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ORIGINAL ARTICLE

Developing a New Vertical Multiplier to Modify the Revised NIOSH Lifting Equation

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ABSTRACT

Amongst occupational disorders, musculoskeletal disorders and, most importantly low back pain is the most frequent ones. The most popular and widely used risk assessment method among ergonomists for estimating LBP exposure risk is the Revised NIOSH Lifting Equation. In order to improve RNLE, many studies have been carried out yet, and their limitations have been described. One of these cases is the inconsistency of vertical multiplier with anthropometric conditions of various workers' societies. Methods: In the present study, by designing a laboratory work, VM has been carefully considered. Thirty-one volunteer students consisting of 19 males and 12 females, participated in two tests, using a dynamometer; and results were analyzed by Minitab software. Results: The results have shown a significant relationship between isometric muscular strength in two tests, but there was no correlation between body mass index and isometric muscle strength. Based on results, VM, permissible, and the optimum range of manual lifting location height were analyzed and adapted to volunteers' condition. Conclusion: It seems that with changes that have been made, the RNLE results can be more proportionate for Iranian workers.

KEYWORDS: *Ergonomics, Manual Handling, Risk Assessment, Vertical Multiplier, Muscle Strength.*

INTRODUCTION

According to the International Labour Organization (ILO) report, there are about 160 million occupational diseases worldwide annually, most involving work-related musculoskeletal disorders (WMSDs) [1]. Also, the cost of fatal work-related diseases is estimated at 1.95 million USD annually [2]. In general, about 70% of musculoskeletal disorders (MSDs) include lower back pain (LBP) and neck pain [3], so that LBP alone form about a quarter of workers' compensation claims in the United States of America [4].

WMSDs can be rooted in various physical, psychological, and individual factors. Physical risk factors can include manual handling (e.g., lifting and pushing/pulling) non-natural postures (e.g., bending and twisting), repetitive movements, and vibration [5].

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According to Liberty Mutual Research Institute’s report, in 2014 direct financial costs incurred to the United States trade attributed to repetitive movements, overexertion due to manual handling operation and adverse posture were estimated around 19.5 billion USD and about one-third of this amount relates to direct costs of disabilities resulting from workplace injuries [5].

In order to reduce healthcare costs and increase workers’ health, many risk assessment methods have been developed so far to assess the risk of LBP caused by manual materials handling tasks. One of these methods is the Revised NIOSH Lifting Equation (RNLE) used by over 80% of ergonomics professionals [6]. This method is the most well-known and widely used for ergonomy related studies.

For the development and improvement of RNLE, extensive studies have been carried out, which will be briefly described below. Due to prior studies on the equation’s various multipliers, limitations of the equation components, and necessity of their modification, in the current study was aimed to investigate Vertical Multiplier (VM) adequacy and suitability in RNLE for anthropometric and physiological conditions of Iranian workers. Besides, guidelines for the optimal design of MMH workstations should be extracted, and where necessary, a step should be taken to develop VM.

Nussbaum et al. [7] point out that there is a nonlinear relationship between asymmetric material lifting and injury risk. They stated that increased risk of injury, in the range of 0 to 30 degrees is moderate but from 30 to 90 degrees, this risk increases strongly and Ergonomic interventions are needed, so asymmetric multiplier (AM) linear modeling is not appropriate enough. Later, the existence of a descending nonlinear relationship between the trunk rotation angle and the maximum acceptable weight for lifting was also confirmed [8].

Dempsey and Fathallah [9] examined the applicability of AM in industry and also problems and variability in measurement of this multiplier, noted the lack of ease in applying AM, and emphasized the necessity of modifying it, considering interactions between multipliers and the effect of being symmetric or asymmetric while lifting. In other words, AM has the least measurement accuracy [10]. Later, Okimoto and Teixeira [11] presented a systematic approach and detailed implementation procedures to measure RNLE variables in industrial units.

Dempsey [12] stated that a high percentage of MMH activities could not be analyzed with RNLE, and the nature of lifting and lowering activities variable is such that it is difficult to apply the equation to many tasks. However, Sesek et al. [13] modified RNLE to be used for one-handed asymmetric lifting; without changing the equation’s predictive performance, which increased its usability range.

The necessity of VM correction has been mentioned in three studies. Muslim et al. [14] modified VM in RNLE according to anthropometric dimensions of Indonesian workers using biomechanical, physiological, and psychological criteria during laboratory work, finally presented two equations for VM for near the floor state and far the floor state. Behjati and Arjmand [15] showed that RNLE failed to control loads on the spine while performing load handling near the floor with large load asymmetry. Mentioned results from AM & VM linear modeling while horizontal multiplier (HM) Logarithmic Modeling controlled loads on the spine represent that VM modification according to the trunk flexion angle seems necessary [16].

Despite the conservative approach in RNLE [17], Garg et al. [18] found that RNLE provides useful indicators for estimating exposure work-related physical stresses. Later by presenting continuous Frequency Multiplier (FM) and Cumulative Lifting Index (CULI), shown that these two indicators can provide a more accurate estimate of LBP exposure risk [19].

The necessity of Coupling Multiplier (CM) correction that has the least measurement accuracy [10], has been mentioned in two studies. Sevene et al. [20] studied differences in hand grip strength concerning gender in older people, and two years later, three values of 1, 0.8, and 0.7 were proposed as substitutes for the three previous values (1, 0.95 and 0.9) in the CM [21].

MATERIALS AND METHODS

METHODOLOGY:

This study, including two parts of laboratory and result analysis, was cross-sectional plus laboratory work, in which anthropometric data of volunteers were recorded through interviews.

In the current study, the dependent variable is isometric muscle strength in Normal Test (NT) and Vertical Test (VT). It had to be mentioned that the Normal Test is the first part of the experiment in which, the volunteer is in an upright position; and Vertical Test is the second part of the experiment in which, the volunteer is on a bent knee (in the procedure section both will be explained in detail). Independent variables of the study are age, gender, height (cm), weight (kg), and body mass index (BMI).

Revised NIOSH Lifting Equation (RNLE):

The Revised NIOSH Lifting Equation (RNLE) consists of six multipliers and a constant load of 23 kg. Recommended Weight Limit (RWL) according to Equation 1 and the values of the six multipliers are calculated according to Table 1 [22, 23].

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \qquad (1)$$

About VM, the 1991 NIOSH committee, in the process of revising 1981 equation, based on biomechanical, physiological and psychological studies, they concluded that although no direct empirical data exist to provide a specific adjustment value for lifting near the floor, VM provides at least a 22.5 percent decrease in the allowable weight for lifts originating near the floor. Also, the maximum acceptable weight of lift decreases as the vertical height of the lift (V) increases above 75 cm. So, the 1991 NIOSH committee chose a discount value of %22.5 to decrease the allowable weight for lifts at shoulder level (150 cm) and for lifts at floor level and finally resulting to VM (based on cm) according to Table 1 [22]. Coupling Multiplier (CM) according to Table 2, holds one of the three values of 1, 0.95, and 0.9, and the penalty for a poor coupling should not exceed %10 [22, 23].

Table 1. Equation multipliers calculations [22, 23]

Metric Standard Calculation	Multiplier Name
$HM = \begin{cases} 1 \ , \ H \leq 25 \\ 25/H \ , \ H > 25 \\ 0 \ , \ H > 63 \end{cases}$	*Horizontal Multiplier*
$VM = \begin{cases} 1 - 0.003\lvert V - 75\rvert \ , \ V \leq 175 \\ 0 \ , V > 175 \end{cases}$	*Vertical Multiplier*
$DM = \begin{cases} 1 \ , \ D \leq 25 \\ 0.82 + \left(\frac{4.5}{D}\right) \ , \ 25 < D \leq 175 \\ 0 \ , \ D > 175 \end{cases}$	*Distance Multiplier*
$AM = \begin{cases} 1 - 0.0032A \ , A \leq 135 \\ 0 \ , A > 135 \end{cases}$	*Asymmetric Multiplier*
According to Table 3	*Frequency Multiplier*
According to Table 2	*Coupling Multiplier*

Table 2. Coupling multiplier (CM) in RNLE [22, 23]

Coupling Type	Coupling Multiplier	
	V < 75 cm	V ≥ 75 cm
Good	1.00	1.00
Fair	0.95	1.00
Poor	0.90	0.90

Table 3. Frequency multiplier (FM) in RNLE [22, 23]

Frequency lifts/min	Work duration					
	≤ 1 hour		> 1 but ≤ 2 hours		> 2 but ≤ 8 hours	
	V < 75 cm	V ≥ 75 cm	V < 75 cm	V ≥ 75 cm	V < 75 cm	V ≥ 75 cm
0.2 ≤	1.00	1.00	0.95	0.95	0.85	0.85
0.5	0.97	0.97	0.92	0.92	0.81	0.81
1	0.94	0.94	0.88	0.88	0.75	0.75
2	0.91	0.91	0.84	0.84	0.65	0.65
3	0.88	0.88	0.79	0.79	0.55	0.55
4	0.84	0.84	0.72	0.72	0.45	0.45
5	0.80	0.80	0.60	0.60	0.35	0.35
6	0.75	0.75	0.50	0.50	0.27	0.27
7	0.70	0.70	0.42	0.42	0.22	0.22
8	0.60	0.60	0.35	0.35	0.18	0.18
9	0.52	0.52	0.30	0.30	0.00	0.15
10	0.45	0.45	0.26	0.26	0.00	0.13
11	0.41	0.41	0.00	0.23	0.00	0.00
12	0.37	0.37	0.00	0.21	0.00	0.00
13	0.00	0.34	0.00	0.00	0.00	0.00
14	0.00	0.31	0.00	0.00	0.00	0.00
15	0.00	0.28	0.00	0.00	0.00	0.00
> 15	0.00	0.00	0.00	0.00	0.00	0.00

Contrary to the 1981 equation, in RNLE, Frequency Multiplier (FM) is obtained from a table rather than from a mathematical expression and table. Three factors were considered to calculate FM: number of lifts per minute (frequency), amount of time engaged in lifting activity (duration), and vertical height of lift from the floor. Also, three short-duration, moderate-duration, and long-duration periods (Table 3) were considered for work duration [22, 23].

The values in Table 3 are divided into two categories based on how they are calculated: For lifting frequencies up to four lifts/min, psychophysical data from Snook and Ciriello (1991) were used to develop FM values. For lifting frequencies above 4 lifts/min, FM values were determined from a three-step process using the energy expenditure prediction equations developed by Garg (1976) [22].

Finally, by calculating the six multipliers and obtaining RWL, Lifting Index (LI) is obtained by dividing the weight of the load lifted (L) over the RWL according to Equation (2), and it is used to estimate the risk of work-related LBP [4].

$$LI = \frac{L}{RWL} \tag{2}$$

If LI is less than one, working conditions are appropriate. If LI is between one and three, we need ergonomic interventions such as job rotation, and if LI is larger than 3, almost all lifting workers are at risk, and working conditions must be corrected immediately [22, 23].

Participants

This study aims to obtain results that can be applied for Iranian workers and Manual Materials Handling (MMH) systems in domestic industries. In this study, 31 volunteer students of Iran University of Science and Technology (IUST) participated. They consisted of 19 males and 12 females, and the experiments were conducted in the Advanced Ergonomics Lab in the School of Architecture and Urban Development at IUST. The experiments' conditions and purposes were fully explained to the students while voluntarily participating in the experiments. Table 4 shows the volunteers' general information.

Table 4. Volunteers' general information

	Age (Mean ± SD)	Weight (Mean ± SD)	Height (Mean ± SD)
Men	21.263 ± 1.147	79 ± 17.356	177.368 ± 5.823
Women	21.5 ± 1.508	59.333 ± 11.610	162.333 ± 3.447
All	21.355 ± 1.279	71.387 ± 18.027	171.548 ± 8.951

Procedure

In the current study, a dynamometer with a gram-force (gr.f) unit was used. This dynamometer can display the isometric force of muscles at any moment (as shown in Fig. 1). This device can also be adjusted to show the maximum isometric force applied in a short interval, and this capability was used in this study.

Fig 1. Dynamometer (Advanced Ergonomics Lab-IUST)

The laboratory procedure has been conducted in two parts with different conditions. In the laboratory procedure's first part, participants stand entirely on the dynamometer base, gripping two-handed chainsaws so that handles are held in the palm of their hand, in a way that fingers are tightened around the handle. The elbow angle is 90 degrees, and the wrist has no flexion (Figure 2a).

Then, the chains are adjusted to fit individual height so that the chains are not too loose or in a stretched state as well as being balanced and unrestrained. Then volunteer pulls the handles upwards in perfectly normal conditions without any excessive force that causes fatigue or overexertion, in that, the purpose of the experiment is to simulate the process of MMH by the worker. Following mentioned steps by volunteers, the maximum isometric power recorded by the dynamometer has been written down as NT.

After enough rest for the volunteer, in the experiment's second part (Vertical Test), volunteer conducts the same test when the knee-popping angle is 120 degrees (Figure 2b). It should be noted that the angle is accurately measured with a goniometer. Then the maximum isometric force recorded by the dynamometer is noted down as VT. At the end of the experiment, every volunteer’s height, weight, and age had been registered.

A notable point about Vertical Test (VT) is that the elbow height in VT decreased in comparison to elbow height in Normal Test (NT) (Figure 2). The mentioned point will be used to modify VM in RNLE for Iranian workers in this research.

Univariate linear regression and Pearson correlation coefficients were used to analyze data while obtaining a meaningful relationship between the independent and dependent variables of the research. The confidence level of 0.95 was also considered for all methods. The Minitab software version 17.1.0 was used for the experiment's data analysis.

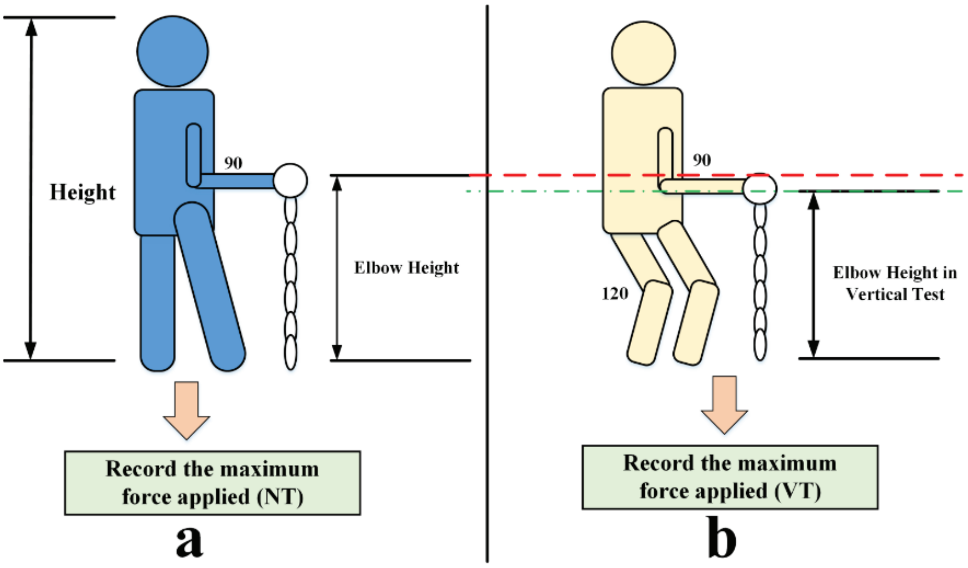


Fig 2. How to perform two tests and elbow height difference in Normal and Vertical Test?

RESULTS

The results of two Normal and Vertical Tests for males and females, as well as in general for all volunteers, can be seen in Table 5 and Figure 3. The Average isometric muscle strength of females in isometric males' muscular strength, respectively. The maximum isometric muscle strength recorded in both tests was for males, and the least was for females.

Normal and Vertical Test was 45% and 36% of According to Figure 4, there is a significant correlation between isometric muscle strength in Normal Test and Vertical Test ($R - Sq = 79.1\%$). However, there is a very weak correlation between BMI, height, and weight with isometric muscle strength in two tests, and this correlation is lower for BMI than for height and weight.

Table 5. Results of the Normal Test and Vertical Test

	NT (gr.f)			VT (gr.f)		
	Mean ± SD	Min.	Max.	Mean ± SD	Min.	Max.
Men	33055.3 ± 16855.4	10700	67250	28115.8 ± 11501.9	14150	54650
Women	12025.0 ± 6111.1	4600	24400	12745.8 ± 5620.9	6900	24500
All	24914.5 ± 17105.1	4600	67250	22166.1 ± 12201.5	6900	54650

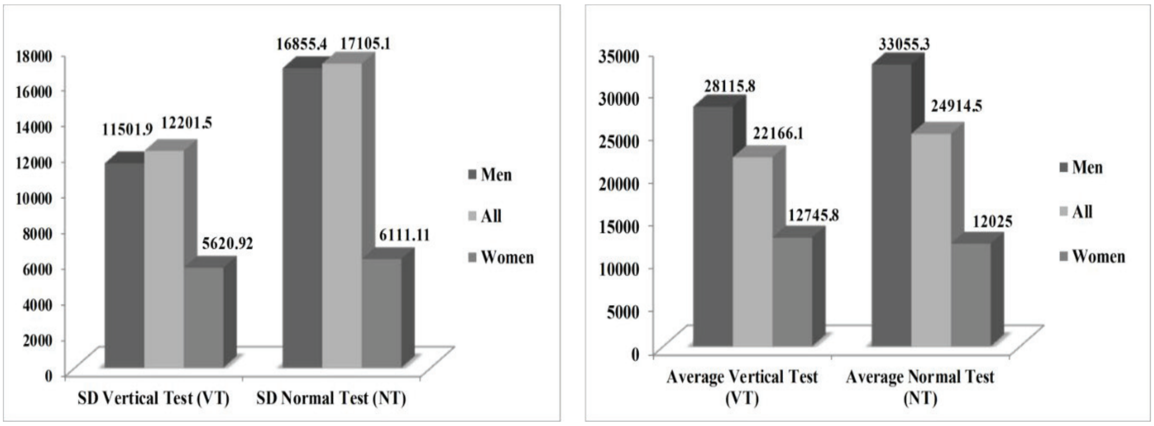
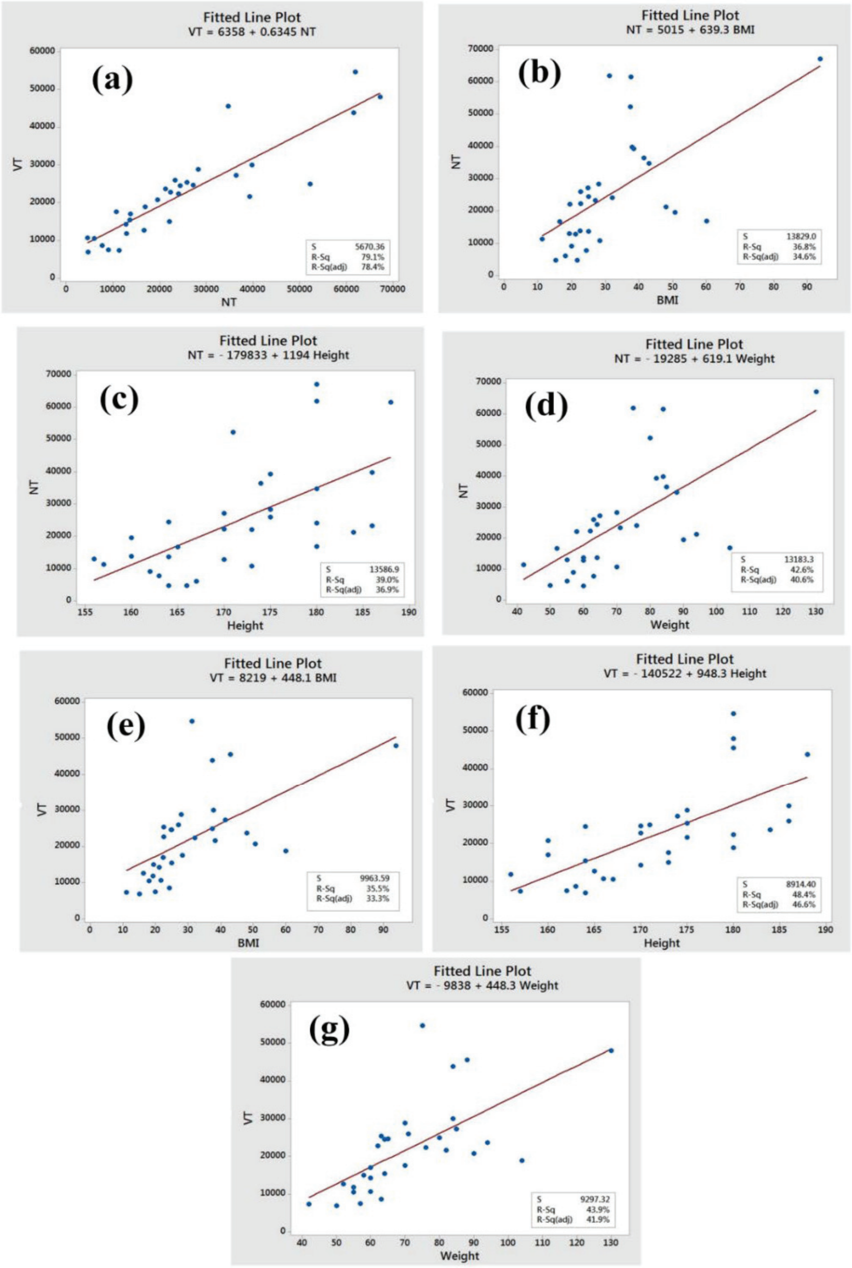
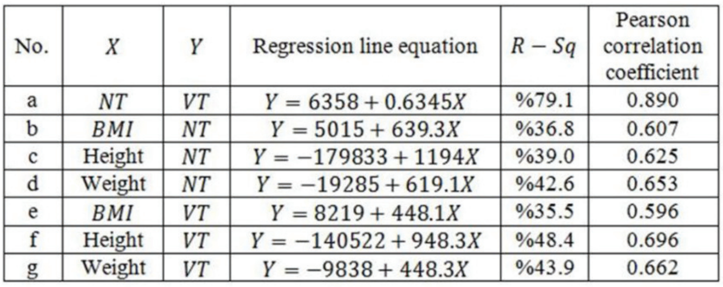


Fig 3. Mean and standard deviation of isometric muscle strength in two tests





No.	X	Y	Regression line equation	$R-Sq$	Pearson correlation coefficient
a	NT	VT	$Y = 6358 + 0.6345X$	%79.1	0.890
b	BMI	NT	$Y = 5015 + 639.3X$	%36.8	0.607
c	Height	NT	$Y = -179833 + 1194X$	%39.0	0.625
d	Weight	NT	$Y = -19285 + 619.1X$	%42.6	0.653
e	BMI	VT	$Y = 8219 + 448.1X$	%35.5	0.596
f	Height	VT	$Y = -140522 + 948.3X$	%48.4	0.696
g	Weight	VT	$Y = -9838 + 448.3X$	%43.9	0.662

Fig 4. Isometric muscle strength in two tests vs personal characteristics regression graphs

DISCUSSION

It is essential to compare isometric muscle strength recorded in the Vertical Test and Normal Test to correct the VM of RNLE. Before comparing, it should be noted that based on anthropometric regression models, the average elbow height in the Normal Test is 108 cm (Calculations in Appendix). On the other hand, while in VM of RNLE, 75 cm load vertical height from the ground is considered the ideal reference point; all volunteers' average isometric muscle strength in the Vertical Test is 11.031% lower than Normal Test. However, the maximum isometric muscle strength for Iranian anthropometric dimensions sample in this study has been recorded in vertical height of approximately 108 cm. Therefore, the optimal point should be replaced with 75 cm in the VM to avoid fatigue and a decrease in isometric muscle strength at a height of more than 108 cm.

To calculate the percentage of isometric muscle strength reduction for 1 cm decrease in elbow height, the decrease in elbow height at Vertical Test must be calculated using mathematical equations first. Elbow height decrease in Vertical Test is about 5.5 cm (Calculations in Appendix), and as mentioned, this reduction in elbow height resulted in an 11.031% decrease in isometric muscle strength. Thus, with a simple proportion, the decrease in isometric muscle strength is 2.01% per 1 cm decrease in elbow height, so this value must substitute %0.3 in VM as a reduction coefficient. Finally, according to the above descriptions, Vertical Multiplier is modified as Equation 3 that is a trapezoidal fuzzy number (Figure 5).

$$VM = 1 - 0/0201\,|V - 108| \tag{3}$$

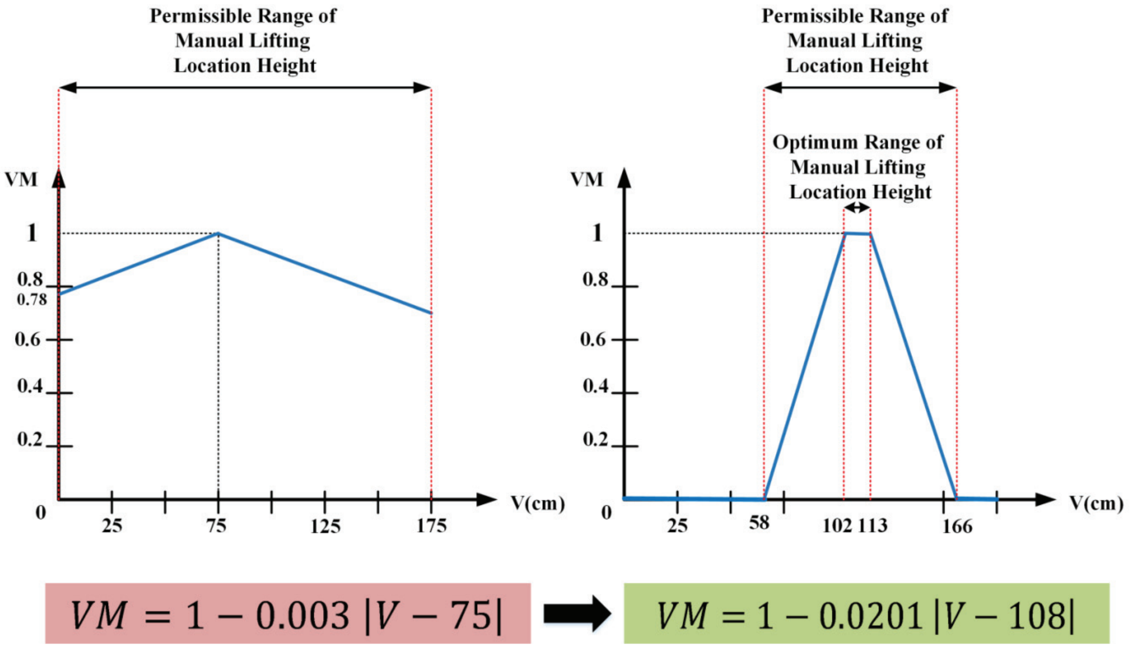


Fig 5. Modified vertical multiplier in RNLE

There are several crucial points about the modified VM equation (Figure 5):

Considering a point as the optimal reference range does not make sense after all. Despite the results of previous studies, saying increasing VM more than 75 cm, reduces the maximum acceptable weight lifted, it has been considered to use standard deviation ($\pm SD$), with the range of 102 to 113 cm as an optimal range for VM [24-26]. On the other hand, in the previous study declared that, e.g., %12 decrease in RWL to change the Vertical Multiplier from 70 cm to 30 cm (Equivalent to the VM reduction from 0.985 to 0.865), is not an appropriate way of modeling since the trunk flexion in this change is manifold [15].

The VM becomes negative for values less than 58 cm and more than 166 cm, in which VM would be considered zero. This way, modified VM present a permissible or recommended range of manual lifting location height (58 to 166 cm) that was not concluded in the VM in previous RNLE at all.

The recommended upper limit (166 cm) is also close to 175 cm in the RNLE and confirms it [22, 23]. However, the main improvement has been made at lower bound where for values less than 55 cm, VM is set to zero. While in RNLE, e.g., when the load is near the floor and the condition is unfavorable, VM takes 0.78, which is very conservative. For a better interpretation of this point, it can be said that other multipliers in the equation adopt zero value at very adverse conditions, but VM does not comply with this law in its lower bound, and for this reason, the previous study emphasized the necessity to modify VM by considering the trunk flexion angle [16]. Also, the modified VM is more in line with a nonlinear model than the previous VM. It seems that the modified VM can fix the problem of failing to control loads on the spine while performing load handling near the floor with large load asymmetry [15].

Due to the development of VM and direct relationship of this multiplier with CM and FM, the correction of CM and FM by considering the single effect of each multiplier and the interactions between multipliers seems necessary [27].

CONCLUSION

According to Figure 3 and Table 5, the average isometric muscle strength of volunteers in the Vertical Test was 11.031% lower than in the Normal Test, and it was used for VM modification. Besides, dispersion (SD) of isometric muscle strength in males was more than females in two tests; likewise, the average isometric muscle strength of males was higher than females in both tests. The dispersion (SD) of isometric muscle strength in both males and females was higher in Normal Test than in Vertical Test. In this study, on the other hand, there was not any correlation between height, weight, and BMI with isometric muscle strength. Nevertheless, there was a significant correlation between the results of isometric muscle strength in the two tests.

It seems that VM in RNLE was not compatible with any anthropometric dimensions. Therefore, 75 cm for vertical height and 0.003 as a reduction coefficient cannot apply to any workers' community without considering anthropometric conditions. Also, by modifying VM, a permissible range (58 to 166 cm) and an optimum range (108±6 cm) of manual lifting location height has been obtained. It is suggested that, in order to apply force in the best conditions, place conveyors in the mentioned height range.

The limitation of statistical sample to the student population, having a small sample size to generalize results to Iranian workers' community and studying the isometric muscle strength of volunteers over short intervals and not long intervals (e.g., one or two hours) were the main limitations of this research.

For further research, since VM is closely related to FM and CM, future research can develop these two multipliers by using the modified VM. Also, investigating the isometric muscle strength trend over longer intervals (e.g., more than one hour) can also be effective in modifying FM timing.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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APPENDIX

The calculation of the elbow height reduction in the Vertical Test compared to the Normal Test is as follows: Volunteers' height is 171.548, cm and the standard deviation is 8.9511 cm. According to anthropometric regression models, the elbow height is 0.63 of height, then we have:

$$\mathrm{E} = 0.63 \times \mathrm{H} = 0.63 \times 171.54 = 108.075 \text{ cm}, \qquad \mathrm{SD_E} = 0.63 \times 8.9511 = 5.639 \text{ cm}$$

Also, according to anthropometric models, knee height is 0.3 of height, and knee length is 0.34 of height, so we have:
$\mathrm{e} = 171.548 \times 0.30 = 51.464$ cm,
$\mathrm{SD_e} = 0.30 \times 8.9511 = 2.685$ cm
$\mathrm{D} = 171.548 \times 0.34 = 58.326$ cm, $\quad \mathrm{SD_D} = 0.34 \times 8.9511 = 3.043$ cm

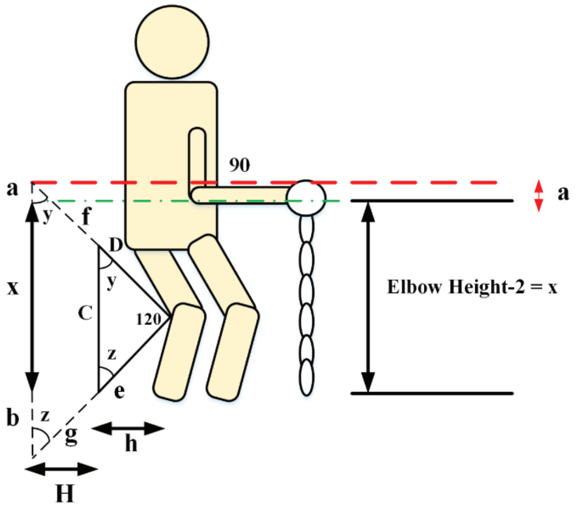

Fig 6. Calculations sample

According to Figure 6 and trigonometric equations we have:

$$\frac{\mathrm{C}}{\sin 120} = \frac{\mathrm{D}}{\sin \mathrm{z}^\circ} = \frac{\mathrm{e}}{\sin \mathrm{y}^\circ} \rightarrow \frac{\mathrm{C}}{0.866} = \frac{58.326}{\sin \mathrm{z}^\circ} = \frac{51.464}{\sin \mathrm{y}^\circ} \rightarrow 58.326 \sin \mathrm{y}^\circ = 51.464 \sin \mathrm{z}^\circ$$

We need to calculate the angles of y and z, and we know that the sum of two angles is 60 degrees, so we have:

$$\mathrm{y}^\circ = 60 - \mathrm{z}^\circ \quad \rightarrow \quad 58.326 \sin(60 - \mathrm{z}^\circ) = 51.464 \sin \mathrm{z}^\circ$$

On the other hand we know:
$\sin(\mathrm{a} - \mathrm{b}) = \sin \mathrm{a}\ .\cos \mathrm{b} - \cos \mathrm{a}\ .\sin \mathrm{b}$

So we can write:

$$58.326\,[0.866\cos z° - 0.5\sin z°] = 51.464\sin z°$$

$$50.510\cos z° - 29.163\sin z° = 51.464\sin z° \quad \rightarrow \quad 50.228\cos z° = 80.627\sin z° \quad \rightarrow$$

$$\cos z° = 1.605\sin z°$$

In addition, we know: $\sin^2 z° + \cos^2 z° = 1$, so we can write: $\sin^2 z° + 2.576\sin^2 z° = 1$

$$\sin^2 z° = \frac{1}{3.576} = 0.280 \quad \rightarrow \quad \sin z° = 0.529 \quad \rightarrow \quad z° = 31.938 \text{ و } y° = 28.062$$

As a result we can write: $\mathrm{C} = \frac{0.866\times 58.326}{0.529} = 95.483 \text{ cm}$

On the other hand, based on trigonometric equations we have:

$$\sin z° = 0.529 = \frac{h}{e} \quad \rightarrow \quad h = 0.529 \times e = 0.529 \times 51.464 = 27.224\ cm$$

$$\sin z° = 0.529 = \frac{H}{g} \quad \rightarrow \quad g = \frac{H}{0.529} = 1.890H$$

$$sin\,y° = 0.470 = \frac{H}{f} \quad \rightarrow \quad f = \frac{H}{0.470} = 2.128\,H$$

$$E - C = 108.075 - 95.483 = 12.592\ cm$$

According to the Pythagorean relation, we can write:

$$H^2 + 12.592^2 = f^2 \ \rightarrow \ H^2 + 158.558 = 4.528\,H^2 \ \rightarrow \ H = 6.704\ cm \ \rightarrow \ f = 14.266\ cm$$

It can also be written according to Thales theorem:

$$\frac{D}{D+f} = \frac{e}{e+g} = \frac{C}{E+b} \quad \rightarrow \quad \frac{58.326}{58.326+14.266} = \frac{51.464}{51.464+g} = \frac{95.483}{108.075+b}$$

$$\rightarrow \quad g = 12.588\ cm \quad , \quad b = 10.762\ cm$$

Finally, using the Pythagorean Theorem, trigonometric relations, and the Thales theorem, we have: $a = 5.5\ cm$