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The Liberty Mutual manual materials handling (LM-MMH) equations

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ABSTRACT

We summarise more than 40 years of Liberty Mutual psychophysical research on lifting, lowering, pushing, pulling and carrying, including the 7 studies used to develop the 1991 Liberty Mutual Tables and 12 subsequent studies. Predictive equations were developed based on 612 mean maximum acceptable loads (MALs), representing 388 unique conditions from 123 female and 149 male participants, starting with a maximum reference load that is scaled based on frequency, height, distance (vertical for lift & lower, horizontal for push, pull and carry tasks) and horizontal reach (for lift & lower tasks). Representative coefficients of variation are provided to allow for the calculation of MALs for any percentile. Each equation performed well and, overall, they explained 90% of the variance in MAL values, with RMS differences of 6.7% and 4.8% of the full range for females and males, respectively. We propose that these equations replace the 1991 Liberty Mutual Tables.

Practitioner summary: We propose predictive equations to replace the 14 manual materials handling tables in Snook and Ciriello (1991). These equations are based on 12 more publications, matched the empirical data well, are easier to use and allow for both a wider range and more specific inputs than the tables.

Abbreviations: ANSUR: anthropometric survey of U.S. army personnel; C: Coupling; CV: coefficient of variation; DH: displacement horizontal; DV: displacement vertical; F: frequency; H: horizontal reach; LM: Liberty Mutual Insurance; MAL: maximum acceptable load; MMH: manual materials handling; RL: reference load; SF: scale factor; V: vertical height; VRM: vertical range middle

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Psychophysics; lifting; lowering; pushing; pulling; carrying; acceptable loads

1. Introduction

Manual materials handling (MMH) involves the lifting, lowering, pushing, pulling or carrying of physical loads. According to the 2020 Workplace Safety Index, in 2017 overexertion associated with these tasks was the leading cause of disabling injuries and cost United States businesses ~$14 billion in direct costs (Liberty Mutual Insurance 2020). During the 20 years the Liberty Mutual Workplace Safety Index has been published, overexertion remained the leading cause of costs associated with disabling injuries. Low back pain, the leading driver of overexertion costs, is the single biggest cause of years lived with disability worldwide (James et al., 2018). Most ergonomics assessments of MMH tasks use some combination of epidemiological, biomechanical, physiological, and psychophysical criteria (Waters et al. 1993). Psychophysics is the study of the relationship between the intensity of a physical stimulus and the strength of its perception. As early as 1957, Stevens demonstrated a nonlinear relationship between the actual and perceived weight of a lift, with sensitivity being higher at lower weights (Stevens 1957).

Liberty Mutual Insurance was the first to use the psychophysical methodology to study occupational tasks, with the goal of setting acceptable limits for loads and forces so that injuries could be prevented through ergonomic task design (Snook and Irvine 1967). Their subsequent studies of lift, lower, push, pull, and carry tasks typically manipulated the vertical height of the handles, distance travelled and frequency – along with box size for lifting, lowering, and carrying tasks – and trained participants over 10 weeks. Participants selected weights for lift, lower, and carry tasks, or initial forces (required to get the

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load moving) and sustained forces (required to keep the load moving) for push and pull tasks, that would be acceptable over an 8-hour workday.

This database resulted in the development of Liberty Mutual MMH tables first published in 1978 (Snook 1978) and then revised 13 years later (Snook and Ciriello 1991). Since then, the revised tables have been a very popular resource for ergonomists and, along with data from other psychophysical studies (Ayoub et al. 1978), were instrumental in the development of the Revised NIOSH Lifting Equation (RNLE) (Waters et al. 1993). A recent survey (Lowe, Dempsey, and Jones 2019) found that MMH psychophysical tables are the tool most commonly tool used by Canadian ergonomists and the third most commonly used tool in the United States, after the Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993) and the RNLE (Waters et al. 1993).

In the 20 years that followed the revised MMH tables, Ciriello and his colleagues continued to conduct and publish psychophysical studies of MMH tasks at the Liberty Mutual Research Institute for Safety (Ciriello 2007, 2005, 2004a, 2004b, 2003, 2002, 2001; Ciriello et al. 2011, 2010, 2008, 2007, 1999). However, with the retirements of Dr. Snook and Dr. Ciriello and the closing of the Institute in 2017, the data from the 12 newer publications were never synthesised into an updated revision of the MMH tables. The purpose of this paper is to collate the data from 7 publications incorporated into the revised tables (Snook and Ciriello 1991), with the data from the 12 publications of new data that followed, to develop equations that predict maximum acceptable loads (MALs) for females and males for lift, lower, push (initial and sustained), pull (initial and sustained), and carry tasks.

2. Methods

2.1. Conditions

We pooled the original empirical MAL data presented in 19 publications from psychophysical studies of manual materials handling conducted over more than 40 years at the Liberty Mutual Research Institute for Safety. The tasks included in each publication are summarised in Table 1. There was a total of 14 dependent variables representing separate MAL values for lift, lower, push initial, push sustained, pull initial, pull sustained, and carry for both females and males. Compared to the 7 studies used in Snook and Ciriello (1991), the addition of 12 more studies to develop our equations resulted in a 129% increase in the total number of participants, including a 141% increase in females.

Within the 19 publications, there were 612 MALs presented from a total of 123 female and 149 male participants and an average of 14.0 participants per MAL (Table 2). Given that some combinations of the independent variables – height, distance, frequency and box width – were presented in multiple publications, there were a total of 388 unique combinations of those independent variables producing mean MALs for the 14 dependent variables – an average of 22.1 participants per unique combination. In cases where mean MALs from the same combination of independent variables were presented in multiple publications, a weighted average of the MAL was calculated for that condition based on the mean MALs and the number of participants contributing to each mean. These weighted averages were assumed to represent the 50th percentile MAL values for females or males. Of these 388 unique combinations with MALs, 46% were with females and 54% were with males, and the relative distribution across task output, in descending order, was lift (28.9%), lower (18.3%), push sustained (16.0%), push initial (14.9%), carry (13.9%), pull sustained (4.1%) and pull initial (3.9%). Compared to the 7 studies used in Snook and Ciriello (1991), the addition of 12 more studies to develop our equations resulted in 140 (30%) more conditions with MAL values, 50 (15%) more unique combinations of conditions and data collected from 1,976 (30%) more condition participants.

2.2. Anthropometry

In the Liberty Mutual psychophysical experiments, all task heights were relative to anatomical landmarks on the individual participants (ie. knee, knuckle, elbow, shoulder, and arm reach). Carry tasks were performed with the hands at (1) elbow and (2) knuckle height. Lift and lower tasks were in the ranges from (1) floor-to-knuckle, (2) knee-to-elbow, (4) knuckle-to-shoulder and (4) shoulder-to-arm reach height. Push & pull tasks were performed with the hands at (1) 0.15 m below knuckle height, (2) midway between the knuckle & elbow, and (3) shoulder height.

Reference heights in the present synthesis were estimated using 50th percentile values from ANSUR II (anthropometric survey of U.S. Army personnel) to be representative of the population (Gordon et al. 2014) (Table 3). Some values were taken directly from ANSUR II (Gordon et al. 2014), including knee height, wrist height, wrist-to-grip length, elbow height (based

Table 1. Summary of the 19 Liberty Mutual publications of maximum acceptable loads for manual materials handling tasks used to develop the equations.

		Female: number of mean MAL values						Male: number of mean MAL values				
Publication	*n*	Lift	Lower	Push	Pull	Carry	*n*	Lift	Lower	Push	Pull	Carry
Snook (1971)*							**28**	9	9	12	3	18
Snook & Ciriello (1974a)*							**16**	1		1		1
Snook & Ciriello (1974b)*	**15**	6	6	8	2	12						
Ciriello & Snook (1978)*							**14**	41		16	4	
Ciriello & Snook (1983)*	**12**	58	16	27	3	7	**10**	16	16	12		7
Ciriello et al. (1990)*	**12**	6	6	1	2	1	**10**	6	6	1	2	1
Ciriello, Snook, and Hughes (1993)*							**6**	28		1	1	12
Ciriello et al. (1999)							**6**			2		
Ciriello (2001)							**6**	4	12			
Ciriello (2002)							**8**			2	2	
Ciriello (2003)							**8**	15				
Ciriello (2004a)	**10**			2	2							
Ciriello (2004b)	**11**			2								
Ciriello (2005)	**10**	4	12	2	1	2						
Ciriello (2007)	**10**	15										
Ciriello et al. (2007)							**14**			2		
Ciriello et al. (2008)							**23**	6	6	2	2	2
Ciriello et al. (2010)	**19**			2								
Ciriello et al. (2011)	**24**	6	6	2	2	2						
Total n and Publications	123	6	5	8	6	5	149	9	5	10	6	6

The publications are shown with the number of participants studied (*n*) and the number of mean MAL values presented for each task type. Totals are provided for the number of female and male participants (total $n = 272$) and the number of publications with data for each task type for females and males. For example, Ciriello (2005) was one of 5 studies of female lowering, and they published data from 10 female participants and 12 different lowering conditions. Studies marked with "*" were used to develop the tables in Snook and Ciriello (1991), though the data in Ciriello, Snook, and Hughes (1993) were unpublished at the time.

Table 2. Summary of the total number of conditions with mean MAL values in the 19 Liberty Mutual publications used to develop the equations, as well as the number of unique combinations of vertical handle height, distance, frequency, and horizontal reach used to create each of the 14 equations.

		Conditions with MAL Values			Unique Combinations	
Task	Gender	Conditions	Total *n*	Mean *n*	Combinations	Mean *n*
Lift	Female	95	1,192	12.5	54	22.1
	Male	126	1,510	12.0	58	26.0
Lower	Female	46	618	13.4	34	18.2
	Male	49	706	14.4	37	19.1
Push						
Initial	Female	39	499	12.8	26	19.2
	Male	47	788	16.8	32	24.6
Sustained	Female	46	604	13.1	30	20.1
	Male	48	804	16.8	32	25.1
Pull						
Initial	Female	11	153	13.9	6	25.5
	Male	14	226	16.1	9	25.1
Sustained	Female	12	168	14.0	7	24.0
	Male	14	226	16.1	9	25.1
Carry	Female	24	344	14.3	22	15.6
	Male	41	718	17.5	32	22.4
Total per Gender	Female	273	3,578	13.1	179	20.0
	Male	339	4,978	14.7	209	23.8
Totals per Task	Lift	221	2,702	12.2	112	24.1
	Lower	95	1,324	13.9	71	18.6
	Push	180	2,695	15.0	120	22.5
	Pull	51	773	15.2	31	24.9
	Carry	65	1,062	16.3	54	19.7
	19 Studies (Equations)	**612**	**8,556**	**14.0**	**388**	**22.1**
	7 Studies (1991 Tables)	**472**	**6,580**	**13.9**	**338**	**19.5**

Values are also provided for the total and the mean number of participants (*n*) for each. The totals from the 7 studies used to develop the Liberty Mutual Tables (Snook and Ciriello 1991) are also provided for comparison.

Table 3. Summary of anatomical landmark heights assumed from the ANSUR II database (Gordon et al. 2014) and the vertical range middle (VRM) values calculated with those landmarks.

	Height (m)	
Landmarks and VRMs	Female	Male
Arm Reach	1.96	2.14
Shoulder-to-Arm Reach VRM	1.65	1.79
Stature	1.63	1.76
Shoulder	1.33	1.44
Knuckle-to-Shoulder VRM	1.03	1.11
Elbow	1.02	1.10
Knuckle-to-Elbow VRM	0.88	0.94
Knee-to-Elbow VRM	0.74	0.80
Knuckle	0.73	0.78
Knuckle − 0.15 m	0.58	0.63
Knee	0.45	0.49
Floor-to-Knuckle VRM	0.37	0.39

on the inferior aspect of the ulna's olecranon with the elbow flexed 90 deg), shoulder height, stature, and arm reach (ie. 'vertical grip reach'). The height of the knuckle was assumed to be the wrist height minus the wrist-to-grip length. The height of the elbow joint centre was assumed to be 0.02 m superior to the landmark used in ANSUR II. Additional heights were calculated for the vertical range middle (VRM) of the floor-to-knuckle, knee-to-elbow, knuckle-to-elbow, knuckle-to-shoulder and shoulder-to-arm reach ranges. The VRM was calculated as the average of the knuckle heights at the origin and destination of lifts and lowers. Separate values were calculated for females and males, and all final heights were rounded to 0.01 m after the calculations. For example, the VRM of the female knuckle-to-shoulder range was calculated as the mean of the knuckle height (wrist height minus wrist-to grip length $= 0.794 - 0.0663 = 0.7277$ m, rounded to 0.73 m) and shoulder height (1.3320 m, rounded to 1.33 m) for a value of $[0.7277 + 1.3220]/2 = 1.02985$ m, rounded to 1.03 m.

2.3. Equation development

A total of 14 equations were developed – one for each table in Snook and Ciriello (1991) – including female and male versions of (1) Lift, (2) Lower, (3) Push – Initial, (4) Push – Sustained, (5) Pull – Initial, (6) Pull – Sustained, and (7) Carry equations. Generally, there were not enough mean MAL values available, within each of the 14 combinations of gender and task output, to allow for the use of a multivariate regression approach because the resulting equations overfit the empirical data and, thus, were not generalisable to all feasible task condition inputs. Instead, we tested the assumption that there were no interaction effects between independent variables and developed 1st, 2nd and 3rd order polynomial 'scale factor formulas' for each relevant independent variable to represent its effect on the weighted average of MALs pooled within each level of that independent variable. For example, the independent variable representing the displacement horizontal (DH) for Carry tasks had three levels (2.1, 4.3 and 8.5 m) and the Carry – Female scale factor formula for this variable (DH_{SF}) was developed with those three inputs and the pooled weighted average MAL within each of those three levels. We repeated the 1st, 2nd and 3rd order polynomials but with the scale factor formula inputs being the natural log of each level of the independent variables (eg. $\ln[2.1] = 0.742$, $\ln[4.3] = 1.459$ and $\ln[8.5] = 2.140$) and ultimately used the method providing the best prediction of mean MAL values based on the relevant inputs. In addition to the scale factor formula for DH, the Carry tasks also had formulas representing the effects of vertical height (V) of the hands and frequency (F) on the pooled weighted average MAL values.

We then used the first derivative of each scale factor formula to predict the value of the input that would result in the highest predicted MAL, within a feasible range of inputs. Each scale factor formula was subsequently normalised to that maximum value so that the resulting formula never predicted a value above 1.0 for the range of inputs. Each of the 14 equations was comprised of the scale factor formulas for the associated independent variables and a 'reference load' (RL). Once the individual scale factor formulas were established for each equation, an iterative approach was used to determine the reference load to multiply them by such that it minimised the RMS difference between the empirical MAL weighted means and the equation outputs. As such, the reference load for each equation represented the highest possible MAL magnitude from that equation. More details are provided below for each specific task type.

2.3.1. Lift and lower equations

During the psychophysical studies, the original lift and lower independent variables were (1) box width – measured anterior to the body, (2) box length – measured between the handles, (3) vertical range middle (VRM), (4) vertical displacement of the hands with half occurring on either side of the VRM, and (5) time per lift or lower – converted to frequency per minute (F) for our analyses and subsequent equations. Separate equations were developed for lifting and lowering for both females and males. Only one study included lift and lower tasks with no handles (Ciriello, Snook, and Hughes 1993) so only data including handles were used to develop the equations presented here.

Box widths were categorised as 'small' (0.33–0.36 mm), 'medium' (0.48–0.49 m), 'large' (0.75–0.76 m), and 'extra-large' (0.96 m). For each category, a weighted average box width was calculated across all relevant conditions and these were: small = 0.355 m, medium = 0.487 m, large = 0.754 m and extra-large = 0.960 m. Box widths were converted to horizontal reach (H) from the ankle to the knuckle, as defined for the Revised NIOSH Lifting Equation (Waters, Putz-Anderson, and Garg, 1994), by assuming a horizontal distance from the ankle-to-toe of 0.20 m for females and 0.25 m for males, such that the horizontal reaches for each box were assumed to be that distance, plus half the box width, and then rounded to 0.01 m. This procedure resulted in the following horizontal reaches for each box width for females and males, respectively: small H = 0.38 & 0.43 m, medium H = 0.44 & 0.49 m, large H = 0.58 & 0.63 m and extra-large H = 0.68 & 0.73 m, respectively.

Box length effects were studied during lifting by females (Ciriello & Snook, 1983) and males (Ciriello & Snook, 1978), and there was no significant effect of increasing the distance between the handles from 0.57 m to 0.89 m in either study, so box length was not included as an independent variable in our equations. In addition to H and VRM, the other two independent variables used in the Lift and Lower equations were: (1) distance travelled vertically (DV) by the hands – which included 0.25 m, 0.51 m and 0.76 m, and (2) frequency per minute (F) – which included various combinations of 15 different frequencies ranging from 1/day (~0.0021/min) to 20/min (Figure 1). The product of displacement (per effort) and frequency (per minute) represents the mean velocity of a task condition. For lifting and lowering, the highest mean velocity (DV x F) studied was (0.51 m)(20/min) = 10.2 m/min.

There were 54 (female) and 58 (male) unique combinations of H, VRM, DV and F published for lift tasks (Table 2) and this was sufficient to develop generalisable scale factor formulas for H (ie. H_{SF}), VRM (ie. VRM_{SF}), DV (ie. DV_{SF}), and F (ie. F_{SF}). In the original Liberty Mutual studies, the largest vertical displacement was DV = 0.76 m. To extend our Lift and Lower equations beyond this vertical distance constraint, psychophysical data summarised in NIOSH (1981) and Mital, Nicholson, and Ayoub (1993), for multiple ranges (ie. floor-to-shoulder, floor-to-arm reach, and knuckle-to-arm reach), were incorporated to determine DV_{SF} formulas for inputs up to DV = 1.96 m for

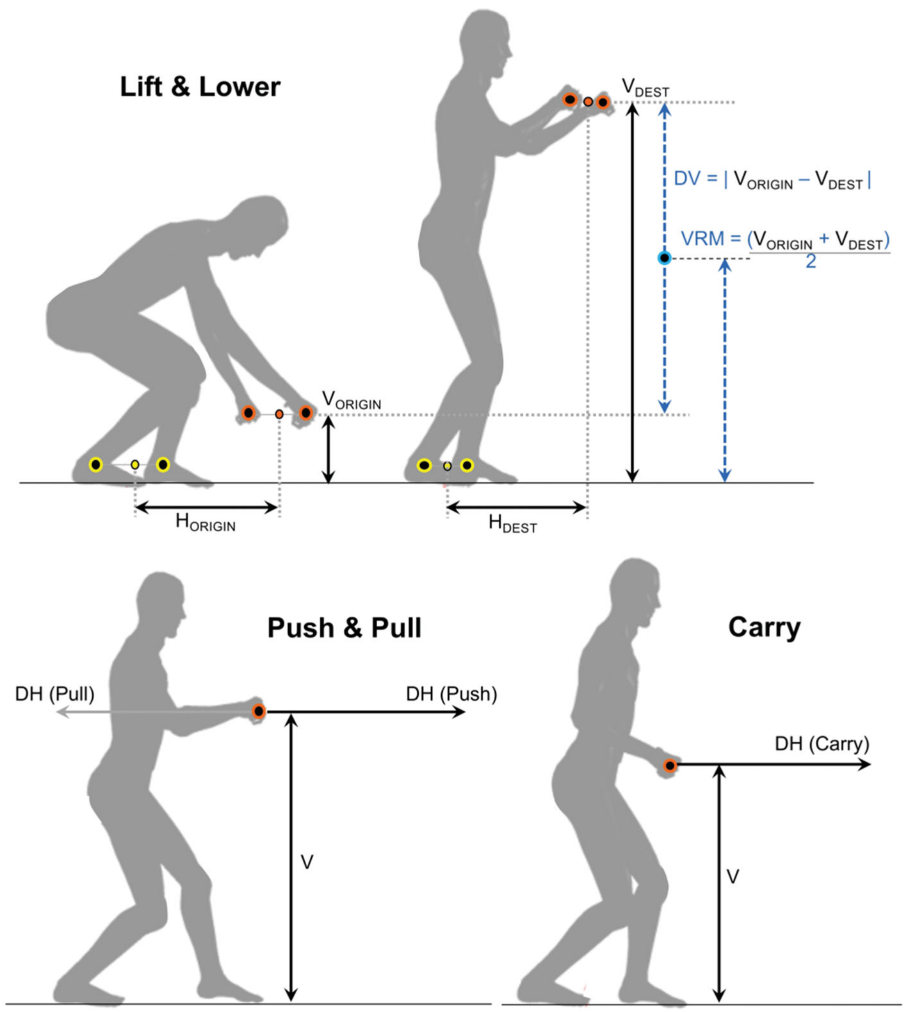

Figure 1. Illustration of the equation inputs. For the Lift and Lower equations, horizontal reach (H) is measured horizontally from the midpoint of the ankles to the midpoint of the hands, vertical height at the origin (V_{ORIGIN}) and destination (V_{DEST}) are measured from the ground to the midpoint of the hands (a lift is shown), displacement vertical (DV) is calculated as the absolute difference between V_{ORIGIN} and V_{DEST} and the vertical range middle (VRM) is calculated as the average of V_{ORIGIN} and V_{DEST}. For the Push, Pull and Carry equations, vertical height (V) is measured from the floor to the midpoint of the hands and displacement horizontal (DH) is the displacement of push, pull or carry.

females and DV = 2.14 m for males. In addition, the horizontal reach scale factor formulas (H_{SF}) were extrapolated back to allow for minimum H values of 0.20 m and 0.25 m for females and males, respectively.

There were 34 (female) and 37 (male) unique combinations of H, VRM, DV and F published for lower tasks (Table 2). Further, there were empirical lowering data from 2 female and 3 male conditions in the shoulder-to-arm reach range, 8 conditions for both females and males at frequencies less than 1/min, and 7 female and 9 male conditions at frequencies greater than 4.3/min. This did not allow for the development of reliable scale factor formulas for H_{SF}, VRM_{SF}, D_{SF} and F_{SF} that were representative of the full range of feasible inputs. However, there were 72 occurrences where the same combination of H, VRM, DV and F was collected for lift and lower tasks within the same publication, allowing trends between lift and lower MAL values to be evaluated. For these 72 conditions, the Lower MAL was divided by the Lift MAL to calculate a lower/lift ratio. For females, there were no systematic differences between the lift and lower tasks for the effects of H, VRM, DV or F, so the scale factor formulas from the Lift – Female equation (for H_{SF}, VRM_{SF}, DV_{SF} and F_{SF}) were also used for the Lower – Female equation. However, the Lower – Female MALs were an average of 6% greater than the Lift – Female MALs, and this was accounted for by increasing the Lower – Female reference load to 37.0 kg by multiplying the Lift – Female RL (34.9 kg) by 1.06. For males, frequency was the only independent variable that affected the lower/lift ratios, so a separate F_{SF} formula was determined for the Lower – Male equation. Also, the Lower – Male MALs were an average of 16.1% higher than the Lift – Male MALs, and this was accounted for by increasing the Lower – Male reference load to 95.9 kg by multiplying the Lift – Male RL (82.6 kg) by 1.161.

2.3.2. Push and pull equations

The original push and pull task-independent variables were (1) height of the handles (V), (2) displacement of the load horizontally for each effort (DH), and (3) time per lift – converted to frequency per minute (F) for our analyses and subsequent equations (Figure 1). The push tasks had 26 initial and 30 sustained (female) and 32 initial and 32 sustained (male) unique combinations of V, DH and F published for push tasks (Table 2) and this was sufficient to develop generalisable scale factor formulas for V_{SF}, DH_{SF} and F_{SF}. Separate Push – Initial, Push – Sustained, Pull – Initial and Pull – Sustained equations were developed for females and males. The V_{SF} scale factor formulas were developed with MALs corresponding to three 3 vertical heights: (1) 0.15 m below the knuckle ($V = 0.58$ m for females, $V = 0.63$ m for males), (2) between the knuckle and elbow ($V = 0.74$ m for females, $V = 0.80$ m for males), and (3) shoulder height ($V = 1.33$ m for females, $V = 1.44$ m for males) (Table 3). The DH_{SF} formulas were developed with MALs corresponding to some combination of 6 distances per push or pull (2.1, 7.6, 15.2, 30.5, 45.7 and 61.0 m). The F_{SF} formulas were developed with MALs corresponding to various combinations of 17 frequencies ranging from 1/day (~0.0021/min) to 10/min. The highest mean velocity studied for pushing or pulling (DH x F) was (15.2 m)(2.4/min) = 36.5 m/min.

There were 6 initial and 7 sustained (female) and 9 initial and 9 sustained (male) unique combinations of V, DH and F (Table 2) published for the pull task. This did not allow for the development of reliable scale factor formulas for V (ie. V_{SF}), DH (ie. DH_{SF}), and F (ie. F_{SF}) that were representative of the full range of feasible inputs. However, there were 22 occurrences where the same combination of V, DH and F was collected for push and pull tasks within the same publication, allowing for trends between Push and Pull MAL values to be evaluated. For each of these 22 conditions, the Pull MAL was divided by the Push MAL to calculate a pull/push ratio. For females, these ratios were generally close to 1.0, such that there were no systematic differences between Push and Pull MAL values, so the Push-Initial-Female and Push-Sustained-Female equations are also recommended for use for Pull-Initial-Female and Pull-Sustained-Female tasks, respectively. For males, vertical height was the only independent variable that affected the pull/push ratios, so separate V_{SF} formulas were determined for the Pull-Initial-Male and Pull-Sustained-Male equations. For the initial tasks, a regression equation was developed to output pull/push ratios based on the input of V, and this was combined with the Push-Initial-Male V_{SF} scale factor formula and reference load (70.3 kg) to establish a new Pull-Initial-Male V_{SF} formula and reference load (69.8 kg). Similarly, for the male sustained tasks, a regression equation was developed to output pull/push ratios with the input of V, and this was combined with the Push-Sustained-Male V_{SF} formula and reference load (65.3 kg) to establish a new Pull-Sustained-Male V_{SF} formula and reference load (61.0 kg).

2.3.3. Carry equations

There were 19 (female) and 24 (male) unique combinations of V, DH and F published for carry tasks (Table 2) and this was sufficient to develop generalisable scale factor formulas for V_{SF}, DH_{SF} and F_{SF}. Separate Carry equations were developed for females and males. The original carry task-independent variables were (1) height of the hands during the carry (V), (2) box width, (3) box length, (4) displacement of the load horizontally each effort (DH), and (5) time per lift – converted to frequency per minute (F) for our analyses and subsequent equations (Figure 1). Box widths (distances away from the body) explained only 18% and 1% of the variance in MAL values for females and males, respectively (Supplementary Table S1). In addition, there were 3 (female) and 5 (male) unique combinations of V, DH and F with more than one box length (distances between hands) with which to base a correction. Further, Ciriello, Snook, and Hughes (1993) found no significant effect of box size on carry MAL values. Thus, box width and box length were eliminated as input variables for the Carry equations.

The V_{SF} formulas were developed with MALs corresponding to two vertical heights: (1) knuckle height ($V = 0.73$ m for females, $V = 0.78$ m for males) and (2) elbow height ($V = 1.02$ m for females, $V = 1.10$ m for males). The DH_{SF} formulas were developed with MALs corresponding to 3 distances per carry (2.1, 4.3, and 8.5 m). The F_{SF} formulas were developed with MALs corresponding to some combination of 17 frequencies ranging from 1/day (~0.0021/min) to 10/min.

The highest mean velocity studied for carrying (DH x F) was (8.5 m)(3.3/min) = 28.1 m/min.

2.4. Statistics

For each unique combination of inputs (Table 2), a difference was calculated with the 50th percentile MALs predicted with the equations minus the corresponding weighted averages of the empirical MAL values. Equation outputs were also compared to the 50% capable MALs from the revised Liberty Mutual Tables (Snook and Ciriello 1991), including 184 conditions with feasible reaches from each Lift and Lower table, the 105 values from each Push-Initial, Push-Sustained, Pull-Initial, and Pull-Sustained table and the 42 values from each Carry table. For each of the 14 equations, mean and RMS differences were calculated. RMS differences and r-squared values were also calculated across all conditions for females ($n = 179$ empirical means, 730 Liberty Mutual Table values) and males ($n = 209$ empirical values, 830 Liberty Mutual Table values) and across all conditions ($n = 388$ empirical values, 1,660 table values).

Coefficients of variation (CV) were calculated with each weighted average MAL and its standard deviation. We analysed each of the 14 combinations of task output and gender, to determine if there was a systematic effect of any of the independent variables on the CV values. However, no such relationships were observed, so a single representative CV was calculated with the pooled mean within all conditions for each of the 14 equations.

3. Results

A total of 14 equations were developed, representing each combination of the 7 task outputs for females and males. The equations output the maximum acceptable load (MAL) outputs for the 50th percentile (ie. 50% capable) in kg. Coefficients of variation (CV) are provided so that standard deviations can be estimated with each unique MAL output from an equation.

3.1. *Lift* and lower equations

The Lift and Lower equations have the form: $MAL = RL\ [H_{SF}]\ [VRM_{SF}]\ [DV_{SF}]\ [F_{SF}]$

Lift – Female

$$MAL = 34.9\left[1.2602 - \frac{H}{0.7686}\right]\left[0.9877 + \frac{VRM}{13.69} - \frac{VRM^2}{9.221}\right]\left[0.8199 - \frac{\ln(DV)}{7.696}\right]\left[0.6767 - \frac{\ln(F)}{12.59} - \frac{\ln(F)^2}{228.2}\right]$$

CV = 0.260

Lift – Male

$$MAL = 82.6\left[1.3532 - \frac{H}{0.7079}\right]\left[0.7746 + \frac{VRM}{1.912} - \frac{VRM^2}{3.296}\right]\left[0.8695 - \frac{\ln(DV)}{10.62}\right]\left[0.6259 - \frac{\ln(F)}{9.092} - \frac{\ln(F)^2}{125.0}\right]$$

CV = 0.276

Lower – Female (note: only the RL and CV values are different from the Lift – Female equation)

$$MAL = 37.0\left[1.2602 - \frac{H}{0.7686}\right]\left[0.9877 + \frac{VRM}{13.69} - \frac{VRM^2}{9.221}\right]\left[0.8199 - \frac{\ln(DV)}{7.696}\right]\left[0.6767 - \frac{\ln(F)}{12.59} - \frac{\ln(F)^2}{228.2}\right]$$

CV = 0.307

Lower – Male (note: only the RL, F_{SF}, and CV values are different from the Lift – Male equation)

$$MAL = 95.9\left[1.3532 - \frac{H}{0.7079}\right]\left[0.7746 + \frac{VRM}{1.912} - \frac{VRM^2}{3.296}\right]\left[0.8695 - \frac{\ln(DV)}{10.62}\right]\left[0.5773 - \frac{\ln(F)}{10.80} - \frac{\ln(F)^2}{255.9}\right]$$

CV = 0.304

Where:

RL is the maximum possible (reference) load from the equations (kg), VRM is the vertical range middle (m) calculated as the mean of the minimum and maximum heights, DV is the distance travelled vertically each lift or lower (m), H is the horizontal reach distance to the handles (m), and F is the frequency per minute.

Constraints:

- Horizontal reach distance (H) must range from 0.20 to 0.68 m for females and 0.25 to 0.73 m for males. If H changes during a lift or lower, the mean H or maximum H can be used.
- Maximum vertical height of the hand is calculated as $VRM + DV/2$ and must not exceed arm reach for the anthropometry being used (e.g. 1.96 m and 2.14 m for 50th percentile females and males, respectively, Table 3).

- Distance travelled vertically (DV) per lift or lower must not be lower than 0.25 m or exceed arm reach for the anthropometry being used.
- Frequency (F) must range from 1 per day (i.e. 1/480 = ~0.0021/min) to 20/min.
- Mean vertical velocity is calculated as DV x F and must not exceed 11 m/min.

3.2. Push and pull equations

The Push and Pull equations have the form: $MAL = RL\ [V_{SF}]\ [DH_{SF}]\ [F_{SF}]$

Push or Pull – Initial – Female

$$MAL = 36.9\left[-0.5304 + \frac{V}{0.3361} - \frac{V^2}{0.6915}\right]\left[1.0286 - \frac{DH}{72.22} + \frac{DH^2}{9782}\right]\left[0.7251 - \frac{\ln(F)}{13.19} - \frac{\ln(F)^2}{197.3}\right]$$

CV = 0.214 for Push – Initial – Female, CV = 0.234 for Pull – Initial – Female

Push or Pull – Sustained – Female

$$MAL = 25.5\left[-0.6539 + \frac{V}{0.2941} - \frac{V^2}{0.5722}\right]\left[1.0391 - \frac{DH}{52.91} + \frac{DH^2}{7975}\right]\left[0.6086 - \frac{\ln(F)}{11.95} - \frac{\ln(F)^2}{304.4}\right]$$

CV = 0.286 for Push – Sustained – Female, CV = 0.298 for Pull – Sustained – Female

Push – Initial – Male

$$MAL = 70.3\left[1.2737 - \frac{V}{1.335} + \frac{V^2}{2.576}\right]\left[1.0790 - \frac{\ln(DH)}{9.392}\right]\left[0.6281 - \frac{\ln(F)}{13.07} - \frac{\ln(F)^2}{379.5}\right]$$

CV = 0.231

Push – Sustained – Male

$$MAL = 65.3\left[2.2940 - \frac{V}{0.3345} + \frac{V^2}{0.6887}\right]\left[1.1035 - \frac{\ln(DH)}{7.170}\right]\left[0.4896 - \frac{\ln(F)}{10.20} - \frac{\ln(F)^2}{403.9}\right]$$

CV = 0.267

Pull – Initial – Male (note: only the RL, V_{SF}, & CV values are different from the Push – Initiate – Male equation)

$$MAL = 69.8\left[1.7186 - \frac{V}{0.6888} + \frac{V^2}{2.025}\right]\left[1.0790 - \frac{\ln(DH)}{9.392}\right]\left[0.6281 - \frac{\ln(F)}{13.07} - \frac{\ln(F)^2}{379.5}\right]$$

CV = 0.238

Pull – Sustained – Male (note: only the RL, V_{SF}, & CV values are different from the Push – Sustain – Male equation)

$$MAL = 61.0\left[2.1977 - \frac{V}{0.3850} + \frac{V^2}{0.9047}\right]\left[1.1035 - \frac{\ln(DH)}{7.170}\right]\left[0.4896 - \frac{\ln(F)}{10.20} - \frac{\ln(F)^2}{403.9}\right]$$

CV = 0.257

Where:

RL is the maximum possible (reference) load from the equations (kg), V is the vertical height of the hands (m), DH is the distance travelled horizontally per push or pull (m), and F is the frequency per minute.

Constraints:

- Vertical height of the hands during the push or pull (V) must range from 0.58 to 1.33 m for females and 0.63 to 1.44 m for males.
- Distance travelled horizontally (DH) per push or pull must range from 2.1 m to 61 m.
- Frequency (F) must range from 1 per day (i.e. 1/480 = ~0.0021/min) to 10/min.
- Mean horizontal velocity is calculated as DH x F and must not exceed 37 m/min.

3.3. Carry equations

The Carry equations have the form: $MAL = RL\ [V_{SF}]\ [DH_{SF}]\ [F_{SF}]$

Carry – Female

$$MAL = 28.6\left[1.1645 - \frac{V}{4.437}\right]\left[1.0101 - \frac{DH}{207.8}\right]\left[0.6224 - \frac{\ln(F)}{16.33}\right]$$

CV = 0.231

Carry – Male

$$MAL = 74.9\left[1.5505 - \frac{V}{1.417}\right]\left[1.1172 - \frac{\ln(DH)}{6.332}\right]\left[0.5149 - \frac{\ln(F)}{7.958} - \frac{\ln(F)^2}{131.1}\right]$$

CV = 0.278

Where:

RL is the maximum possible (reference) load from the equations (kg), V is the vertical height of the hands (m), DH is the distance travelled horizontally per carry (m), and F is the frequency per minute.

Constraints:

- Vertical height of the hands (V) during the carry must range from 0.71 to 1.03 m for females and 0.78 to 1.10 m for males.
- Distance travelled horizontally (DH) per carry must range from 2.1 m to 10 m.
- Frequency (F) must range from 1 per day (i.e. 1/480 = ~0.0021/min) to 10/min.
- Mean horizontal velocity is calculated as DH x F and must not exceed 29 m/min.

3.4. Example

An example is provided to illustrate the use and utility of the equations to determine (1) the percentage of females capable of a given load, and (2) the maximum load acceptable to 75% of females ($MAL_{75\%CAP}$). Designing for at least 75% of females has been identified as a criterion sensitive to injury risk for both males and females (Snook, Campanelli, and Hart 1978; Marras et al. 1999) and has been used as a minimum design threshold for manual handling tasks.

A task requires the repetitive lifting of 12 kg load with good coupling at a frequency of F = 1.0/min, from an origin height of 0.775 m to a destination height of 1.285 m with a reach of 0.38 m. For this example, DV = 1.285 − 0.775 = 0.51 m, VRM = (1.285 + 0.775)/2 = 1.03 m, and H = 0.38 m. The mean vertical velocity is (1.0) (0.51) = 0.51 m/min, which is well under the maximum limit of 11 m/min.

Next, the 50th percentile Lift – Female MAL is calculated as:

$$MAL = 34.9\left[1.2602 - \frac{0.38}{0.7686}\right]\left[0.9877 + \frac{1.03}{13.69} - \frac{1.03^2}{9.221}\right]\left[0.8199 - \frac{\ln(0.51)}{7.696}\right]\left[0.6767 - \frac{\ln(1)}{12.59} - \frac{\ln(1)^2}{228.2}\right]$$

$$MAL = 34.9\ [0.766]\ [0.948]\ [0.907]\ [0.677] = 15.56\ \text{kg}$$

Assuming CV = 0.260 for the Lift – Female data, the standard deviation is estimated to be (0.260)(15.56) = 4.05 kg. Thus, assuming a normal distribution with a mean of 15.56 kg and standard deviation of 4.05 kg, the actual load of 12 kg would be acceptable to 81.0% of females (using the 'NORM.DIST' function in Excel 16.44). With a z-score of −0.675 for the 25th percentile, the 75% capable value MAL ($MAL_{75\%CAP}$) would be:

$$MAL_{75\%CAP} = MAL - (MAL)(CV)(Z) = MAL\ [1 - (CV)(Z)] = 15.56[\ 1 - (0.260)(0.675)\ ] = 12.83\ \text{kg}$$

The following will illustrate how a difference value was calculated, between the equation outputs and empirical weighted average MAL values, for this condition. The empirical weighted average was based on 4 publications with data for this combination of H, VRM, DV and F (Ciriello & Snook, 1983; Ciriello et al. 1990; Ciriello et al. 2007; Ciriello et al. 2011). Across those studies, there was a total of 94 empirical values used to calculate a weighted average MAL of 13.34 kg. Thus, the difference for this condition is calculated as the 50th percentile MAL, predicted with the Lift – Female equation, minus the empirical weighted average MAL value, or 15.56 − 13.34 = 2.22 kg.

3.5. Comparisons with the empirical MAL data and the 1991 Liberty Mutual Tables

Overall, the equations matched the empirical weighted means very well and confirm that there were no significant interactions between the input variables' effects on the MAL values. For comparisons with the empirical weighted average MALs, the female equation MALs were an average of 0.4 kg lower (–1%), had an RMS difference of 2.5 kg (6.7%) and $r^2 = 0.78$ ($n = 179$ conditions), while the male equation MALs had no mean difference, had an RMS difference of 4.6 kg (4.8%) and $r^2 = 0.86$ ($n = 209$ conditions). Pooled across all 14 equations and conditions, there was a mean difference of −0.2 kg (–0.2%), RMS difference of 3.8 kg (3.9%), and $r^2 = 0.90$ ($n = 388$ conditions) (Table 4, Figure 2). The mean differences ranged from −1.1 kg (–3.1%, Lift) to +0.4 kg (+1.0%, Lower) for females and −1.5 kg (–1.8%, Lift) to 2.1 kg (+2.8%, Lower) for males. The RMS differences ranged from 1.6 kg (Pull – Sustained) to 3.0 kg (both Lift & Lower) for females and 1.7 kg Pull – Initial) to 6.3 kg (Lower) for males (Table 4).

For comparisons with the original Liberty Mutual Tables (Snook and Ciriello 1991), the equation MALs were an average of 1.4 kg higher when pooled across all 830 female table conditions, 1.2 kg lower when pooled across all 830 male table conditions and only 0.1 kg higher when pooled across all 1,660 revised table conditions. The mean differences ranged from the equation being 0.8 kg (–2.3%) below (Lower) to 3.0 kg (11.7%) above (Push – Sustained) the empirical means for females, and 7.3 kg (–10.4%) lower (Push – Initial) to 4.7 kg (11.7%) above (Carry) the empirical means for males (Table 4).

4. Discussion

In this paper, we introduce the fourteen Liberty Mutual Manual Materials Handling Equations ('LM-MMH

Table 4. Summary of the number of conditions, reference loads, mean CVs, maximum 75% capable reference loads, as well as the mean and RMS differences in absolute terms (kg) and relative to the 50th percentile maximum loads (%), for each equation and also pooled within females and males and across all equations.

					Difference with Empirical Data				Difference with Snook and Ciriello (1991)				
					Mean		RMS			Mean		RMS	
Equation	Conditions	Reference Load (kg)	Mean CV	75% Capable Max (kg)	(kg)	(%)	(kg)	(%)	Conditions	(kg)	(%)	(kg)	(%)
Lift													
Female	54	34.9	0.260	28.8	−1.1	−3.1%	3.0	8.6%	184	1.6	4.7%	2.7	7.7%
Male	58	82.6	0.276	67.2	−1.5	−1.8%	5.8	7.1%	184	2.8	3.4%	6.3	7.7%
Lower													
Female	34	37.0	0.307	29.3	0.4	1.0%	3.0	8.2%	184	−0.8	−2.3%	2.5	6.7%
Male	37	95.9	0.304	76.2	2.1	2.2%	6.3	6.6%	184	3.6	3.8%	7.1	7.4%
Push													
Initial													
Female	26	36.9	0.214	31.6	−0.2	−0.6%	1.7	4.5%	105	1.4	3.7%	2.7	7.2%
Male	32	70.3	0.231	59.3	0.2	0.3%	2.6	3.7%	105	−7.3	−10.4%	9.3	13.3%
Sustained													
Female	30	25.5	0.286	20.6	−0.2	−0.7%	1.6	6.4%	105	3.0	11.7%	3.5	13.8%
Male	32	65.3	0.267	53.5	0.2	0.3%	2.4	3.6%	105	−7.0	−10.7%	9.6	14.7%
Pull													
Initial													
Female	6	36.9	0.234	31.1	−0.9	−2.3%	2.8	7.6%	105	2.2	6.0%	4.6	12.4%
Male	9	69.8	0.238	58.6	0.0	0.0%	1.7	2.5%	105	−4.3	−6.2%	6.1	8.7%
Sustained													
Female	7	25.5	0.298	20.4	−0.8	−3.1%	1.6	6.1%	105	2.8	10.8%	3.3	13.1%
Male	9	61.0	0.257	50.4	−0.6	−1.0%	3.0	4.9%	105	−4.2	−6.9%	6.8	11.1%
Carry													
Female	19	28.6	0.231	24.1	0.2	0.8%	1.7	6.0%	42	0.4	1.5%	2.2	7.6%
Male	24	74.9	0.278	60.9	−0.3	−0.4%	3.5	4.7%	42	4.7	6.3%	9.0	12.0%
Pooled													
Female	176	37.0			−0.4	−1.0%	2.5	6.7%	830	1.4	3.7%	3.1	8.4%
Male	201	95.9			0.0	0.0%	4.6	4.8%	830	−1.2	−1.3%	7.6	7.9%
All	377	95.9			−0.2	−0.2%	3.8	3.9%	1660	0.1	0.1%	5.8	6.0%

The mean differences are also shown for comparisons with the Liberty Mutual (LM) Tables (Snook and Ciriello 1991). Differences represent the equation output (representing the estimated 50% capable value) minus the empirical weighted average MAL.

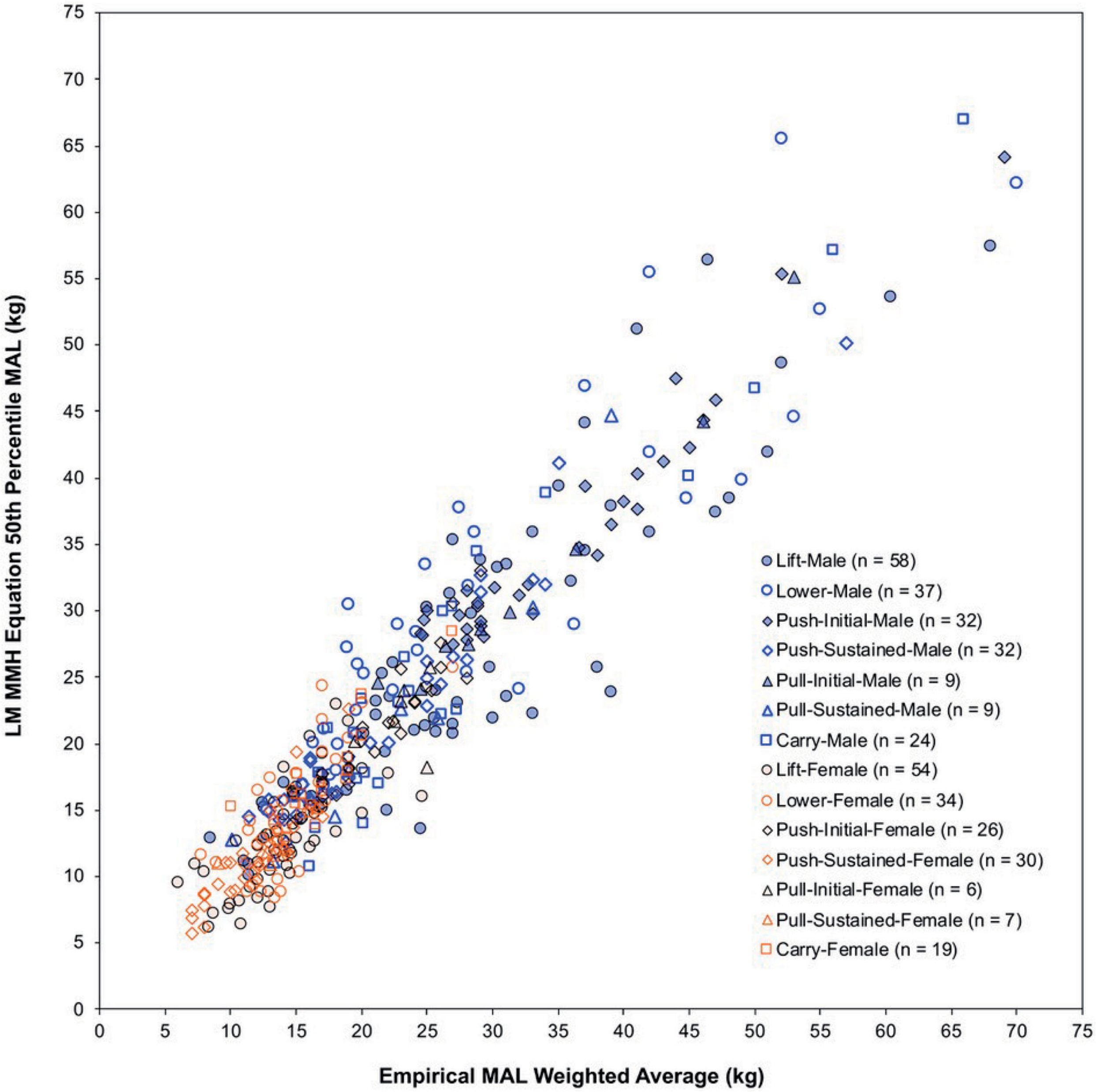

Figure 2. Scatter plot of the estimated 50th percentile MAL values from the Liberty Mutual Manual Materials Handling Equations (y-axis) versus the weighted averages of the MAL values from the empirical data (x-axis). Data are organised by task output for females (orange) and males (blue). The female, male and overall r-squared values are shown as the number of conditions (n) used for each comparison.

Equations') to estimate maximum acceptable loads for females and males performing lift, lower, push (initial and sustained), pull (initial and sustained) and carry tasks performed over 8 hours. These equations incorporate the data from 7 publications used to create the revised Liberty Mutual Tables (Snook and Ciriello 1991), as well as original data from 12 subsequent publications of psychophysical studies of MMH tasks. These LM-MMH Equations have a structure similar to the Revised NIOSH Lifting Equation (Waters et al. 1993), with a maximum reference load and scale factor formulas to determine the reduction in the maximum acceptable loads for non-optimal vertical heights, distances and frequencies (for all task types), as well as horizontal reaches (for lifting and lowering tasks).

4.1. Comparisons with the empirical data and revised 1991 Liberty Mutual Tables

The equations compared very well with the empirical data across 388 unique conditions, explaining 90% of the overall variance (Figure 2) and having RMS differences of only 6.7% and 4.8% of the full range for females ($n = 179$) and males ($n = 209$), respectively (Table 4).

Compared to the revised Liberty Mutual Tables (Snook and Ciriello 1991), the female equations estimated MALs that were an average of 1.4 kg higher ($n = 894$), and the male equations estimated MALs that were an average of 1.2 kg lower ($n = 894$), but the overall mean difference was only 0.1 kg ($n = 1,788$). There were specific equations that produced outputs that were an average of up to 7.3 kg lower (Push – Initial – Male) and 3.6 kg higher (Lower – Male) when compared to the weighted averages of the empirical MALs. It is possible that the equations, which incorporated additional data from studies conducted up to 20 years after the last study used in Snook and Ciriello (1991), could be accounting for secular changes in the population tolerance to manual materials handling workload. There are data from one study with males (Ciriello et al. 2008) and one study with females (Ciriello et al. 2011) showing an overall average decrease in acceptable loads of 23% with more recent participants (ranging from 3% increases for female pushing to 40% decreases with female carrying). While our equations are based on all the data from 40 years of research, it is possible that the inclusion of the older data does not fully reflect potential secular decreases in tolerance.

It is also feasible that the equations are a more valid representation of the actual MALs, given the much larger dataset available to create them and the corresponding reduction in random error. The reference loads were higher than the maximum 50th percent capable values in each revised Liberty Mutual Table, but that was generally because they are based on theoretically optimal conditions not necessarily tested empirically and, as such, they are not always represented in the revised Liberty Mutual Tables. For example, the optimal heights were not always included as a condition in the lab studies and the minimum H values are now 0.20 m and 0.25 m, instead of the 0.38 m and 0.43 m associated with the smallest box widths studied with females and males, respectively.

4.2. Strengths of the equations

The LM-MMH Equations provide many advantages over the revised tables of Snook and Ciriello (1991). Notably, the current equations are based on many more conditions and participants. While the revised tables were based on a total of 119 participants (51 females, 68 males) (Snook and Ciriello 1991), the current equations are based on a total of 273 participants (123 females, 150 males). This represents a 129% increase in the total and a 141% increase in females.

The equations are easier to use than the tables because any values can be input, within the minimum and maximum constraints, so there is no longer a need to interpolate between available input values. The equations can also be easily implemented into existing ergonomics software packages and an Excel spreadsheet app is available from the corresponding author on request.

The revised Liberty Mutual Tables for lifting and lowering were constrained to the minimum horizontal reach values associated with the smallest box width studied. However, the equations have been extended back to make it possible to input H values as low as 0.20 m for females and 0.25 m for males. In addition, the revised tables were limited to a maximum lift and lower vertical distance of 0.76 m, but the LM-MMH Equations can now assess lift and lower tasks through the full vertical range from floor to arm reach.

The stated goal of the revised tables was to 'contribute to the reduction of disability from low back pain' (Snook and Ciriello 1991). However, recent data indicate that, during psychophysical studies of manual materials handling, participants chose MALs based on the most stressed joint (Banks and Caldwell 2019) such that the MALs from our equations likely output loads acceptable to the whole body, and not just the low back.

A useful feature of the equations, like the RNLE, is that the scale factor format of the equations allows for a determination of the independent effect of each input variable on the MAL values. As an illustration, the example provided in Section 3.4 shows that the scale factors were $H_{SF} = 0.766$, $VRM_{SF} = 0.948$, $DV_{SF} = 0.907$ and $F_{SF} = 0.677$, indicating that the horizontal reach and frequency are the limiting factors for this specific task. This information can be used to identify the variable(s) most responsible for reducing the maximum acceptable loads for manual materials handling tasks.

Finally, the representative coefficient of variance values, provided for each equation, allow for the estimation of standard deviation values to accompany any MAL output and facilitate: (1) the determination of maximum acceptable loads for any percentile of the working population and/or (2) the calculation of the percent capable of any given load.

4.3. Assumptions and limitations

The equations are limited to the same conditions and independent variables as those evaluated in the 19

Liberty Mutual MMH studies used for their development. The estimated MAL outputs are applicable to tasks performed for 8 hours in favourable ambient temperatures. The lifting and lowering equations should only be used for smooth, two-handed tasks without significant trunk twisting or lateral bending. As with the revised Liberty Mutual Tables, the proposed Lift, Lower and Carry equations do not account for box length or height. However, this was justified by the observations that those variables did not have any systematic effect on the MALs selected by the participants in the studies that evaluated these factors.

Only one of the Liberty Mutual studies included conditions with no handles (Ciriello, Snook, and Hughes 1993), so the Lift and Lower equations are only directly applicable to conditions where the boxes or containers have handles. In that one study, poor coupling typically resulted in the loads being lifted with asymmetrical hand locations and, consequently, the MAL values were an average of 16% lower than those with handles (Ciriello, Snook, and Hughes 1993). So, for lift and lower conditions with no handles, we recommend an additional coupling scale factor (C_{SF}) 0.84. For conditions with poor handles or a slippery hold, $C_{SF} = 0.925$ should be used (Mital, Nicholson, and Ayoub 1993)

As noted, there were many more conditions with empirical data for lifting versus lowering and for pushing versus pulling. However, there were 72 cases where direct comparisons could be made between lift and lower MALs and 22 cases where they could be made between push and pull MALs. These cases were used to determine the lower/lift and pull/push ratios so that the Lift and Push equations could be modified to account for estimated differences when applied to lower and pull tasks, respectively

Snook and Ciriello (1991) noted that some of their psychophysical-based MAL values exceeded the physiological criteria over an 8-hour workday. Based on 75% capable values italicised in their tables 2 through 10, and organised based on the mean velocity, we recommended that the LM-MMH Equations be used with caution when lift or lower mean vertical velocity exceeds ~3 m/min and when push or pull total mean vertical velocities exceed ~10 m/min and 15 m/min for females and males, respectively. For example, the lift and lower equation outputs should be supplemented by the physiological criterion if the frequency exceeds 12/min for DV = 0.25 m, 4/min for DV = 0.75 m and 2/min for DV = 1.5 m as all result in a mean vertical velocity of 3 m/min. Caution should also be used when carry mean horizontal velocity exceeds ~10 m/min for females, however, there were no male carrying conditions where MAL values exceeded the physiological criterion. More comparisons with other tools and criteria will be made in a future paper.

As noted by Snook and Ciriello (1991), their psychophysical studies established MAL values for single tasks, but they may not be directly applicable to combinations of tasks (eg. lift then carry then lower). To evaluate this potential limitation, Liberty Mutual studied combined tasks (Ciriello 2005, 2001; Ciriello et al. 2011, 2008, 1990) and concluded that their MALs were often lower than the minimum of each subtask in isolation, especially as frequency increased. Thus, the outputs from the LM-MMH Equations should be used with caution when many tasks are performed in sequence. Energy expenditure limits (Garg, Chaffin, and Herrin 1978; Dempsey et al. 2008) and other methods based on cumulative low back loading (Gallagher et al. 2017; Marras et al. 2014) should be considered when tasks are combined.

While these equations can inform acceptable physical loads for occupational task designs that control musculoskeletal pain, injury reporting and length of disability, practitioners should be aware that personal, work environment and psychosocial factors can also have a significant effect on these outcomes (Shaw et al. 2006).

5. Conclusions

We propose that these fourteen Liberty Mutual Manual Materials Handling (LM-MMH) Equations can now replace the corresponding revised tables in Snook and Ciriello (1991). The equations are an advancement on the original Liberty Mutual Tables because they: (1) are based on more empirical data (from 171% more studies, 30% more MAL conditions and condition participants and 15% more unique conditions), (2) incorporate more recent data, (3) are based on more participants (129% increase in total, 141% increase in females), (4) can be applied to a wider range of reaches for lifting and lowering, (5) can be used for all lifting and lowering vertical ranges, not just ranges <76 cm, (6) do not require interpolations, (7) calculate scale factors for each input so the user can determine the variables with the largest effect on the MAL, (8) estimate MAL mean and standard deviation values for each condition to facilitate both the determination of maximum acceptable loads for any target percent and/or the calculation of a percent capable of any given load, and (9) are much easier to use with resources like the spreadsheet app available on request from the corresponding author.

Disclosure statement

Liberty Mutual Insurance is currently utilising the LM-MMH Equations in their *ErgoValuator*^{TM} iPhone App.

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