SPECIAL SECTION: *Impact of Thomas Waters on the Field of Ergonomics*

Evaluation of the Impact of the Revised National Institute for Occupational Safety and Health Lifting Equation

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Objective: The objective of this article is to evaluate the impact of the Revised National Institute for Occupational Safety and Health Lifting Equation (RNLE).

Background: The RNLE has been used extensively as a risk assessment method for prevention of low back pain (LBP). However, the impact of the RNLE has not been documented.

Methods: A systematic review of the literature on the RNLE was conducted. The review consisted of three parts: characterization of the RNLE publications, assessment of the impact of the RNLE, and evaluation of the influences of the RNLE on ergonomic standards. The literature for assessing the impact was categorized into four research areas: methodology, laboratory, field, and risk assessment studies using the lifting index (LI) or composite LI (CLI), both of which are the products of the RNLE.

Results: The impact of the RNLE has been both widespread and influential. We found 24 studies that examined the criteria used to define lifting capacity used by the RNLE, 28 studies that compared risk assessment methods for identifying LBP, 23 studies that found the RNLE useful in identifying the risk of LBP with different work populations, and 13 studies on the relationship between LI/CLI and LBP outcomes. We also found evidence on the adoption of the RNLE as an ergonomic standard for use by various local, state, and international entities.

Conclusion: The review found 13 studies that link LI/CLI to adverse LBP outcomes. These studies showed a positive relationship between LI/CLI metrics and the severity of LBP outcomes.

Keywords: Revised NIOSH Lifting Equation, lifting index, manual lifting, low back pain, impact

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INTRODUCTION

To pay tribute to Thomas R. Waters for his contributions to ergonomics, this paper is aimed at evaluating the impact of the Revised National Institute for Occupational Safety and Health (NIOSH) Lifting Equation (RNLE). Thomas R. Waters spent most of his career at NIOSH developing and evaluating the RNLE as one of his main research interests. In 1981, NIOSH published the original NIOSH Lifting Equation (NLE) in the *Work Practices Guide* (WPG) to address work-related musculoskeletal disorders (WMSDs) and in particular low back pain (LBP) from lifting and lowering of loads (NIOSH, 1981). Based on additional scientific findings related to manual lifting in the areas of physiology, biomechanics, psychophysics, and epidemiology, the NIOSH proposed to revise the WPG to address the limitations of the original NLE. A panel of experts in these research areas was commissioned to review the scientific literature on manual lifting. The experts included M.M. Ayoub, Don B. Chaffin, Colin G. Drury, Arun Garg, Suzanne Rodgers, Vern Putz-Anderson, and Thomas R. Waters. In 1991, Putz-Anderson and Waters presented the RNLE based on findings from this review at a conference held at the University of Michigan, Ann Arbor (Waters & Putz-Anderson, 1991). In 1993, the RNLE was published in a scientific journal to provide the rationale and justification for the RNLE (Waters, Putz-Anderson, Garg, & Fine, 1993). In 1994, the NIOSH published the applications manual for using the RNLE (Waters, Putz-Anderson, & Garg, 1994).

Publication of the RNLE generated a growing interest among researchers and field safety professionals in improving risk assessments for manual lifting jobs. The popularity of using the RNLE among field safety professionals is attributed to the simplicity and quantitative nature of the RNLE. A weight scale, a tape measure, a goniometer, and a stopwatch can be used to determine the lifting task variables required for using the RNLE. The RNLE allows one to compute a recommended weight limit (RWL) and a lifting index (LI) for a limited number of manual lifting tasks. The RWL is computed from six mathematical expressions, requiring measurement of six variables: horizontal location of hands, vertical location of hands, travel distance of the load, frequency of lifting, asymmetric angle, and hand-to-object coupling (i.e., quality of hand grip). Asymmetric angle and hand coupling are two new task variables in the RNLE that were not in the original NLE. The LI is the ratio of the load lifted to the RWL and provides a method for comparing the lifting demands of different lifting tasks. For multiple lifting tasks, a composite LI (CLI) is calculated using an incremental approach with all the tasks (Waters et al., 1994). An LI or CLI above 1.0 is considered to pose a risk of LBP in most populations (Waters et al., 1994). This theoretical risk threshold, however, was not validated at the time of the publication of the RNLE in 1991.

Since the publication of the RNLE, there has been a growing body of evidence indicating the effect of the LI or CLI on the development of LBP. An LI or CLI > 1 has been associated with different LBP outcomes in previous studies (Garg, Boda et al., 2014; Lavender, Oleske, Nicholson, Andersson, & Hahn, 1999; Lu, Waters, Krieg, & Werren, 2014; Wang et al., 1998; Waters et al., 1999; Waters, Lu, Piacitelli, Werren, & Deddens, 2011). However, there has been no systematic review of the evidence into the relationship between different levels of the LI/CLI and LBP outcomes. Another research void, until now, is the lack of an assessment of the comprehensive impact of the RNLE on the ergonomic research community. This review starts characterizing the RNLE-relevant literature, followed by assessing scientific evidence in different research applications, especially the risk function of the RNLE. Finally, the impact of the RNLE on ergonomic standards for manual material handling/lifting is discussed.

METHODS

The first part of this review assessed the general citation impact and characteristics of the RNLE research publications. The focus of the first part was to gain an understanding of the use of the RNLE in the published literature and to understand the breadth of the usage independent of scientific merits. To assess the breadth of the impact, different forms of publications were included such as conference proceeding papers, peer-reviewed journal articles/letters, guideline documents, trade magazines, government publications, and book chapters. We used articles published in several bibliographic databases including Pubmed, Ergonomic Abstracts, Scopus, Google Scholar, and NIOSH Technical Information Center-2. Because many researchers did not include the term *revised* or *NIOSH* in their articles relating to the RNLE, we decided to use the search string *lifting equation* or *lifting index* to encompass all relevant articles. Because the RNLE was first announced in 1991, the search period was set from January 1, 1991 to December 30, 2014. Reference lists of identified manuscripts were also read to identify any missing studies not found in the search.

The second part of the review was to provide a systematic and critical review of the peer-reviewed studies that either supported the scientific credibility of the tool or investigated the relationship between the RNLE and LBP outcomes. Therefore, trade journals, proceeding papers, letters, book chapters, and government publications were excluded. Non-English documents were also excluded. Identified articles were grouped into four predefined categories described as follows:

- Category 1 (methodology description/comparison/review): articles using existing data for methodology comparison purposes or demonstrating the methodology of the RNLE
- Category 2 (laboratory study): articles showing results of experiments in a laboratory setting
- Category 3 (field study): studies conducted in the field without LBP-related outcomes
- Category 4 (field risk exposure assessment): epidemiological studies assessing the risk exposure relationship between LI/CLI and LBP outcomes

The third part of the review was to discuss the influences of the RNLE on developing

TABLE 1: Type of RNLE Literature (Sorted by Number of Documents in Descending Order)

Type	Number	Percentage
Journal articles	96	70.1
Conference proceeding papers	23	16.8
Government documents[a]	9	6.6
Book chapters	5	3.6
Trade magazines	2	1.5
Guideline document	1	0.7
Journal letter	1	0.7
Total	137	100.0

[a]All documents are published by NIOSH except one by the Health and Safety Executive, United Kingdom.

and implementing standards and guidelines for manual lifting. Federal, state, and industry-specific standards in the United States as well as international standards for manual lifting were reviewed. Non-English standards or guidelines were excluded from this part of the review.

RESULTS AND DISCUSSION

Citation and Usage Impact of the RNLE Applications Manual

Thousands of copies of the paper version of the applications manual for RNLE have been disseminated since 1994. The digital version of the applications manual for RNLE has been downloaded from the NIOSH website (http://www.cdc.gov/niosh/docs/94-110/pdfs/94-110.pdf) over 18,726 times since the inception of the NIOSH document tracking system in 2005, showing that the applications manual for the RNLE is the most downloaded NIOSH publication. The RNLE scientific paper that is included in the applications manual has also been cited by other research papers 1,258 times (accessed May 18, 2015 on Google Scholar). The RNLE scientific paper has been the second most cited paper in the journal *Ergonomics* (accessed April 14, 2015 on http://www.tandfonline.com/loi/terg20#cited).

Dempsey, McGorry, and Maynard (2005) found that RNLE was the most widely used job analysis method and was preferred by 83.1% among all 13 different ergonomic risk assessment tools. In another study, the RNLE was reported as the best known risk assessment tool for manual materials handling among Portuguese Health and Safety professionals (Arezes, Miguel, & Colim, 2011). The Health Council of the Netherlands concluded that the RNLE was a reasonable approach to assessing risk of manual lifting (Health Council of the Netherlands, 2012). Clearly, the RNLE has been a widely accepted method for assessing the risk of low back problems associated with manual lifting.

Characteristics of RNLE Publications

The article search and manuscript identification was completed by the first author. One relevant publication (Pinder & Frost, 2011) was found in the reference list of an identified journal article (Lu et al., 2014). In total, 137 documents were included in the first part of the review. Of the documents, 70% were published in peer-review journals and 17% were published as conference proceeding papers (Table 1). The remaining documents were book chapters, trade articles, a journal letter, a guideline document, and government publications. The vast majority of the publications were published in English. Three documents (Chen & Yang, 2006; Xiao, Lei, Dempsey, Ma, & Liang, 2004; Xiao & Liang, 2008) were published in a Chinese scientific journal. One article was published in a Dutch journal (Vink, Smitt, & Van Den Berg, 1993). Three documents were published in three Italian journals (Maso et al., 2011; Occhipinti & Colombini, 2011; Ranavolo et al., 2014). It should be noted that publications in limited non-English journals do not indicate limited international research in the RNLE. A further investigation into the authors' institutions or affiliations shows that the documents were published

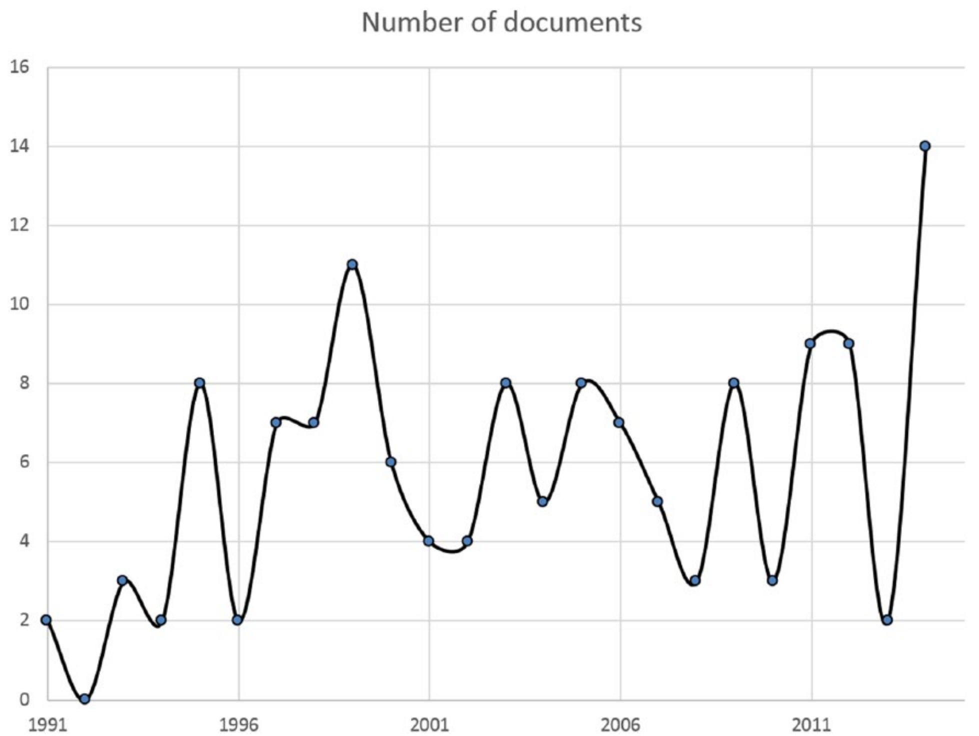

Figure 1. Number of documents (N = 137) relevant to the RNLE from January 1, 1991–December 31, 2014

by researchers in 23 countries. Researchers in the United States accounted for 54% of the published work, followed by Italy (7%) and Canada (6%). It appears that the RNLE has had an impact on the international research community, both as a tool for research as well as practice.

Thomas R. Waters contributed to the largest number of publications (n = 28) of the RNLE-relevant documents, followed by Patrick Dempsey, Arun Garg, and Ming-Lun Lu (n = 9 each). A further analysis of the type of Thomas R. Waters's publications shows 14 journal articles, 8 conference proceeding papers, 3 NIOSH publications, 1 guideline document, and 2 book chapters.

Figure 1 shows the number of the published documents by year. There was an increasing trend of the RNLE-relevant publications from the inception of the RNLE to 1999. The number reached the peak at 11 and then stagnated between two and nine from 2000 to 2013. In retrospect, this initial increasing trend from 1991–1999 may have been in part due to the federal ergonomic standard that was being proposed and implemented in the United States. The RNLE was listed as one of the ergonomic risk assessment methods in the federal ergonomic standard, although it was repealed in 2001. In 2014, the number reached the highest at 14 publications. As shown in Figure 1, there is no specific trend in the number of the RNLE documents in recent years.

The Impact of the RNLE on the Four Research Categories

Eighty-nine RNLE-relevant journal articles were found and categorized into one of the four research categories that we identified. Namely, 25 publications dealt with the methodology description/comparison/review (Category 1), 28 were identified as laboratory studies (Category 2), 23 were field studies (Category 3), and 13 were considered as field risk exposure assessments (Category 4). Of the studies in Category 1, three reviewed ergonomic methods for assessing exposures to risk factors for WMSDs including the RNLE (David, 2005; Kuijer et al., 2014; Waters, Putz-Anderson, & Baron, 1998). Garg (1995) and Waters et al. (1993) presented the methodology selection criteria and methodology description for RNLE in two separate papers.

On methodology description/comparison/review. The methodology selection criteria for the RNLE were cross-validated in a study (Hidalgo et al., 1995). In that study, the RWL was found to be highly correlated with the data of Snook and Ciriello (1991) in the lower lifting frequency range (Hidalgo et al., 1995), validating that the RNLE made use of data of Snook and Ciriello (1991) in the lower lifting frequency range. In 1995 and 1997, respectively, Stambough, Genaidy, and Guo (1995) and Hidalgo et al. (1997) published a study extending the RNLE to include heat stress, age, and body weight factors. A "relative lifting safety index" was developed to protect a group of workers, and a "personal lifting safety index" was developed to protect individual workers (Hidalgo et al., 1997). The same research team that conducted the above studies published a paper describing a general LI (GLI) based on the mechanical work concept and compared it to the LI (Abdallah et al., 2005). The results of that study showed the RNLE appeared to be a good approximation on the basis of physics and various mechanical laws (Abdallah et al., 2005).

The biomechanics criteria for generating the RWL were challenged by Jager and Luttmann (1999). In their critique, cadaver data used for the RWL or the 3.4 kN limit for back compression force at the L5/S1 disc was questionable, especially for workers beyond age 40 (Jager & Luttmann, 1999). They pointed out that the load bearing capacity of human spine varied over a wide range due to age and gender. They proposed that the RNLE be revised to include age and gender factors (Jager & Luttmann, 1999). In addition to the suggested additions/revisions to the RNLE by the aforementioned studies (Hidalgo et al., 1997; Jager & Luttmann, 1999; Stambough et al., 1995), Magnusson, Pope, Wilder, Szpalski, and Spratt (1999) suggested adding the factor of "stiffness change" as yet another multiplier. The recommendation was to be added to accommodate "post-surgery workers" who typically have restricted lifting capabilities. The rationale for this addition was described in a subsequent paper (Pope, Magnusson, Wilder, Goel, & Spratt, 1999). To our knowledge, all the suggested revisions to the RNLE model have not been validated.

The aerobic capacity criterion for repeated lifting used by the RNLE was reviewed by a study using the maximum oxygen uptake (VO_{2max}) limits for various industrial tasks (Jackson & Ross, 1996). It was found that the RWL for 8-hr repetitive lifting represented low VO_{2max}. The finding suggests that from an energy consumption perspective, the RWL is protective for most workers (Jackson & Ross, 1996). However, Jackson and Ross (1996) debated about the fact that the role of aerobic capacity on injury risks lacks empirical verification. Using the RNLE baseline aerobic capacity for design lifting tasks may have adverse health effects (Jackson & Ross, 1996). This argument was based on the notion that workers with low-level aerobic fitness may have low levels of overall fitness and health, which may lead to risk of injury.

The remaining studies in Category 1 are summarized as follows. Potvin (2014) developed a composite acceptable load (CAL) table for a variety of lifting conditions based on the most conservative load of the three design criteria used for the RNLE. He found that the RWL is generally in agreement with the biomechanical criteria (i.e., 3,400 N of lumbar compressive force) for lifts below knuckle height but more conservative (i.e., below CAL) for lifts greater than knuckle height. Similarly, in a separate study comparing different assessment methods, the RNLE was found to provide a high level of risk protection to the worker and captures most primary risk factors (Townley, Hair, & Strong, 2005). Four risk assessment tools including the RNLE were used and compared in a case study (Marklin & Wilzbacher, 1999). That study found that RNLE is best suited for simple lifting tasks involving two-handed lifting. For complex lifting tasks, the Ohio State's Lumbar Motion Monitor (LMM) and the University of Michigan's three-dimensional static strength prediction program (3DSSPP) are more suited. Results of the RNLE are in line with those from the Snook Tables and a 2D biomechanical model (Townley et al., 2005). Although the RNLE was described as one of the easy-to-use methods for assessing the risk of MSDs (Roman-Liu, 2014), some measurement issue was addressed by a study (Dempsey & Fathallah, 1999). The study indicated that the operationalized definition of the lift asymmetry may be difficult to use, as many users may be confused by the trunk asymmetry. A categorical method for measuring the lift asymmetry was suggested (Dempsey & Fathallah, 1999). Additionally, several researchers proposed procedures to improve the reliability and quality of the measurements needed for using the RNLE (Lu, Waters, Werren, & Piacitelli, 2011; Okimoto & Teixeira, 2009; Waters, Lu, Werren, & Piacitelli, 2011). A number of studies added recommendations on patient lifting and lifting by pregnant women (Waters, Baptiste, Short, Plante-Mallon, & Nelson, 2011; Waters, MacDonald, Hudock, & Goddard, 2014). Two new variations were proposed for computing the LI (i.e., sequential LI and variable LI) for jobs involving rotations and variable lifting, respectively (Colombini, Occhipinti, Alvarez-Carsado, & Waters, 2013; Waters, Lu, & Occhipinti, 2007). The final document in this category acknowledged that a popular ergonomic checklist, the Occupational Repetitive Actions (OCRA), was conceptually based on the calculation procedure of the RNLE (Occhipinti, 1998).

On studies examining RNLE in a laboratory setting. Studies in Category 2 are pertinent to reviewing the scientific credibility of the RNLE using data collected in a laboratory setting. Two studies on the accuracy of measurements for the RNLE are worth mentioning. In Waters, Baron, and Kemmlert's (1998) study, the "between observers measurement variability" for the RNLE variables was found to be small, especially for the horizontal distance, whereas the coupling and asymmetry angle measurement had the highest variability. One-day training on the RNLE seemed appropriate for obtaining accurate measurements for the RNLE task variables (Waters, Baron, & Kemmlert, 1998). However, in Dempsey, Burdorf, Fathallah, Sorock, and Hashemi's (2001) study, significant differences were found between average measurements that were taken by study subjects and reference measurements. Length of training and complexity of the lifting task can affect users' ability to measure the RNLE task variables (Dempsey et al., 2001). A case study highlighted the need to train users on how to take RNLE measurements properly (Cole & McGlothlin, 2009). Without proper training, users had a difficult time understanding the RNLE task variables, causing measurement errors (Cole & McGlothlin, 2009).

The remaining studies in Category 2 are relevant to the usability and validation of the RNLE multipliers. The usability of the RNLE was evaluated using data collected for 1,103 lifting and lowering tasks (Dempsey, 2002). The main findings of the study were that a large portion (35%) of lifting tasks had at least one RNLE task variable outside of the applicable ranges and that a fairly high percentage (56%) of workers were involved in pushing/pulling/carrying tasks that could not be analyzed by the RNLE (Dempsey, 2002). Similarly, a study reported that 57% of lifting tasks could not be analyzed by RNLE because these required either one-handed lifting or lifting in seated positions (van der Beek, Mathiassen, Windhorst, & Burdorf, 2005). Work organization factors such as job rotation and flexible manufacturing may further limit the usability of the RNLE for some modern jobs. Although sequential LI (for job rotation) and variable LI (for flexible and variable lifting) have been developed for accommodating the modern jobs (Colombini et al., 2013; Waters et al., 2007), no research has been conducted to validate the newly derived LI metrics.

Lift asymmetry angle was a new task variable introduced to the RNLE (Waters et al., 1993) and was examined in several studies (Han, Stobbe, & Hobbs, 2005; Lavender, Li, Natarajan, & Andersson, 2009; Lee, 2005; Wu, 2003). The reductions in the RWL due to the lift asymmetry was found to be appropriate, compared with a kinematic-driven three-dimensional biomechanical model (Lavender et al., 2009). Other studies employing psychophysical methodology for comparisons with the effects of life asymmetry on maximal acceptable lifting weights showed disagreements with the RWL. Compared to the RWL, increased maximal acceptable weights at different lift asymmetry angles were reported in these studies (Han et al., 2005; Lee, 2005; Wu, 2003). The maximal acceptable weight (15% reduction from condition without lift asymmetry) for a lifting task with a 90°

asymmetry was about one half of the RWL (30% reduction) determined by the RNLE (Han et al., 2005). These studies concluded that the RWL was more conservative in comparison with the results from the psychophysical studies (Han et al., 2005; Lee, 2005; Wu, 2003).

Another newly introduced task variable to the RNLE was the coupling factor (Waters et al., 1993). The coupling factor was assessed in a study using physiological and psychophysical measures (Adams et al., 2010). The results showed subjects performing lifting tasks with good coupling had increased physiological and psychophysical stress, compared to poor coupling (Adams et al., 2010). The finding contradicted the data used to define the discount value for poor coupling built into the RNLE (Waters et al., 1993). The reduction in the RWL in response to the coupling factor was examined in a separate study using a biomechanical approach (Davis, Marras, & Waters, 1998). It was found that the reduction in the RWL resulting from poor coupling adequately represents the physical demands associated with lifting at a vertical height of 133.8 cm (Davis et al., 1998). The coupling multiplier, for this range of lifting heights, may be more protective if the reduction factor is set at 0.85 than the established 0.9 value (Davis et al., 1998). The conflicting finding of Adam et al.'s study with the RNLE may have resulted from improper controls of other factors such as the horizontal distance and lifting pace or essentially the different evaluation methods that were used (Adams et al., 2010). The physiological response to lifting is highly sensitive to lifting speed, which was not addressed by the RNLE or in Davis et al.'s study.

The horizontal distance of the RNLE was associated with box widths in the Liberty Mutual or Snook lifting table in a study (Potvin & Bent, 1997). It was found that the horizontal distance of the RNLE might be used to substitute for the box width that was required for using the Liberty Mutual lifting tables for a risk analysis (Potvin & Bent, 1997). The horizontal distance and vertical distance of the RNLE were used along with other variables to estimate compression force at the L5/S1 disc (Potvin, 1997). It was found that the revised biomechanical model using some of the RNLE task variables may be more accurate for determining safe loads, compared to the RNLE (Potvin, 1997).

Interaction effects of the RNLE multipliers on the LI were investigated by Singh and Kumar (2012). Object weight and lift asymmetry interaction and object weight and lifting frequency interaction were found to be significant (Singh & Kumar, 2012). It should be noted that the horizontal multiplier was not examined in the above study. The horizontal multiplier has a strong effect on the LI, as shown by its reductions rate on the RWL (Waters et al., 1993). Research into its interaction with other task variables may provide more insight than the observed interactions. The interaction effects of the RNLE multipliers were also assessed by a factorial analysis on working heart rates (Maiti & Bagchi, 2006). The overall interaction effect contributed to 10% of the total variance of the normalized working heart rate (Maiti & Bagchi, 2006). The exploratory finding of this study suggests a nonlinear nature of interactions of the RNLE multipliers. It is recommended that interaction of some multipliers be included in the RNLE (Maiti & Bagchi, 2006). This recommendation, however, may be premature because heart rate data used in Maiti and Bagchi's study were not based on MSD risk data. Nonetheless, the aforementioned studies indicate a need to further validate the assumed multiplicative property of the RNLE multipliers in predicting the risk of MSDs.

The RNLE was compared with dynamic biomechanical models in several studies (Elfeituri & Taboun, 2002; Kee & Chung, 1996; Lavender, Andersson, Schipplein, & Fuentes, 2003). It was observed that for low-level lifting, the RNLE underrepresents increased peak-sagittal moment, which was estimated using a linked segment-dynamic biomechanical model (Lavender et al., 2003). Kee and Chung (1996) indicated the RNLE may not fully estimate the risk of dynamic asymmetrical lifting. They examined the correlations between the different biomechanical models and the LI values and found that the LI was well correlated (r = 0.82–0.86) with static models such as 3DSSPP, while moderately correlated (r = 0.56) with an electromyography-driven dynamic model (Kee & Chung, 1996). This finding is not surprising because predicted compression force acting on the spine using a dynamic model has been reported to be 33%–60% higher than a static model (Leskinen et al., 1997). The panel of experts for the development of the RNLE was aware of the limitations of the biomechanical criteria used for the RNLE and explicitly stated in the RNLE applications manual that one of the requirements for using the RNLE is smooth and controlled lifting motion (Waters et al., 1994). If the lifting speed is faster than 76.2 cm/sec, an additional analysis of dynamic biomechanical modeling may provide more accurate risk information (Waters et al., 1994).

The remaining studies in Category 2 were concerned about (1) work designs for risk of injury using the RNLE as the assessment method (Balasubramanian & Sharma, 2009; Koltan, 2009; Plamondon, Delisle, Trimble, Desjardins, & Rickwood, 2006; Stuart-Buttle, 1995), (2) the relationship between subjective assessments of risk exposures and the LI (Kee & Chung, 1996; Yeung, Genaidy, Karwowski, & Leung, 2002), (3) an investigation of the maximal lifting load limit for adult Indian women using the physiological criteria from the RNLE (Maiti & Ray, 2004), (4) a comparison of the Isernhagen Functional Capacity Evaluation (FCE) and the RNLE for safe patient lifting (Kuijer et al., 2006), (5) an evaluation of participatory ergonomic (PE) training against the RNLE (Saleem, Kleiner, & Nussbaum, 2003), and (6) testing for automating measurements for some RNLE task variables that could be used in the field (Spector, Lieblich, Bao, McQuade, & Hughes, 2014). Two of the above-mentioned studies are worth elaborating. In the study investigating the PE training against the use of RNLE, it was found that the PE training alone led to better improvement than use of the RNLE in terms of risk factors identified and eliminated (Saleem et al., 2003). Caution should be exercised in interpreting the above study finding, because the ergonomic risk factors identified and eliminated in the above study were not based on lifting hazards only. Other risk factors (e.g., no posture change, glare in eyes when lifting) were also asked in the assessment, which would have favored the PE training (Saleem et al., 2003). Additionally, another caution of that study was the predetermined ergonomic risk factors that were not weighted according to the risk of MSDs. For example, poor handle coupling was considered as having the same risk level as large horizontal distance of the lifting task. The nonweighted quantifications of the risk factors may lead to limited interpretations of the study results.

Spector et al. (2014) attempted to automate the measurements of some of the RNLE task variables. Previous studies have acknowledged that the measurments of the RNLE variables are time consuming and cumbersone (Dempsey et al., 2001; Lavender et al., 2009; Lu et al., 2011; van der Beek et al., 2005). In Spector et al.'s study, the Microsoft Kinect (a 3D infrared depth camera) was used to measure position of a worker performing a lifting task. Although the data collected with the Microsoft Kinect tended to overestimate the RWL (Spector et al., 2014), the novel instrumentation seemed a promising tool for automating measurements of the RNLE. Future studies should focus on development of automating measurements of hand force and coupling factors that were not tested in Spector et al.'s study.

On studies using RNLE in the field. Studies conducted in the field but irrelevant to assessing the risk exposure relationship between the LI and low back disorders (LBDs) were grouped in Category 3. Twenty-three studies were identified in this category. Two studies were surveys of risk assessment tools used by field professionals (Arezes et al., 2011; Dempsey et al., 2005). Four studies were evaluations of risk reductions after implementation of interventions (Bernardes, Wanderck, & Moro, 2012; Dormohammadi, Amjad Sardrudi, Motamedzade, Dormohammadi, & Musavi, 2012; Pires, 2012; Torres & Vina, 2012). Exposures to MSD risks using the RNLE in different working populations were investigated in 10 studies, including grocery stockers (Davis & Orta Anés, 2014), firefighters (Gentzler & Stader, 2010), preschool teachers (Grant, Habes, & Tepper, 1995), neighborhood pub workers (Jones, Strickfaden, & Kumar, 2005), fishermen (Kucera et al., 2008; Kuruganti & Albert, 2013), fish processing workers, cooks (Xu & Cheng, 2014), workers in a fire brick manufacturing plant (Chung & Kee, 2000), and workers in many manufacturing and distribution sectors (Ciriello & Snook, 1999; Dempsey, 2003).

Other studies in Category 3 fell into the research area of a comparison of different MSD risk assessment methods in the field. One study validated the LI using a correlation analysis between the LI and the moment ratio (i.e., ratio of actual moment vs. capacity moment) using a 2D biomechanical model (Lin, Wang, & Chen, 2006). Results of the study showed a correlation coefficient of 0.7 between the moment ratio and the LI (Lin et al., 2006). Three studies reported results of the comparison between the RNLE, 3DSSPP, LMM, and some industry lifting guidelines (Lavender et al., 1999; Mirka, Kelaher, Nay, & Lawrence, 2000; van der Beek et al., 2005). These studies basically concluded that the different methods considered the risk of LBP from different perspectives. The risk of LBP revealed by the methods may tap into different underlying causes of LBP (Lavender et al., 1999). Without a complete understanding of the underlying causes of LBP, a comprehensive risk assessment method is difficult to select. A hybrid assessment methodology may be employed for an effective risk evaluation (Mirka et al., 2000).

In addition to the above studies using different objective risk assessment methods for validating the RNLE, two studies used subjective methods for comparisons. An investigation of the relationship between the LI and perceived risk of injury or work dissatisfaction was carried out (Yeung, Deddens, Genaidy, Karwowski, & Leung, 2006). The main finding of the above study was that the multiplicative structure of the RNLE is better than an additive model, but the weighting of the RNLE multipliers needs further investigation (Yeung et al., 2006). In another study, a self-reporting worker-based risk assessment was evaluated against the task variables of the RNLE (Yeung, Genaidy, Deddens, & Leung, 2003a). Results of that study demonstrated that the subjective self-reporting risk assessment method appeared to be a promising approach (Yeung et al., 2003b).

On field studies investigating the relationship between the LI/CLI and risk of LBP outcomes. To assess the evidence about the relationship between the LI/CLI and risk of LBP outcomes, studies in Category 4 were used. The characteristics of the 13 field risk exposure studies in this category and their main findings are presented in Table 2. Of the 13 studies, 3 utilized an existing injury database collected in the field for an analysis of the relationship between the LI and health/injury outcomes (Marras, Fine, Ferguson, & Waters, 1999; Sesek, Gilkey, Drinkaus, Bloswick, & Herron, 2003; Yeung et al., 2003b). Individual or grouped LI data were used for associating the LI values with health outcomes in the remaining studies (Garg, Kapellusch et al., 2014; Kapellusch et al., 2014; Kucera et al., 2009; Lu et al., 2014; Schneider, Grant, Habes, & Bertsche, 1997; Wang et al., 1998; Waters et al., 1999; Waters, Lu, Piacitelli et al., 2011; Xiao, Dempsey, Lei, Ma, & Liang, 2004). As seen in Table 2, the RNLE studies were conducted primarily in the manufacturing and wholesale and retail trade (WRT) sectors. Only one study was carried out in the fishing industry (Kucera et al., 2009) and one in unknown industry sectors (Wang, Garg et al., 1998).

The LI values were first used to associate the prevalence of back pain in a small study with a sample size of 19 (Schneider et al., 1997). In that study, high LI values were found to be related to the high prevalence of back pain among those working in the shipping department of a cabinet manufacturing company (Schneider et al., 1997). In 1999, the first large-scale, cross-sectional, epidemiologic study on the RNLE was published by Waters et al. (1999) at NIOSH. In that study, data from 308 workers in various manufacturing facilities were analyzed. The results of the analysis showed a significant odds ratio (OR) of 2.2 with a 95% confidence interval (95% CL = 1.01–4.96) for self-reported LBP when an LI was between 2 and 3, compared to an LI $\leq$ 1.0. Waters, Lu, Piacitelli et al. (2011) expanded the dataset by combining it with additional data (total sample size = 677) and published the analysis results in 2011. The results of the expanded cross-sectional analysis showed that an LI ranging from 1 to 3 had a significant OR for self-reported LBP, compared to an LI $\leq$ 1.0. Finally, Waters and his colleagues published a prospective study on the RNLE in 2014 (Lu et al., 2014). In that study, exposure to a CLI between 2 and 3 was associated with LBP in one year. Compared with CLI values less than 1, the mean and maximum CLI above 2.0 posed a significant OR of 5.1 (95% CL = 1.1–24.5) and 6.5

TABLE 2: Characteristics of Studies Investigating the Relationship Between the LI/CLI and LBDs

Study	Sample Size	Age Range	Study Design	Industry Sector	LI/CLI Values	% Reporting LBP/ Symptoms	Main Finding
Garg, Boda et al. (2014)	258	19–65	Prospective	Manufacturing and WRT	Mean peak task CLI = 2.8	48% had self-reported LBP during 4.5-year follow-up	Peak LI and CLI are useful metrics for estimating physical job risk exposures
Garg, Kapellusch et al. (2014)	258	19–65	Prospective	Manufacturing and WRT	Mean peak task CLI = 2.8	9% reported seeking care for LBP during 4.5-year follow-up	Peak LI and CLI are useful metrics for estimating risk of sickness absence due to LBP
Kapellusch et al. (2014)	258	19–65	Prospective	Manufacturing and WRT	Mean peak task CLI = 2.8	14% reported use of medication for LBP during 4.5-year follow-up	Peak LI and CLI are useful metrics for estimating medication use for LBP
Kucera et al. (2009)	105	*M* = 46	Prospective	Fishing	Range 0–5.4	61%	The LI > 3.0 is associated with LBP
Lu et al. (2014)	78	*M* = 40	Prospective	Manufacturing	Mean CLI = 1.5	32% reported LBP during 1-year follow-up	The CLI > 2.0 may be useful for predicting LBP
Marras, Fine, Ferguson, & Waters (1999)	353[a]	N/A	Cross-sectional	Manufacturing	—	N/A	RNLE identifies high-risk jobs well but not low-risk jobs
Schneider et al. (1997)	19	21–46	Cross-sectional	Manufacturing	Range 3.9–8.2	47%	High prevalence of back pain is related to high LI values
Sesek et al. (2003)	182[a]	N/A	Retrospective	Manufacturing	—	N/A	OR for back injury were found to be 2.1 and 4.0 for LI values of 1.0 and 3.0, respectively
Wang et al. (1998)	97	17–62	Retrospective	8 industry sectors	—	90%	The LI is a reliable measure for assessing discomfort rating due to LBP
Waters et al. (1999)	308	*M* = 46	Cross-sectional	Manufacturing	—	30%	OR for LBP is 2.45 for 2 < LI < 3
Waters, Lu, Piacitelli et al. (2011)	677	*M* = 36 (19–68)	Cross-sectional	Manufacturing	0–9.37	20%	Within a range of LI from 1.0–3.0, there is an exposure–response relationship between the LI values and LBP
Xiao, Dempsey, Lei et al. (2004)	69	*M* = 41	Cross-sectional	Manufacturing	1.9–2.4 (median value)	64%	Lifting repetitiveness and work age contributed to the occurrence of LBP
Yeung et al. (2003a)	217	*M* = 39	Cross-sectional	WRT	N/A	N/A	Workers' perceived effort is significantly associated with RNLE task variables and MSD symptoms

Note. — = categorical LI data were used; CLI = composite lifting index; LI = lifting index; LBP = low back pain; MSD = musculoskeletal disorder; N/A = not available; OR = odds ratio; RNLE = Revised National Institute for Occupational Safety and Health Lifting Equation; WRT = wholesale and retail trade.
[a]The number is for jobs, not persons.

(95% CL = 1.4–29.7) for self-reported LBP, respectively (Lu et al., 2014).

Garg and his colleagues published three additional prospective studies on the RNLE in 2014 (Garg, Boda et al., 2014; Garg, Kapellusch et al., 2014; Kapellusch et al., 2014). Based on the same study cohort (the BackWorks Cohort Study), the three studies were aimed at investigating the relationship between the peak LI/CLI and three health outcomes (self-reported LBP, seeking care due to LBP, use of medication for LBP), respectively. An increase in the peak LI was associated with an increased risk of self-reported LBP. The association of the peak CLI with LBP was similar to the peak LI but attenuated at greater exposure magnitudes (CLI > 3.0) (Garg, Boda et al., 2014). The risk of seeking care and use of medication for LBP exhibited a similar pattern (Garg, Kapellusch et al., 2014; Kapellusch et al., 2014). Unlike most previous studies using grouped data with no adjustments for other relevant covariates, the three studies published by NIOSH and the three BackWorks studies were based on each individual's LI/CLI and health outcome data. Personal factors, work-related psychosocial factors, and many other relevant covariates (individual, psychosocial, and work organization factors) were accounted for in the NIOSH and the BackWorks studies (Garg, Boda et al., 2014; Garg, Kapellusch et al., 2014; Kapellusch et al., 2014; Lu et al., 2014; Waters et al., 1999; Waters, Lu, Werren et al., 2011). A prospective study conducted by the Health and Safety Executive of the United Kingdom (Pinder & Frost, 2011), however, indicated an unclear relationship between the CLI and LBP. Overall, these epidemiological studies allow us to gauge the percentage of the workforce that is likely to be at risk for developing lifting-related LBP or simply that the RNLE is a risk assessment tool for LBP-related health outcomes.

It should be noted that three NIOSH and one of the BackWorks studies showed an interesting pattern (Garg, Boda et al., 2014; Lu et al., 2014; Waters et al., 1999; Waters Lu, Piacitelli et al., 2011). The risk for self-reported LBP started to reduce when the maximum/peak CLI reached 3.0 (Garg, Boda et al., 2014). Similarly, the NIOSH studies showed a reduced risk when the maximum CLI was above 3.0 (Lu et al., 2014; Waters et al., 1999; Waters, Lu, Piacitelli et al., 2011). The same effect was also observed in two additional studies where the LBP incidence peaked at CLI/LI = 3.0 and then decreased when CLI/LI > 3.0 (Dempsey et al., 2001). When the RNLE was published, there was a notion that the LI > 3.0 posed a high risk of LBP for most people (Waters et al., 1993). It has been accepted in the ergonomic research community that a job with an LI > 3.0 is a high-risk job. The higher levels of LI/CLI have been demonstrated to be associated with varying levels of LBP outcomes in several other studies (Kucera et al., 2009; Marras et al., 1999; Sesek et al., 2003). This counterintuitive finding deserves an explanation. One potential explanation is due to selective survival or healthy worker effect (Kleinbaum, Morgenstern, & Kupper, 1981). Indirect evidence from the studies include a significantly longer tenure of the workers in the LI > 3.0 category (Waters et al., 1999; Waters, Lu, Piacitelli et al., 2011) and some personal attributes (excellent self-reported health, no history of LBP, highly satisfied with their job, male gender) (Lu et al., 2014). A pooled data analysis of combined data from studies pertinent to the risk exposure assessment may provide additional insight into the potential survival effect. Moreover, future studies are needed with a balanced distribution of physical risk exposures to determine accurate and generalizable risk estimates.

In summary, the importance of measurement and training for using the RNLE has been documented. Many studies have contributed to the body of evidence that supports the use of the RNLE as a tool for assessing high-risk jobs. The assessment of the risk function of the LI may also be complicated by the precision of measures for LBP. Thus, it seems unlikely to quantify the precise degree of risk associated with increments in the LI. However, it is likely that a lifting task with an LI > 1 poses an increased risk for lifting-related LBP for some fraction of the work force. Further research is needed to identify the shape of the risk function.

Standards and Guidelines Based on the RNLE

Review of standards and guidelines was primarily based on authors' knowledge and selected literature (Colombini et al., 2013;

Karwowski, 2006). The main influences of the RNLE on the standards are the manual materials handling standards of the International Standard Organization (ISO) and European Union (EU) (Colombini et al., 2013). The two international standards adopted the RNLE as the reference method. Specifically, the ISO 11228-1 (ISO, 2003) and EN 1005-2 (CEN: European Committee for Standardization, 2003) are standards for manual lifting tasks. It should be noticed that unlike the RNLE, age and gender are part of the analysis process using the ISO 11228-1 standard adopted from the RNLE. These two factors (female gender and age older than 45) act as additional RWL reduction factors, respectively. Many European countries, such as Spain, Italy, and the Netherlands, have adopted the standards as application guidelines for their national legislations regarding manual materials handling (Colombini et al., 2013). For example, the lifting guidelines (A-document) in the Dutch Working Conditions Act contain requirements for optimal lifting situation, which were derived from the RNLE (Karwowski, 2006). The ergonomic standard of the United Kingdom lists the RNLE as one of the validated risk assessment tools (Monnington, Pinder, & Quarrie, 2002). Many American industry organizations also adopted the RNLE for their industry standards or guidelines, such as the American National Standards Institute (ANSI) Ergonomic Standard, American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limits Values for Lifting (ACGIH, 2007), and Automotive Industry Action Group (AIAG) OHS-5 Ergonomic Guidelines for Small Lot Delivery (AIAG, 2007).

In 1997, California was the first state in the United States to adopt an ergonomic standard, however the standard does not describe RNLE. In 2000, the federal ergonomic standard in the United States was passed, which included the RNLE as one of the validated risk assessment methods. After the federal ergonomic standard was repealed in 2001, the state of Washington passed its ergonomic standard including lifting guidelines based on RNLE. Similar to the federal standard, the Washington State ergonomic standard was revoked in 2003. In lieu of a state standard for manual lifting, California OSHA and NIOSH co-published the ergonomic guidelines for manual material handling, which includes RNLE (NIOSH, 2007). Other states, such as Washington and Ohio, have adopted state ergonomic guidelines for manual lifting. The main difference between the state guidelines for lifting and the RNLE is the simplified measuring method for risk identification. Precise measurements of each task variable need to be taken for calculating the LI, whereas a zone system (i.e., grouped distances from the body to the object lifted) is used in these state guidelines.

There are some limitations in this review. First, the evaluation of the impact of the RNLE is in large part predicated on the quantity of the research documents we found, rather than the quality. We made a choice to include all relevant documents without assessing their quality for inclusion in the first part of the review to have a broader sense of the impact. To improve relevance and review quality, only peer-reviewed articles were used in the second part of the review. The scientific merit of the selected articles, however, was not scored or weighted for the evaluation. Second, the review of lifting standards and guidelines is incomplete because of our language limitations (i.e., English only) and the nonsystematic approach to identifying the standards and guidelines. Third, RNLE software applications including apps on mobile devices were not covered by this review because they were not considered to have an impact.

CONCLUSION

The worldwide impact of the RNLE is diverse, including validation of the selection criteria of scientific evidence for the RNLE, comparison of risk assessment methodologies for MSDs, assessment of risks for MSDs in different working populations, relationship between the LI/CLI and LBDs, and most importantly adoption of the RNLE in many state, national, and international ergonomic standards. The current state of the literature suggests a relationship between the LI/CLI and LBP outcomes. However, complete validation of the risk function of the LI/CLI variable and its relationship with different health outcomes of MSDs remains elusive. Future studies are needed with a balanced distribution of physical and nonphysical risk exposures to determine accurate and generalizable risk estimates. The multiplicative property of the RNLE remains to be substantiated by additional research. Lifting speed, trunk flexion, gender, and age have been suggested to be included in the RNLE for improving the limitations of the RNLE (Hidalgo et al., 1997; Jager & Luttmann, 1999; Lavender et al., 1999; Marras et al., 1999; Potvin, 2014; Yeung et al., 2003b). Research is needed to address the aforementioned issues and extend the application of the RNLE to encompass a wider range of lifting tasks, such as one-handed lifting, lifting while being seated, dynamic lifting, lifting combined with pushing/pulling/carrying, lifting in a longer period than 8 hr, and lifting in suboptimal conditions.

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KEY POINTS

- The impact of the RNLE has been both widespread and influential.
- The RNLE has been the most widely used job analysis tool for assessing or designing manual lifting tasks among all ergonomic risk assessment tools.
- The state of the scientific literature suggests a positive relationship between LI/CLI metrics and the severity of LBP outcomes.
- Evidence was found on the adoption of the RNLE as an ergonomic standard for use by various local, state, and international entities.

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