 lbs.). These cart weights were noted by a partner company to be common targets when designing cart/caster pairs for manual materials handling tasks.

2.3.2. Dependent variables

Dependent measures included the mean angle of force application relative to the three-dimensional hand transducer, peak forces recorded by the three-dimensional hand transducer and (where used) single-axis force gauge, and the mean velocity of the cart throughout each trial. In straight pushing and pulling, cart motion was decomposed into the mean velocity for the initial push/pull (first meter of travel) and sustained push/pull (everything past the first meter); however, in turning, the mean velocity of the cart throughout the duration of the trial was recorded together. Peak hand force measures were also utilized to draw inferences about the agreement between technologies (three-dimensional hand transducer vs. single-axis gauge) and test conditions (namely, natural test condition vs. test conditions using the single-axis force gauge).

2.4. Instrumentation and apparatus

Kinetic data were obtained at a sampling frequency of 1000 Hz using a three-dimensional hand transducer (Bertec HT0825, Worthington, OH, USA). Where indicated by the study design, kinetic data were also obtained at a sampling frequency of 12.3 Hz from a single-axis digital force gauge (Shimpo FGV-500HXY, Cedarhurst, NY, USA). Kinematic data for the cart were collected at a sampling frequency of 120 Hz using a 42-camera optical motion capture system (OptiTrack Prime 41, NaturalPoint, Corvallis, OR, USA). The accuracy of this system has been validated to be less than 200 μm in 97% of the capture volume (Aurang et al., 2017). While kinetic data for the three-dimensional hand transducer and kinematic data were collected with custom laboratory software written in MATLAB (MathWorks, Inc., Natick, MA, USA) and synchronized using a data acquisition board (USB-6225, National Instruments, Austin, TX, USA), kinetic data from the single-axis digital force gauge were collected using the Toriemon-USB plugin (Shimpo, Cedarhurst, NY, USA) in Excel (Microsoft, Redmond, WA, USA) and were time-synchronized with all of the other data during post-processing using a custom script written in MATLAB (MathWorks, Inc., Natick, MA, USA).

A manual materials handling cart (CarryMore Tugger Cart System, East Peoria, IL, USA) measuring 127 cm (50 in.) wide by 127 cm (50 in.)

deep, outfitted with two kingpinless swivel casters and two rigid casters 20.32 cm (8 in.) in diameter (Caster Connection, Columbus, OH, USA) was used for this study. The cart alone had a mass of 113.4 kg (250 lbs.), but the cart was brought up to the correct weight via stacking boxes filled with metal. The handle of the cart was removed and replaced with the three-dimensional hand transducer at the same vertical height (100 cm), affixed to the cart using a custom-built frame made from T-slotted aluminum (80/20 Inc., Columbia City, IN, USA), as shown in Fig. 1.

2.5. Experimental procedure

Subjects were briefed on the study protocol and gave informed consent. Subjects were shown the cart and were given the opportunity to push, pull, and turn the cart around the room in order to get a feel for its weight. Once they felt comfortable, push, pull, and turning exertion types were collected for the subject for the natural test condition (described previously, 3 exertion types x 2 weights x 3 repetitions = 18 trials). During these trials, the subjects were asked to move the cart at a pace that felt comfortable to them, “as if they were a worker at a distribution center performing regular job responsibilities.” During straight pushing and pulling exertion types, subjects moved the cart from a standstill through a total distance of 3 m. Likewise, during turning exertions, subjects were asked to turn the cart as sharply as possible from a standstill 90° counterclockwise. Subjects always pushed, pulled, or turned along the same path in the motion capture space in order to control for any irregularities or slight uphill/downhill grades in the floor. The back casters were always oriented perpendicular to the direction of travel, so as to represent the ‘worst-case’ scenario to initiate cart motion.

After collecting all of the natural test condition trials, subjects were shown the single-axis force gauge that they would be using for the rest of the study and were provided instructions on how to use it. Subjects were instructed to exert forces horizontally rather than at an angle relative to the floor, since existing guidelines for pushing and pulling ask practitioners to record the peak horizontal (rather than resultant) hand forces required to move the object in question. Subjects were also given the opportunity to practice using the single-axis gauge to push, pull, or turn the cart. During pushing and turning exertion types, subjects were instructed to use a flat, round attachment for the single-axis force gauge to move the cart. Likewise, for the pulling exertion type, wire was tied around the cart handle, and a hook accessory for the single-axis force gauge was used.

Once comfortable using the single-axis gauge, the test conditions using the single-axis force gauge were collected. This included all combinations of the 3 exertion types (push, pull, turn), the 3 remaining testing conditions (single-axis gauge trials at self-selected, fast, and slow paces), 2 weights (light, heavy), and 3 repetitions of each condition; however, as fast and slow paces were not collected for the turning exertion type, this summed to 42 trials. Because the forces recorded by the three-dimensional hand transducer and single-axis gauge were both

important, these trials relied on ‘piggy backing’ the single-axis gauge and three-dimensional hand transducer together. That is, subjects pushed, pulled, or turned using the single-axis gauge, and also applied the single-axis gauge force directly onto the three-dimensional hand transducer (as shown in Fig. 1B). For all turning exertions and the subset of the pushing and pulling exertion types that were performed using a self-selected pace, subjects were asked to “recall and match their previous efforts as best as possible.” During straight pushing and straight pulling with the single-axis gauge at the fast and slow paces, a metronome set to 60 beats per minute was used to help the subject time the exertion accordingly.

Because of the difficulty involved in adding or removing 226.8 kg (500 lbs.) to the cart, cart weight was changed as infrequently as possible. Thus, subjects performed either the natural test condition with the light cart, then all test conditions with the heavy cart, and then finished with the remaining test conditions with the single-axis force gauge and the light cart, or vice versa in regard to cart weight. The order of the other conditions (combinations of exertion type and test conditions with the single-axis force gauge) were randomized, and repetitions of each trial type were collected back-to-back.

2.6. Signal processing and statistical analysis

Kinetic data derived by both the three-dimensional hand transducer and single-axis force gauge and kinematic data for the cart derived from motion capture were low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 10 Hz. Kinetic data from the three-dimensional hand transducer and kinematic data for the cart were also downsampled to 12.3 Hz to match data collected by the single-axis force gauge. Where appropriate, kinetic data for the three-dimensional hand transducer and kinematic data for the cart were time-synchronized with the single-axis force gauge data via a function that plotted three-dimensional hand transducer and single-axis force gauge data against one another and determined the proper time delay that maximized the correlation between the signals (the correlation (r^2) between the signals was consistently high with a mean r^2 of 0.989 across all conditions).

The mean angle of force application relative to horizontal was recorded for both natural and single-axis force gauge test conditions and was calculated as the mean of the arctangent of the vertical and horizontal (normal) components of the three-dimensional hand forces recorded by the three-dimensional hand transducer. The peak horizontal force reading from the three-dimensional hand transducer and (where appropriate) the peak reading from the single-axis force gauge were extracted and retained for statistical analysis. The error between the technologies was calculated as the difference between the peak reading from the single-axis force gauge and the peak horizontal force reading from the three-dimensional hand transducer. Mean cart velocity was extracted as an additional source of comparison and was further decomposed into initial (first meter) and sustained (beyond the first meter) components where appropriate.

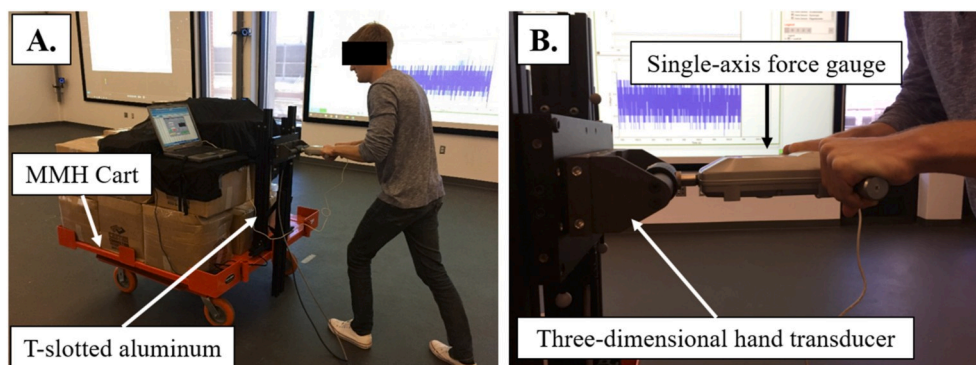


Fig. 1. Experimental apparatus. (A) A manual materials handling cart was outfitted with a three-dimensional hand transducer via a custom T-slotted aluminum frame. (B) While subjects exerted directly onto the three-dimensional hand transducer during natural test conditions, a ‘piggy back’ approach (as shown) was used to collect kinetic data for test conditions using the single-axis force gauge, in which subjects exerted directly onto the three-dimensional hand transducer with the single-axis gauge.

Results were analyzed using JMP 14 Pro software (SAS Institute Inc., Cary, NC, USA). Effects of test condition, cart weight, and their interaction on the dependent measures of interest were assessed via a generalized linear mixed model treating test condition, cart weight, and the test condition * cart weight interaction as fixed effects and subject and interactions with subject as random effects. Effects were assessed relative to a significance level (α) of 0.05. Separate analyses were performed for each exertion type, and post-hoc analyses were performed using Tukey HSD tests where appropriate. Additionally, the agreement between technologies (single-axis gauge vs. three-dimensional hand transducer) and agreement between test conditions (natural, single-axis force gauge self-selected pace, single-axis force gauge fast pace, single-axis force gauge slow pace) were quantified via intraclass correlation coefficients (ICC). ICC estimates were calculated based on mean-rating ($k = 3$), absolute agreement, two-way mixed effects models. Agreement between technologies was assessed via comparison of the peak values recorded from the three-dimensional hand transducer and peak values recorded from the single-axis force gauge during the three test conditions performed with the single-axis force gauge (including self-selected, fast, slow paces). Likewise, agreement among test conditions were assessed pair-wise using the peak horizontal force values recorded from the three-dimensional hand transducer across the varied exertion types and cart weights. According to recommendations from Koo and Li (2016), values less than 0.5 were determined to be indicative of poor agreement, values between 0.5 and 0.75 indicative of moderate agreement, values between 0.75 and 0.9 indicative of good agreement, and values greater than 0.90 indicative of excellent agreement.

3. Results

3.1. Angle of force application

Descriptive statistics for the mean angle of force application relative to horizontal as measured by the three-dimensional hand transducer are shown in Table 1, separated by exertion type and test condition. During the natural (self-selected pace) test condition, the mean angle of force application was highly variable, as indicated by large standard deviations in the data. In contrast, test conditions using the single-axis force gauge (at all paces) were applied nearly horizontally, and there was less variability in the data. The linear mixed model revealed a significant main effect of test condition for pushing ($p < 0.0001$), but not

Table 1

Angle of force application for each condition relative to horizontal. * denotes values that differ significantly from the other test conditions for that particular exertion type at a significance level of 0.05.

| Exertion Type | Test Condition | Mean (SD) Angle of Force Application Relative to Horizontal |
|---------------|--|---|
| Push | Natural (Self-Selected Pace) | 21.2 (10.4) * |
| | Single-axis gauge (Self-Selected Pace) | 4.4 (4.3) |
| | Single-axis gauge (Fast Pace) | 4.0 (4.4) |
| | Single-axis gauge (Slow Pace) | 4.5 (4.4) |
| Pull | Natural (Self-Selected Pace) | 3.4 (11.1) |
| | Single-axis gauge (Self-Selected Pace) | 2.5 (3.8) |
| | Single-axis gauge (Fast Pace) | 2.0 (4.0) |
| | Single-axis gauge (Slow Pace) | 1.7 (3.9) |
| Turn | Natural (Self-Selected Pace) | 18.7 (26.5) |
| | Single-axis gauge (Self-Selected Pace) | 7.5 (6.3) |

pulling or turning. The corresponding post hoc analysis showed that the mean angle of force application for the natural (self-selected pace) test condition differed significantly from all of the test conditions using the single-axis force gauge, though no significant differences among the test conditions using the single-axis force gauge (self-selected, fast, slow paces) were observed. The subjects' ability to exert horizontally was not influenced by cart weight or any interaction between test condition and cart weight.

3.2. Peak push/pull force magnitude

As shown in Fig. 2, peak hand forces recorded by the three-dimensional hand transducer were heavily influenced by the test condition, where a significant main effect was observed for all three exertion types ($p < 0.0001$). Post hoc analyses revealed that during straight pushing, the highest peak hand forces were observed for natural pushing, and this group differed significantly from test conditions using the single-axis force gauge at self-selected and slow paces, but not the fast pace. The second highest peak forces were observed for single-axis force gauge test conditions performed at the fast pace, and this group differed significantly from the single-axis force gauge test conditions performed at the slow pace. The last two groups (single-axis force gauge test conditions at self-selected and slow paces) did not differ significantly between each other. Likewise, during straight pulling, peak hand forces for natural (self-selected paced) test conditions and single-axis force gauge test conditions performed at the fast pace were significantly higher than peak hand forces for single-axis force gauge test conditions performed at self-selected or slow paces. Contrary to the results for straight pushing and pulling, peak hand forces during turning were significantly higher for turns performed with the single-axis force gauge at a self-selected pace than for natural cart turning. Surprisingly, cart weight had little influence on peak hand forces; the only statistically significant difference observed was during pushing, where peak hand forces were noted to be higher when pushing the heavy cart than when pushing the light one ($p = 0.02$). There was no significant interaction effect between test condition and cart weight for any of the exertion types.

3.3. Cart velocity

As shown in Fig. 3, mean velocity was influenced by a main effect of test condition across all three exertion types. Post-hoc tests revealed that in pushing, mean initial velocity was significantly faster for the natural (self-selected pace) test condition and the test condition using the single-axis force gauge at the fast pace than test conditions using the single-axis force gauge at either the self-selected or slow paces ($p < 0.0001$). Likewise, in straight pulling, initial velocity was fastest in single-axis force gauge test conditions at the fast pace, followed next by mean initial velocity for self-selected pacing (both natural and single-axis force gauge test conditions), and finally by single-axis force gauge test conditions at the slow pace ($p < 0.0001$). However, during both sustained pushing and sustained pulling, only single-axis force gauge test conditions at the slow pace differed from any of the other groups ($p = 0.0001$). Mean velocity during turning exertions were higher in natural turning conditions than turning conditions performed with the single-axis gauge ($p = 0.0003$).

A significant main effect of cart weight was observed for initial velocity in pushing ($p = 0.014$), initial velocity in pulling ($p = 0.0066$), sustained velocity in pulling ($p = 0.0003$), and velocity for turning ($p = 0.0076$); in all instances, mean velocity was higher for the light cart than for the heavy cart. However, significant test condition * cart weight interaction effects were also observed for initial velocity in pushing ($p = 0.03$) and sustained velocity in pulling ($p = 0.03$). The significant interaction effect for pushing suggested that the effect of cart weight was only significant for natural pushing and test conditions using the single-axis force gauge at the fast pace, not for test conditions using the single-axis force gauge at either the self-selected or slow paces. The significant

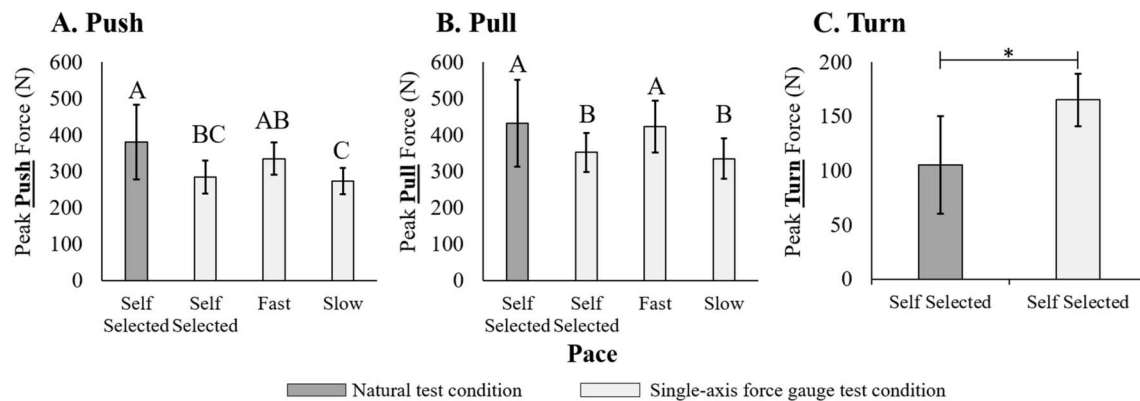


Fig. 2. Magnitude of peak hand force estimates separated by test condition for (A) pushing, (B) pulling, and (C) turning exertion types. Letters above groups denote post-hoc Tukey results, where groups not connected by the same letter differ significantly from one another. * represents a statistically significant difference $p < 0.05$.

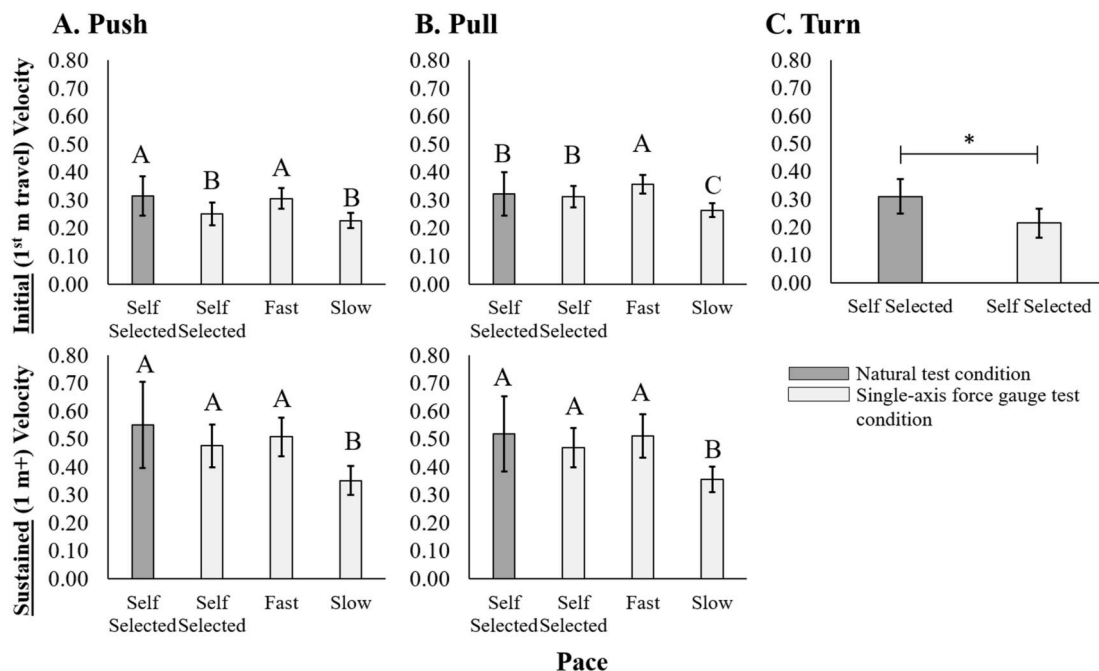


Fig. 3. Mean cart velocities (m/s), separated by test condition. Mean velocity for the cart was also separated into initial (first meter of travel) and sustained phases for pushing and pulling exertion types. Letters above groups denote post-hoc Tukey results, where groups not connected by the same letter differ significantly from one another. * represents a statistically significant difference $p < 0.05$.

interaction effect for sustained pulling suggested that the effect of cart weight was only significant in natural pulling, not for any test conditions using the single-axis force gauge (at any pace).

3.4. Agreement measures (ICCs)

The ICCs describing the agreement between technologies and test conditions are shown in Table 2. There was excellent absolute agreement between the horizontal component of force recorded by the three-dimensional hand transducer and the force recorded by the single-axis gauge (ICC point estimate of 0.998) across the three exertion types. However, the single-axis gauge did tend to overestimate force slightly relative to the three-dimensional hand transducer. As shown in Fig. 4, the error between the single-axis gauge and three-dimensional hand transducer was worse for the turning exertion type than for pushing and pulling exertion types; whereas the single-axis gauge overestimated forces relative to the three-dimensional hand transducer by 3.85 N (0.87 lbf) on average for pushing and straight pulling exertion types, the mean

error between the single-axis gauge and three-dimensional hand transducer was 17.2 N (3.87 lbf) on average for the turning exertion type.

Regarding test condition, the agreement between natural (self-selected pace) conditions and any of the test conditions using the single-axis force gauge was generally poor, though agreement was best between the natural test condition and the test condition using the single-axis force gauge with the fast pace (ICC point estimate of 0.447 for pushing and 0.631 for pulling). The agreement among the test conditions using the single-axis force gauge at any of the three paces was better than agreement with the natural test condition, yielding good to moderate agreement for all comparisons but one.

4. Discussion

During ergonomic assessments, practitioners often record peak forces for pushing, pulling, and turning exertion types using a single-axis force gauge. As these force readings are used as inputs for guidelines aimed at assessing the injury risk associated with the given task (Snook

Table 2

ICCs describing agreement between technologies and agreement among the test conditions.

| Pair-wise Comparison | Exertion Type | ICC Point Estimate | Agreement Rating |
|---|---------------|--------------------|------------------|
| Technologies | | | |
| Single-axis force gauge vs. three-dimensional hand transducer | All | 0.998 | Excellent |
| Test Conditions | | | |
| Natural vs. single-axis force gauge self-selected pace | Push | 0.123 | Poor |
| | Pull | 0.456 | Poor |
| | Turn | 0.113 | Poor |
| Natural vs. single-axis force gauge fast pace | Push | 0.447 | Poor |
| | Pull | 0.631 | Moderate |
| Natural vs. single-axis force gauge slow pace | Push | 0.413 | Poor |
| | Pull | 0.438 | Poor |
| Single-axis force gauge self-selected vs. fast pace | Push | 0.850 | Good |
| | Pull | 0.653 | Moderate |
| Single-axis force gauge self-selected vs. slow pace | Push | 0.713 | Moderate |
| | Pull | 0.451 | Poor |
| Single-axis force gauge fast vs. slow pace | Push | 0.809 | Good |
| | Pull | 0.543 | Moderate |

and Ciriello, 1991; Weston et al., 2018), inaccurate or imprecise force estimates from the single-axis gauge would also cause injury risk to be assessed incorrectly. This study endeavored to investigate how using a single-axis force gauge to record push/pull force measurements affects kinetic and kinematic measures associated with pushing, pulling, and turning exertions and to determine the level of agreement of forces recorded from various technologies (single-axis gauge versus three-dimensional hand transducer) and test conditions (namely, the natural test condition versus those using single-axis gauge at multiple paces). The results of this study suggested that despite the fact that it is most natural to apply push/pull forces at some angle relative to horizontal (Table 1), practitioners can successfully apply push/pull forces horizontally when using a single-axis gauge, which led to good agreement between the magnitudes of push/pull forces recorded from a single-axis gauge and the horizontal component of force derived from a three-dimensional hand transducer. However, the recommended pace laid out in ISO 11228-2 (Standards, 2007) is too slow and results in an underestimation of the push/pull forces workers might naturally encounter in a real work context, thus also underestimating risk for occupationally-related injuries.

Given that pushing and pulling guidelines ask practitioners to record the horizontal push/pull force for a given trial, this study chose to compare the kinetic data derived from the single-axis force gauge to the horizontal (normal) component of force recorded by the three-dimensional hand transducer. As the single-axis gauge provides the magnitude of the resultant push/pull force rather than breaking down the resultant force into components, it is not particularly surprising that the single-axis force gauge tended to slightly overestimate push/pull forces relative to the three-dimensional hand transducer. However, the slight overestimation observed across the exertion types (3.1 N on average in pushing, 4.6 N on average in pulling, 17.2 N on average in turning) should not be particularly concerning, given that a slightly higher force reading would yield a more protective result when practitioners estimate the risk associated with a particular exertion type via push/pull guidelines. In addition, the absolute agreement between technologies was classified as excellent. These results align with those published by Hoozemans et al. (2001), which also concluded that a single-axis force gauge can reliably be used to assess push/pull forces in the workplace, especially when peak push/pull forces are the primary measure of interest. The only difference observed between that study and the present study is that Hoozemans et al. (2001) found that a single-axis gauge can slightly underestimate forces relative to a highly accurate measuring frame, whereas this study found that the single-axis gauge tends to overestimate. This difference comes from the fact that Hoozemans et al. (2001) compared the resultant force from the

single-axis gauge to the resultant force from the measuring frame, whereas this study compared the resultant force from the single-axis gauge to the horizontal component of force from the three-dimensional hand transducer.

In straight pushing and pulling, ISO 11228-2 (Standards, 2007) suggests that practitioners assess push/pull forces for both the initial and sustained phases of the exertion. The standard suggests pushing or pulling the cart 1 m in 10 s to derive the initial push/pull force and at a sustained velocity of 0.33 m/s thereafter to derive the sustained push/pull force. Presumably, this rather slow trajectory was chosen in order to derive more precise push/pull force estimates, under the assumption that pushing or pulling more quickly would be harder for practitioners to do consistently. The authors saw during pilot testing that the pace currently prescribed by ISO 11228-2 significantly underestimates pushing and pulling forces when compared to the natural test condition, which led to our choice of fast (1 m in 3 s, 0.5 m/s sustained) and slow (1 m in 5 s, 0.33 m/s sustained) test conditions using the single-axis force gauge; both paces were somewhat faster than ISO 11228-2. The authors were also interested in seeing if practitioners could subjectively reproduce a natural cart push or pull without prescribing any sort of target speed to them, which led to inclusion of the self-selected cart test condition with the single-axis gauge. Of all of the test conditions performed with the single-axis force gauge, the fast pace best matched the natural test condition. After all, there was not a statistically significant difference between peak hand forces recorded for the natural test condition and peak hand forces recorded for test conditions using the single-axis force gauge at this pace. It should be noted, however, that despite the fact that the fast pace best matched the natural test condition for pushing and pulling exertion types, the level of agreement between these two test conditions as quantified by ICCs was still poor to moderate. Regardless, these results still highlight the need to update current best practices for push/pull force testing, namely testing push/pull forces with a faster initial acceleration and sustained velocity to more accurately approximate push/pull forces for use in context with available pushing and pulling guidelines.

Although several pushing and pulling studies have aimed to provide recommendations and maximum acceptable torque limits for turning (Weston et al., 2017, 2018), there remain no standards or best practices for assessing turning forces with a single-axis force gauge, including recommendations about the correct pace and direction of force application for this exertion type. The results of this study suggest a drastic need for future work aimed to develop best practices for testing cart turning forces, given that the single-axis force gauge overestimated turning forces by 17.2 N (3.9 lbf) on average relative to the three-dimensional hand transducer, representing an overestimation of about 10% on average. Moreover, the level of agreement between the natural test condition and the test condition using the single-axis force gauge at a self-selected pace was very poor for the turning exertion type. Peak force estimates for cart turns performed with the single-axis force gauge were 56.7% higher on average than peak force estimates for the natural test condition, despite the fact that mean velocity of the cart during the turn was actually 30.1% lower on average during the test condition using single-axis force gauge the natural turning test condition.

This discrepancy for turning exertions can at least partially be explained by the experimental setup. Because one three-dimensional hand transducer was used for turning and it was placed in the center of the cart, participants also exerted forces laterally during turning rather than normal to the three-dimensional hand transducer surface. However, only the normal force going directly into the three-dimensional hand transducer was reported herein (not the lateral force component). This could account for the apparent increase in turning force observed for the test condition using the single-axis force gauge relative to natural cart turning, despite a reduction in mean velocity. During natural cart turning, laterally oriented forces were most efficient at turning the cart than those directed normal to the three-

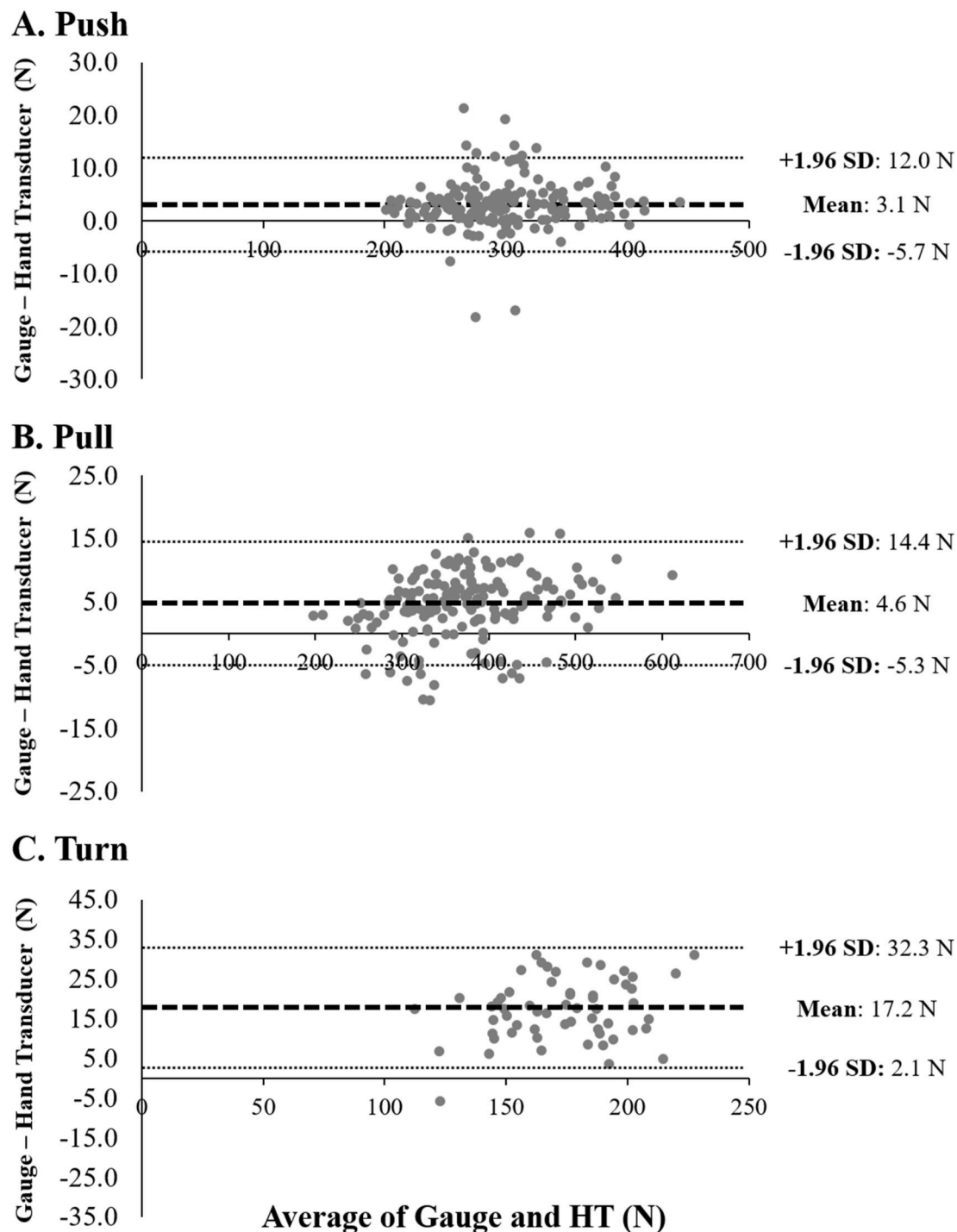


Fig. 4. Error between peak force reading from the single-axis force gauge and the peak horizontal component of force from the hand transducer (N) for (A) pushing, (B) pulling, and (C) turning exertion types across test conditions using the single-axis force gauge at all paces (self-selected, fast, slow). The single-axis force gauge tended to overestimate slightly, most so during cart turning.

dimensional hand transducer because there was a larger moment arm between the cart handle and center of rotation of the cart in this direction. In contrast, subjects were required to change their direction of force application during trials collected with the single-axis gauge, orienting their force less laterally and more normal to the three-dimensional hand transducer. Otherwise, the single-axis gauge would have slipped off of the handle of the three-dimensional hand transducer.

The results of this study should of course be placed in context with its limitations. First, the study was run under laboratory conditions. Unfortunately, the floor of the laboratory was not completely level in the

longer direction of the motion capture space, which required subjects to push and pull the cart along the shorter dimension of the room. Thus, during pushing and pulling exertion types, subjects only pushed or pulled for 3 m, as opposed to the 10 m distance recommended in ISO 11228-2 (Standards, 2007). Given that the highest risk for injury is associated with the peak push/pull force associated with the exertion and the peak generally occurs during the initial (first meter) phase, the authors did not see this smaller 3 m distance as too problematic for generalization of the results. However, this could be seen more so as a limitation if practitioners are interested in assessing sustained push/pull

forces, consistent with recommendations from Snook and Ciriello (1991). Additionally, participants were college-aged with little to no familiarity with the push/pull force testing procedure, nor did subjects have any significant prior experience performing push/pull testing. However, the use of inexperienced subjects allowed for observation of the 'worst-case' scenario in the study, potentially resulting in less precise peak force estimates during test conditions using the single-axis force gauge than a population that is experienced (i.e., ergonomics practitioners) might have derived. It is possible that performing the same experiment with experienced subjects would have yielded a better level of agreement among the test conditions, particularly between natural test conditions and single-axis force gauge test conditions. Nonetheless, it was encouraging to note that even inexperienced subjects were capable of exerting push/pull forces horizontally using the single-axis gauge with little other training or practice, at least at the handle height tested (100 cm). That being said, the handle height tested was also fairly optimal, and data was not collected for lower or higher handle heights to determine if subjects would be as successful at exerting push/pull forces horizontally in those circumstances. Finally, the cart weights tested (680 and 907 kg) were both rather heavy. Future studies should aim to investigate similar dependent measures to those tested herein with much lighter cart weights, since it is unclear how the results would change under these circumstances. It is expected that the self-selected initial and sustained velocities of the cart during natural pushing and pulling would increase even further at much lighter cart weights. In that scenario, even the fast pace recommended herein could still underestimate push/pull forces.

5. Conclusion

A single-axis hand held force gauge can accurately approximate pushing and pulling forces relative to a 'gold-standard' three-dimensional hand transducer, assuming pushing and pulling forces are exerted horizontally against the cart handle with the single-axis force gauge. Current best practices surrounding push/pull force testing laid out in ISO 11228-2 (Standards, 2007) may underestimate the pushing and pulling forces that workers actually encounter in a real work context. Push/pull forces should be tested with a faster initial acceleration and sustained velocity if practitioners are to accurately approximate push/pull forces for use in context with available pushing and pulling guidelines. In straight pushing and pulling exertions, it is recommended that practitioners move the cart the first meter in 3 s and keep the cart at a sustained velocity of 0.5 m/s thereafter. Future work

needs to be done relative to recommendations for best practices for cart turning.

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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