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Manual material handling guidelines for the shoulder: Biomechanical support for the Liberty Mutual Tables as developed by Snook and Ciriello

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ABSTRACT

Stover Snook and Vincent Ciriello laid the groundwork for psychophysical material handling guidelines in the 1970s. Since then, further research into psychophysical guidelines has been performed by numerous researchers. However, there still exists a gap between psychophysical and biomechanical guidelines. Snook and Ciriello's work eventually led to development of the Liberty Mutual Tables to reduce low-back pain episode in workers due to MMH tasks. Epidemiological evidence indicates pushing tasks may be more related to shoulder pain than low-back pain. A novel approach to protecting worker's shoulder complex by comparing the Liberty Mutual Table guidelines for pushing tasks to biomechanically derived pushing guidelines is presented. These biomechanically derived guidelines are based on muscle activation levels of the subscapularis muscle as determined using a biomechanical model of the shoulder complex. The subscapularis muscle may be a marker for subacromial impingement syndrome. In general, the psychophysical guidelines and the biomechanical guidelines achieve general agreement with respect to magnitude and shape. Differences between the two models range from 6 to 67%.

Relevance to industry: The results of this study should provide insights into the similarities and differences in biomechanically driven and psychophysically driven pushing guidelines. These insights may help lead to more comprehensive pushing recommendations for workers.

1. Introduction

Redesigning manual material handling (MMH) jobs to fit a large percentage of the working population is a common ergonomic activity employed to reduce expensive compensable loss in industry (Ciriello et al., 1999). One method of determining forces which large percentages of the population are able to safely exert is the *psychophysical method.* Work in manual material handling by Stover Snook and Vincent Ciriello in the 1970s provided the groundwork for developing psychophysically based MMH guidelines (Snook et al., 1970; Snook, 1978; Snook and Ciriello, 1991). The psychophysical approach to MMH guidelines is based on two assumptions: (1) a worker is able to estimate with reasonable accuracy the maximum tolerable workload and (2) an acceptable workload selected by a worker in a simulated task is safe. Psychophysical research is usually performed by controlling for important variables (i.e. gender, age, training, fitness of worker, size of object being handled, frequency, initial and final height for lifting, and height of handle for pushing/pulling) and then allowing the worker, based on self-monitoring his or her feelings of exertion and fatigue, to adjust the weight/force of a simulated task or to evaluate the degree of acceptability of the selected weights (Karwowski et al., 1999; Ayoub and Dempsey, 1999). The work done by Snook and Ciriello in the early 1970s eventually culminated in the Liberty Mutual Tables (LMT) – extensive guidelines for various MMH tasks (Snook, 1978; Snook and Ciriello, 1991).

Since then, a great deal of research into psychophysical MMH guidelines has been conducted for lifting tasks (Adams et al., 2010; Ayoub et al., 1978; Elfeituri and Taboun, 2002; Fox, 1993; Gallagher, 1991; Gamberale et al., 1987; Garg and Badger, 1986; Karwowski and Yates, 1986; Karwowski et al., 1999; Legg and Myles, 1981; Maikala et al., 2010; Mital, 1984a,b; Nicholson and Legg, 1986; Smith et al., 1992), pushing tasks (Ciriello et al., 1999, 2010) or both (Ciriello and Snook, 1978, 1983; Ciriello et al., 1990, 1993), although none of these studies have been performed specifically to protect the shoulder joint. There is epidemiological evidence that

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psychophysical models can be used to predict both incidence and severity of certain types of overexertion injuries (Herrin et al., 1986).

The instructions used by Snook and Ciriello (1991) in their psychophysical protocol (and most psychophysical research since) were developed by Snook and Irvine (1967). These instructions required the subjects in the psychophysical studies to imagine working as hard as they can on an incentive basis without straining themselves or becoming unusually tired, weak, overheated, or out-of-breath. However, one study by Karwowski et al. (1999) suggests that these instructions given to workers may have influenced the maximum acceptable loads from which the Liberty Mutual Tables were derived. Since these instructions focus on work productivity (incentive based pay) without any mention of worker safety or injury avoidance, it may be more appropriate to use a psychophysical protocol that focuses less on strain and fatigue but, instead, asks workers to select weights they felt they could safely lift over an 8 h shift without increased risk of low-back pain or muscular overexertion (Karwowski et al., 1999). This study showed a 16.8% decrease in the weight subjects felt was *safe* for an 8 h shift versus weights they found *acceptable* on an incentive work basis (Karwowski et al., 1999). This shows that the Liberty Mutual Tables may slightly overestimate worker capabilities in lifting tasks because of how instructions were given to study participants.

Several studies indicate that worker's perceptions of acceptability may not be closely related to the actual biomechanical stresses in the lumbar spine. A study by Thompson and Chaffin (1993) found that Borg's rating of perceived exertion from manual lifting tasks did not correlate well with biomechanically calculated L5/S1 compression forces. A study by Chaffin and Page (1994) found that the maximum acceptable weight of lifting values for infrequent floor to knuckle height lifts as determined by most young males were higher than acceptable loads determined using a 3400 N spinal compression tolerance limit. Nicholson (1989) found that when accounting for dynamic forces, most of Snook's psychophysical values exceeded a 3400 N limit for spinal compression.

Additionally, some of the acceptable sustained pushing forces given in the Liberty Mutual Tables exceed work physiological expenditure criteria (Snook and Ciriello, 1991). Research into psychophysical guidelines gives subjective ratings of acceptability for MMH tasks. The use of both biomechanical and physiological models may assist in adjusting psychophysical guidelines and provide a more quantitative approach to injury prevention and exposure to MMH tasks (Hoozemans et al., 2004).

These studies suggest that modest adjustments to the Liberty Mutual Tables may be appropriate since a gap exists between psychophysical guidelines and biomechanics, at least for spinal compressive forces. However, it is not surprising that biomechanical and psychophysical approaches will result in different task limits (Ayoub and Dempsey, 1999). Thus it is unclear whether the differences reported in these studies are great enough to represent a clear need to develop biomechanically derived guidelines for occupational pushing tasks. What is clear is the prevalence of shoulder injuries in the workplace and the burden placed on individuals and society from treatment and rehabilitation. Shoulder MSDs are the third most common reason for seeking healthcare for musculoskeletal pain with an annual cost over $7 billion (Bongers et al., 2001; Dinnes et al., 2003) In general, shoulder MSDs have a high recurrence rate (Croft et al., 1996) and are often associated with worse general health status. Epidemiological data indicate a strong relationship between pushing and pulling and shoulder complaints, and only limited evidence of a relationship between pushing and pulling and low-back complaints (Hoozemans, 2002a,b).

Subacromial Impingement Syndrome (SAIS) is reported to account for 44–65% of shoulder pain and is the most common disorder of the shoulder (Michener et al., 2003). SAIS may occur as the result of mechanical impingement of the tissues passing through the subacromial space as it narrows (Michener et al., 2003). This narrowing is critical during pushing tasks as 30–60° of shoulder elevation, which is common in pushing tasks, results in the narrowing of this space up to 3 mm due to the elevating force of the deltoid muscle and the geometry of the humeral head. Weak, dysfunctional, or fatigued rotator cuff muscles have been shown to result in increased superior translation of the humeral head, resulting in narrowing of the subacromial space (Chopp et al., 2010; Deutsch et al, 1996; Michener et al., 2003; Paletta et al., 1997; Poppen and Walker, 1976; Pradhan et al., 2000; Yamaguchi et al., 2000). One of the functions of the subscapularus and infraspinatus muscles of the rotator cuff is to act together to provide a stabilizing and inferior force to the humeral head. This force acts to prevent narrowing of the subacromial space. Although it has traditionally been accepted that muscle activation below 15% of maximum will not result in muscle fatigue (Rohmert, 1973), recent research indicates that muscle forces as low as 10–15% may result in muscle fatigue (Jorgensen et al., 1988; Søgaard et al., 2003). Thus, 10% of maximum muscle activation is a logical limit for pushing force guidelines for high repetition and high distance pushes.

The purpose of this comparison study was to evaluate acceptable push forces based on a computationally derived biomechanical model of the shoulder during pushing tasks with similar conditions as presented in the Liberty Mutual Tables. This approach originated from the hypothesis that even though workers during psychophysical studies performed by Snook and Ciriello were primarily focused on minimizing back stress, these selected maximum values may also be associated with preventing shoulder injuries.

2. Methods

Pushing data were taken from previously published research on biomechanical cart pushing as reported by de Looze et al. (2000) ($n = 8$) and Granata and Bennett (2005) ($n = 11$). From these data, representative pushing forces and associated force line of action for specific handle heights were identified and are shown in Table 1. Two handle heights were chosen based on anatomical shoulder heights and waist heights of 50th percentile males (145, and 104 cm, respectively) (Pheasant, 1996), with whom the populations from the biomechanical studies had similar characteristics (de Looze et al., 2000; Granata and Bennett, 2005).

From images of industrial workers during pushing tasks (Hegmann, 2006), two common postures were identified: pushing with arms extended, and pushing with arms close to body, as shown in Fig. 1. Pictures were taken as a single subject pushed against a bar at appropriate heights using these common postures. These postures were replicated using the University of Michigan's 3-Dimensional Static Strength Prediction Program (3DSSPP) using manual manipulation of the mannequin. Joint locations and segment angles were exported from 3DSSPP to a text file. This text file was then imported to a biomechanical model of the shoulder complex, the Shoulder Loading Analysis Modules (Dickerson et al.,

Table 1
Handle heights, horizontal hand forces and force line of actions used in the computational study.

Hand force (N):	133	267
Force line of action (degrees)		
Shoulder height (145 cm)	5	20
Waist height (104 cm)	−25	−10

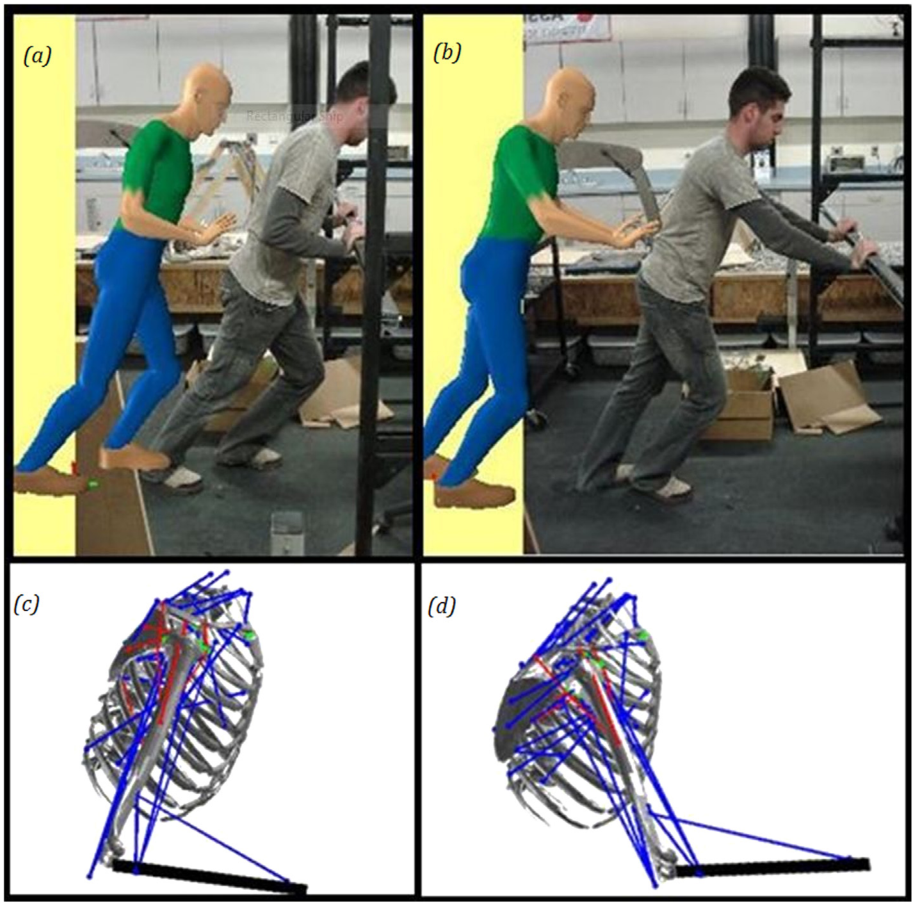

Fig. 1. Illustrations of models geometry for two common pushing postures – arms close for (a), arms extended for (c). models geometry output from Matlab® is shown below these postures in (b) and (d).

2007) using a built in Matlab® (MathWorks, Massachusetts) graphical user interface. The pushing forces identified from literature were applied to the hand link in the model in the sagittal plane, with the positive *x*-direction defined as anterior to the subject and positive *y*-direction defined as superior to the subject.

The biomechanical model utilizes three linked modules, created in the Matlab® software package: a musculoskeletal geometry module, an external dynamic joint moment module and an internal muscle force prediction module (Dickerson et al., 2007). The model incorporates scapula, clavicle, and torso segments as well as a right arm consisting of a humerus link, combined radial/ulnar forearm link and hand link. This shoulder model predicts the force in 23 muscles composed of 38 muscle elements (Dickerson et al., 2007). The model utilizes a previously developed integrative muscle stress optimization objective function Θ to predict muscle forces as shown in Eq. (1) (Nieminen et al., 1995; Laursen et al., 1998, 2003; Dickerson et al., 2007)

$$\min\Theta, \Theta = \sum (f_i/\mathrm{PCSA}_i)^3, i = 1:38 \quad (1)$$

where f_i is the muscle force and PCSA_i is the physical cross-sectional area in muscle *i*. This minimization of the cube of the muscle stresses promotes load sharing between muscles (Dickerson et al., 2007).

The assumptions and predictions derived using this biomechanical model have been supported empirically and compared with other current biomechanical models (Dickerson et al., 2007, 2008). The model achieves general agreement with respect to magnitude values for prime movers. Using an electromyography concordance procedure, the model attains robust identification of highly active and inactive muscles during load handling tasks.

This average percentage of maximum force in the muscle elements for both the subscapularis and infraspinatus muscles resulting from the applied pushing forces and postures was determined using the model. A linear interpolation and extrapolation from the muscle force calculated using the data shown in Table 1 was then used to predict the percentage of maximum force for other loading conditions. Once acceptable horizontal pushing forces were determined by limiting the subscapularis and infraspinatus muscles to 10% of maximum activation, the acceptable horizontal pushing forces were compared to values taken from the Liberty Mutual Tables with similar conditions. The Liberty Mutual Table values have a frequency component not present in the biomechanical model. Researchers averaged the pushing values (50% male capable) for the four highest frequencies on the Liberty Mutual Tables for the shoulder and waist handle heights with pushing speeds of approximately 30.5 m/min. These averages (132.3 N for shoulder height, 134.6 N for waist height, SD = 2.6 N for each) were compared to limits determined using the biomechanical model limiting the subscapularis muscle to 10% of maximum force, which should prevent muscle fatigue. The percent difference of the biomechanically predicted maximums compared to the Liberty Mutual Table values was calculated by dividing the difference of the two models by their average as shown in Eq. (2):

$$\%\mathrm{Difference} = (\mathrm{BMV} - \mathrm{LMTV})/\mathrm{average}(\mathrm{BMV}, \mathrm{LMTV}) \quad (2)$$

where, BMV is the biomechanical model value and LMTV is the Liberty Mutual Table Value.

In order to evaluate the comparison of user's perceptions with the 10% criterion, researchers used the biomechanical model to determine the forces in the subscapularis associated with the pushing force values from the Liberty Mutual Tables.

3. Results

The biomechanical pushing limits determined by restricting the subscapularis muscle to 10% of maximum and the psychophysical limits taken from the Liberty Mutual Tables are given in Table 2. These are compared at similar handle height conditions (145–145 and 104–94 cm, respectively) and the percent difference between the two guidelines is presented in Table 2 in order to demonstrate the general agreement of the two models.

In order to further explore the relationship between the biomechanical guidelines and the psychophysical guidelines, the subscapularis muscle percentage of maximum as a result of applying the Liberty Mutual Table values is given in Table 3.

4. Discussion and conclusions

The biomechanical model predicts the subscapularis and infraspinatus muscles to have the highest activation of all the rotator cuff muscles. This is to be expected for pushing tasks since the external rotation function of the teres minor muscle and the abduction function of the supraspinatus muscle are less necessary than the stabilizing function of the subscapularis and infraspinatus muscles. This is supported by the fact that the model predicted negligible activation levels for the supraspinatus and teres minor. Of the subscapularis and inftraspinatus muscles, the subscapularis muscle had higher activation levels across conditions, which supports using the subscapularis as an appropriate marker for the development of SAIS.

While differences between biomechanically derived and psychophysical models are to be expected, the biomechanical model still showed agreeability with the Liberty Mutual Table values (similar orders of magnitude). Three of the four conditions were within 26% difference between the two models. The greatest difference was found in the waist height condition which had a 10 cm difference in handle heights between the two models due to using hand force line of action data from previous studies with slightly different handle conditions. Without biomechanical studies and psychophysical studies reporting data collected under similar conditions, it will be difficult to fully understand the relationship between these methods. The linear interpolation/extrapolation may also account for some of the difference between the models.

Both the biomechanical model and the Liberty Mutual Tables predict the waist height condition to have larger pushing capabilities than at shoulder heights. This agrees with other biomechanical studies which report higher external shoulder moments for handles at shoulder height versus waist height (Hoozemans et al., 2004). The biomechanical model was consistently lower than the LMT data for the shoulder height condition, while higher than the LMT data for the waist height condition. Working with arms at or above shoulder height is already a known risk factor for developing shoulder injuries (Sommerich et al., 1993). Thus the LMT values may protect workers shoulders for the waist height handles, while still exposing them to unfavorable forces at higher hand locations. LMT guidelines in use were designed to prevent episodes of back pain and as such may have some conditions with pushing limits higher than what may initiate shoulder complaints. This could also explain why some epidemiological studies find only limited evidence for a relationship between back pain and pushing but a large relationship between shoulder complaints and pushing.

Table 2
Maximum allowable initial push forces (N) as determined by biomechanical model (BM) with subscapularis limited to 10% of maximum and Liberty Mutual Tables (LMT), and the % difference comparing the biomechanical values to the Liberty Mutual Table values.

	Handle height	BM (N)	LMT (N)	% Difference
Close arm posture	Shoulder height (145 cm)	102	132.6	26%
	Waist height (BM-104 cm, LMT- 94 cm)	169	134.8	23%
Extended arm posture	Shoulder height (145 cm)	125	132.6	6%
	Waist height (BM-104 cm, LMT- 94 cm)	271	134.8	67%

Table 3
Biomechanically predicted subscapularis % of maximum for pushing values taken from Liberty Mutual Tables.

	Handle height	LMT (N)	% Maximum of subscapularis
Close arm posture	Shoulder height (145 cm)	132.6	14.0%
	Waist height (BM-104 cm, LMT- 94 cm)	134.8	6.2%
Extended arm posture	Shoulder height (145 cm)	132.6	10.9%
	Waist height (BM-104 cm, LMT- 94 cm)	134.8	1.2%

Subscapularis forces in the range of 1.2–14% of maximum are associated with user-perceived maximums for initial push forces, which are all still below the classical 15% limit proposed by Rohmert (1973). Except for the waist height push with extended arm posture, the percent of maximum subscapularis ranges from 6.2 to 14.0%, approximating the 10% of maximum, a value below which fatigue is generally not an issue. However, the model (and many other biomechanical models in general) is developed with a basic assumption that force generation in a muscle is proportional to physical cross-sectional area, called specific tension. The biomechanical shoulder model uses a value of 88 N/cm^2. However, this value is by no means exact – values have been reported ranging from 20 to 140 N/cm^2 (Chang et al., 2000). A different value used for specific tension with the same force in the muscle will have a direct effect on the percentage of maximum in that muscle. The specific tension plays a significant role in the limits of the biomechanically driven model and the technique explored in this study. Since the focus is on percentage of maximum, further work is needed to evaluate model sensitivity and differences in model assumptions as they relate to exertion levels and potential muscle fatigue. The similarity between the muscle activation levels from Liberty Mutual Tables may indicate some level of unconscious recognition of force generation by user's under the psychophysical testing instructions. The biomechanical model presented and the novel technique to evaluate shoulder injury potential using percent activation of the rotator cuff complex seem to suggest that the values given in the Liberty Mutual Table as developed by Snook and Ciriello have promise as guidelines for push/pull tasks, especially for the waist height handle condition. These LMT guidelines tend to keep muscle forces at or near fatigue threshold values.

Several limitations to this study are important to note. First, this study only considered two basic postures. These postures were selected after examining photos of workers involved in pushing tasks, and are representative of the most common postures seen.

However, it must be noted that biomechanical models, including the one used in this research, are sensitive to posture; the developed guidelines may not relate as well to pushing postures vastly different than the basic ones considered for this research. Additionally, while the hand forces used in the analysis represent hand force requirements for the noted tasks, the postures used for the biomechanical analysis did not come from the same source as the hand forces and lines of action. The postures from the subjects could not be perfectly replicated in the software.

Second, the shoulder complex is a highly complex system and using a single muscle force as a predictor variable for injury is a major simplification of a very complex system.

Additional research is needed to address these limitations and to study the potential biomechanical stress in the muscles of the shoulder and shoulder muscle forces most associated with user-perceived maximums at other push heights. Data should be collected dynamically in conditions similar to those currently reported in psychophysical studies for more direct comparisons with psychophysical tests. Future work will include collecting dynamic pushing postures, forces, and force lines-of-action using advanced motion capture systems and multi-axis force sensors. The similarities and differences between initial and sustained pushing phases will also be explored. Finally, investigating the interaction of handle height and force capability may be necessary to fully understand the biomechanics during pushing tasks. Future research will include six handle height conditions: three anatomical (knee, waist and shoulder height), and three absolute (94 cm, 122 and 152 cm measured from the floor). These new data will be used to verify and improve the simulations reported in this study – which may be used to adjust or generalize current MMH guidelines.

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