Job Level Risk Assessment Using Task Level ACGIH Hand Activity Level TLV Scores: A Pilot Study

Phillip Drinkaus
Richard Sesek
Donald S. Bloswick

Department of Mechanical Engineering, University of Utah, Salt Lake City, UT, USA

Clay Mann

School of Medicine, University of Utah, Salt Lake City, UT, USA

Thomas Bernard

College of Public Health, University of South Florida, Tampa, FL, USA

Existing upper extremity musculoskeletal disorder analytical tools are primarily intended for single or mono-task jobs. However, many jobs contain more than 1 task and some include job rotation. This case/control study investigates methods of modifying an existing tool, the American Conference of Governmental Industrial Hygienists (ACGIH) Hand Activity Level (HAL) Threshold Limit Value (TLV), to assess the upper extremity risk of multi-task jobs. Various methods of combining the task differences and ratios into a job level assessment were explored. Two methods returned significant odds ratios, (p < .05) of 18.0 (95% CI 1.8–172) and 12.0 (95% CI 1.2–120). These results indicate that a modified ACGIH HAL TLV may provide insight into the work-related risk of multi-task jobs. Further research is needed to optimize this process.

HAL   TLV   hand activity level   multitask   work-related risk assessment

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1. INTRODUCTION/BACKGROUND

1.1. Introduction

Upper extremity cumulative trauma disorders (UECTDs) are a problem in the workplace [1] and may be underreported in the USA [2]. These injuries are costly [3] and have the longest time away from work of all injuries [1]. In 1997, the U.S. National Institute for Occupational Safety and Health (NIOSH) published a comprehensive review of the epidemiologic literature on musculoskeletal disorders (MSDs) and occupational exposures [4]. NIOSH concluded that there was adequate evidence for causal relationships between MSDs of several body regions and repetitive motion, forceful exertions, non-neutral postures, vibration, and combinations of occupational exposures [5].

Existing work-related risk assessment tools used to estimate the risk to the upper extremity include Rapid Upper Limb Assessment (RULA) [6], American Conference of Governmental Industrial Hygienists (ACGIH) Hand Activity Level (HAL) Threshold Limit Value (TLV) [5], the Strain Index (SI) [7] and Loading on the Upper Body Assessment (LUBA) [8]. These tools are intended to evaluate single-task jobs, but many industrial/assembly line jobs are multi-task in nature. These multi-task jobs, while perhaps decreasing work-related risk by introducing variation, increase the difficulty of assessing the work-related risk of a job.

An ergonomic analysis tool that can evaluate the risk to the upper extremities of a multi-task job would be invaluable, not only to assess the risk of existing jobs (reactive), but it could also be used to assess the risk of jobs that have not yet been implemented (proactive). This would allow companies to allocate resources to the jobs that need to be corrected, and, ultimately, to prevent the creation of risky jobs. Previous studies have shown that analysis tools developed for mono-task jobs may be modified to assess multi-task jobs [9].

The purpose of this paper is to investigate various methods of modifying the ACGIH HAL TLV to estimate the risk of multi-task jobs. These methods include a maximum individual HAL task score for a job and various weighted averages of individual HAL task scores for each task within a multi-task job. The ACGIH HAL TLV is a very flexible analysis tool; however, this flexibility increases the number of permutations that can be investigated to determine the most effective method of combining the single-task scores. This flexibility is due primarily to how the two independent variables, normalized peak force (NPF) and HAL, can be determined. These variables can be defined objectively and subjectively and investigating all of these variations led to 900 different combinations.

There are five main steps of development in this study:

1. The independent variables, NPF and HAL are discussed and alternative methods for operationalizing these metrics are explored.

2. Different methods of measuring the work-related risk of each task are discussed.
3. A modifier called the busy ratio is introduced.
4. Alternative equations of the TLV are presented.
5. Odds ratios for each permutation are calculated.

As an aid to the reader, the end of this paper contains a list and definitions of all the acronyms used in this paper (Table 2).

ACGIH HAL TLV

The following is an overview of the ACGIH HAL TLV, which was proposed in 2000 and adopted in 2001. This is not intended to replace the original documentation and the reader is encouraged to read the original publication [5]. The reader should be aware that HAL is an independent variable used in the ACGIH HAL TLV. This can lead to some confusion and care must be taken when reading, discussing or writing about this TLV. In this paper, ACGIH HAL TLV will refer to the entire process. HAL will refer, exclusively, to the independent hand activity level variable.

The ACGIH HAL TLV addresses mono-task jobs that take place longer than 4 hrs per day. A mono-task job may be defined as a job that requires performing the same set of motions and/or exertions repeatedly [5]. The two independent variables used in the ACGIH TLV are HAL and NPF.

HAL characterizes repetition on a scale from 0 to 10. Where 0 is *completely idle* and 10 is *the greatest level of repetition imaginable*, or *continuous exertion*. This scale was proposed by Latko et al. [10, 11]. HAL is a function of both frequency and speed of work. Table 1 and Figure 1 illustrate the quantitative and qualitative approaches to determining HAL.

NPF is the peak hand force required to perform the task normalized on a scale of 0 to 10, which corresponds to 0 to 100% of the applicable reference strength. The reference strength may be the strength of the worker performing the task, the industrial population strength or some other reference. The normalized peak hand force is determined for a task by

TABLE 1. Hand Activity Level (HAL) (0–10) as Related to Exertion Frequency and Duty Cycle (% of Work Cycle Where Force Is Greater Than 5% of Maximum)

Frequency (exertion/s)	Period (s/exertion)	Duty Cycle (%)				
		0–20	20–40	40–60	60–80	80–100
0.125	8.0	1	1	—	—	—
0.250	4.0	2	2	3	—	—
0.500	2.0	3	4	5	5	6
1.000	1.0	4	5	5	6	7
2.000	0.5	—	5	6	7	8

Notes. Shaded values are HAL scores associated with that frequency (or period) and percent duty cycle; round HAL values to the nearest whole number; use Table 1 or Figure 1 to obtain HAL values.

Motion & exertion description	Hand idle most of the time; no regular exertions	Consistent conspicuous, long pauses; or very slow motions	Slow, steady motions/exertions; frequent, brief pauses	Steady motions/exertions; infrequent pauses	Rapid, steady motions/exertions; no regular pauses	Rapid, steady motions/difficult keeping up or continuous exertion
HAL Score	0	2	4	6	8	10

Figure 1. HAL can also be determined with these qualitative guidelines. *Notes.* HAL—hand activity level.

- Measuring hand forces and corresponding postures;
- Obtaining strength data for that posture and that worker or worker population. In most cases, strength values can be obtained directly or extrapolated from the literature; and
- Calculating normalized peak hand force by dividing required force by the appropriate strength or population reference.

Methods for assessing hand force include

- Worker ratings;
- Observer ratings;
- Biomechanical analyses;
- Force gauges;
- Electromyography.

After determining HAL and NPF for a task, a vertical line is drawn from the HAL value and a horizontal line from the NPF value as shown in Figure 2. The relationship between the intersection of these two lines with respect to the TLV and action limit (AL) lines (defined below) determines the ACGIH HAL TLV measure of work-related risk of the task.

If the intersection of these two lines is on or above the TLV line, this represents "those combinations of force and hand activity level associated with a significantly elevated prevalence of musculoskeletal disorders. Appropriate control measures should be utilized so that the force for a given level of hand activity is below the upper solid line in Figure 1. It is not possible to specify a TLV® that protects all workers in all situations
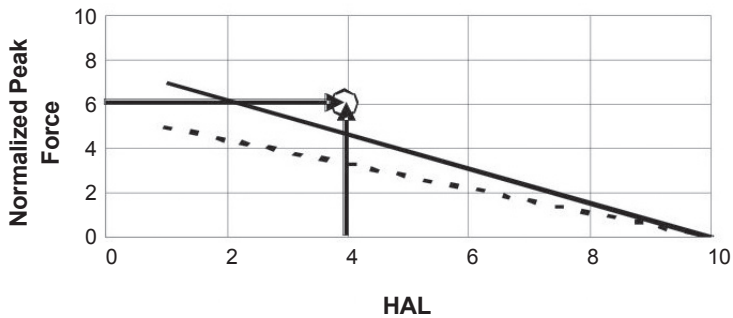

Figure 2. Example of ACGIH HAL TLV with NPF score of 6 and a HAL score of 4. *Notes.* ACGIH HAL TLV—American Conference of Governmental Industrial Hygienists Hand Activity Level Threshold Limit Value, NPF—normalized peak force; TLV is represented by solid line, AL is represented by dashed line.

without profoundly affecting work rates. Therefore, an action limit is prescribed at which point general controls, including surveillance, are recommended" (p. 111) [5].

For example, if the task has a HAL rating of 4 and an NPF of 6, then the intersection is above the TLV line (Figure 2). The ACGIH HAL TLV for the mono-task job would recommend that the job be modified. These modifications may include a reduction of NPF, HAL, or a combination of the two.

Limitations of, and work conditions not incorporated into, HAL TLV:

- Applicable to mono-task jobs that last 4 or more hours per day.

Professional judgment and TLV modifications are required for

- Sustained non-neutral postures such as wrist flexion, extension, wrist deviation or forearm rotation;
- Contact stresses;
- Low temperatures;
- Vibration.

It is interesting to note that the HAL guidelines presented in Figure 1 are dependent upon two factors: the number and length of pauses (a function of frequency and cycle time) and/or the speed of work. These variables may be independent. For example, if a worker assembles parts quickly and then waits for more parts, should the fact that the person works quickly override the consistent pauses (HAL 6 or 8) or should the fact that there are frequent pauses be more important (HAL 2 to 4)? Such a scenario occurs frequently in automobile assembly plants.

Another difficulty arises when a worker carries/holds a tool throughout a task. If holding the tool requires greater than 5% of the maximum effort associated with that task, then holding and using the tool would be considered a continuous effort and a HAL score of 10 is indicated; however, this score means the task is necessarily above the TLV, because no amount of force is allowed with a HAL of 10. It is proposed that this may overestimate the risk of that task. Therefore, in addition to an analysis in accordance with the ACGIH HAL TLV instructions, a modified HAL

was determined solely on the basis of speed of work. This modification was applied to instances where a tool or object was held throughout the task and the effort required to hold the object was ≥5% of the maximum effort level for that task.

Hand strength data for the industrial populations for various, non-neutral postures, are difficult to find. This information is important because automobile assembly often requires non-neutral, awkward postures. Without these data, it is difficult to accurately estimate NPF using the biomechanical model.

1.2. Study Background

Two automotive plants were selected from the six plants originally included in a larger study sponsored by the UAW-Ford. The original study collected data for 677 jobs. These jobs were selected randomly. Job analysis included collection of weights, forces, distances and other data including worker feedback, speed of work and other qualitative and quantitative data. Each job was videotaped.

Two workers from each job were asked to fill out symptom surveys. The workers from each job were selected randomly, though because of the production schedule, most worked the day or swing shift. Occupational health nurses (OHNs) administered the symptom surveys. First time office visits (FTOVs) and injuries associated with each job were also collected from each plant's medical database. FTOVs were limited to reports of ergonomic disorders for the 12 months previous to the site visit. This time frame was used because jobs and job descriptions may change with every model year.

The two plants used in this pilot study were selected for two primary reasons: (a) the job cycle times were consistent within these plants; (b) there was little job rotation at these plants. That is, while each job was multi-task in nature, the workers did not rotate between jobs.

2. METHODS

2.1. Definitions and Data Collection

A job was considered to be a case when every person who performed that job and who was interviewed by the nurses reported a symptom attributed to that job *and* there had been at least one FTOV that attributed the reported injury to that job during the past 12 months. A control job was defined as a job on which no participants reported symptoms *and* there had been no FTOV associating that job as a source of injury for the past 12 months. Of the 217 jobs at these two plants, 28 jobs met the strict criteria to be a case or to be a control. A total of 13 control and 15 case jobs were identified and used in this study.

Video data of each case/control job were collected from the UAW-Ford archives and analyzed. The videos were randomly analyzed so that the observers would not know if a particular job was considered a case or a control. Each job was divided into work elements or tasks. Tasks are contiguous activities of a job that could be removed from the job and transferred to another workstation.

HALs were estimated from these videos, and grip type was recorded. Also recorded were the semi-qualitative ratings from the SI for speed of work (SISW) and intensity of effort (SIIE) for each task. These SI metrics were used to determine if the operationalization of HAL and NPF could be improved. The weights of objects and the forces required to perform the task had already been measured and recorded during the original plant visits.

During the video analysis, two task attributes were timed with a stopwatch. The first attribute was Time Busy. Time Busy was defined as time during which the operator was occupied performing that task and would be unable to perform another task at that time with that hand. (This is not the same as the HAL variable, since a worker can be busy without a sustained effort of >5% of the maximum effort.) The ratio of Busy Time to Cycle Time provides insight into how much "non-busy" time is available to the worker. This non-busy time may be used for rest or it may

provide "slack time" if an error occurs. Such a ratio may also give insight into the psychophysical and psychosocial demands of a job. For the purpose of this study, Busy Time was used to determine the "allocated time" for each task and Cycle Time was determined using average daily production. Allocated time for a task is the amount of time a person is busy plus the amount of rest (or non-busy time) associated with that task.

The ratio of busy time to cycle time is also used in this study to modify the job scores.

$$\text{Busy Ratio}_{\text{Job}} = \frac{\sum_{i=1}^{j} \text{Time Busy}_i}{\text{CT}}, \qquad (1)$$

where CT—Cycle Time.

The second timed attribute was effort duration. This is the time during which the operator is exerting a significant force for that task. This time of exertion is used to determine the Duration of Effort SI variable

The ratios of Busy Time to Cycle Time and effort time to Cycle Time were used in this study to modify the task level HAL TLV scores.

Observer ratings, described in the ACGIH HAL TLV and the SI, and biomechanical analyses were used to estimate NPF.

The biomechanical NPF calculation used the forces required for the task, the grip type and the grip and pinch strength data provided in the ACGIH HAL TLV documentation [5]. These data provide grip strengths for males and females, and for the dominant and non-dominate hands using various grips. The average of these four values was used because both women and men performed these jobs, and it was assumed that the worker may not be able to use their dominant hand due to the workstation layout or task requirement. The average grip strength is 342.1 N, and pinch strength 41.8 N.

This study assumes that most pinches were between digits I–II (thumb and index finger). While this may not always be the case, it is often difficult to determine which fingers are active in the pinch process. Using the average strength values may overestimate the NPF if the most powerful grips (i.e., power grips) are used, and

may underestimate the NPF if less powerful grips are used (i.e., pinch grips between thumb and small finger). The ramifications of this assumption are not trivial and underscore the need for more basic research in hand/posture strength data.

2.2. The Equations of the TLV and AL Lines

By examination it can be determined that the equation for the TLV and AL are

$$\text{NPFTLV} = -\frac{7}{9} \bullet \text{HAL} + 7\frac{7}{9}, \qquad (2)$$

$$\text{NPFAL} = -\frac{5}{9} \bullet \text{HAL} + 5\frac{5}{9}. \qquad (3)$$

To determine where the task fell in relation to the TLV and AL lines, the observed HAL was placed into the TLV equation and the Actual Normalized Peak Force (NPFACT) (the *y* axis) was compared with the NPF allowed based on the TLV line (NPFTLV).

For example, if a task required a power grip of 22.7 N and had a HAL of 4,

TLV:

$$\text{NPFACT} = \frac{\text{Actual Grip Force}}{\text{Average Woker Population Strength}} \bullet 10,$$

$$\text{NPFACT} = \frac{22.7\,\text{N}}{342.1\,\text{N}} \bullet 10 = 0.66,$$

$$\text{NPFTLV} = -\frac{7}{9} \bullet \text{HAL} + 7.78 = -\frac{7}{9} \bullet 4 + 7.78 = 4.67,$$

$$\text{NPFACT} - \text{NPFTLV} = 0.66 - 4.67 = -4.01.$$

Because the difference between the NPFACT and NPFTLV is negative, the point (4, 0.66) is below the TLV.

AL:

$$\text{NPFACT} = \frac{\text{Actual Grip Force}}{\text{Average Worker Population Strength}} \bullet 10,$$

$$\text{NPFACT} = \frac{22.7\,\text{N}}{342.1\,\text{N}} \bullet 10 = 0.66,$$

$$\text{NPFAL} = -\frac{5}{9} \bullet \text{HAL} + 5.56 = -\frac{5}{9} \bullet 4 + 5.56 = 3.34,$$

$$\text{NPFACT} - \text{NPFAL} = 0.66 - 3.34 = -2.68.$$

Because the difference between the NPFACT and NPFAL is negative, the point (4, 0.66) is also below the AL.

It can be concluded that if NPFACT – NPFTLV or NPFACT – NPFAL is negative, the task is below the TLV or AL lines, respectively, and the predicted risk of an UECTD is relatively low. If the difference is positive, the task is above the line in question and the risk of the job is predicted to be relatively high.

Another measure of relative distance is the ratio between the actual NPF value and the maximum allowable NPF on the TLV line. This ratio may be defined as

$$\text{Ratio}_i = \frac{\text{NPFACT}_i}{\text{NPFTLV}_i}. \qquad (4)$$

For example, using the numbers in this section,

$$\text{Ratio}_{\text{TLV}} = \frac{\text{NPFACT}_1}{\text{NPFTLV}_1} = \frac{0.66}{4.67} = 0.14.$$

Therefore, it can be concluded that if this ratio is less than 1, the task is below the line in question (the TLV or AL) and the predicted risk to UECTD is relatively low. If the ratio is greater than 1, the task is above the line in question and the job is predicted to be relatively high risk.

The relative position of the intersection of HAL and NPF to the TLV and AL lines is important. It is suggested that the vertical distance (or ratio) may be used as a measure of risk in order to develop a task level metric that can be combined for multi-task jobs. The dose-response curve has been investigated and suggests that the greater the dose (in this case dose is the combination of force and repetition), the more likely a response (i.e., symptoms or injury). This curve has been explored by many researchers including Latko [11] and Silverstein [12]. It is suggested that the magnitude of the distance from the TLV line may be a metric for the relative risk of a task.

It is also suggested that there are various surrogates that may be used to determine NPF and HAL. Some of these surrogates and their combinations are explored in this paper. The ACGIH HAL TLV for each task will be calculated various ways:

1. As originally intended by the authors for single task jobs:

$$\text{HAL vs. NPF.} \qquad (5)$$

2. Modifying the HAL score when a tool is held throughout the task. That is, use a modified HAL. The modified HAL is based on speed of work alone. Since automatically assigning a HAL score of 10 for holding a tool throughout a task may over rate the risk of the task:

$$\text{Modified HAL vs. NPF.} \qquad (6)$$

3. Using the metrics as proposed in the SI. This method uses two variables (Speed of Work and Intensity of Effort) from the SI rating system. This method was pursued to determine if alternative ways of operationalizing the independent variables (HAL and NPF) of the ACGIH HAL TLV might improve the results. This rating system for Speed of Work provides a different method of operationalizing HAL. The SI rating system is from 1 to 5 and was normalized to 1–10 by multiplying the SI rating by 2.

a. Using SI speed of work (SISW) in place of HAL (normalized to 10):

$$\text{SISW} \bullet 2 \text{ vs. NPF.} \qquad (7)$$

b. Using the SI intensity of Effort rating (SIIE) in place of NPF (normalized to 10):

$$\text{HAL vs. SIIE} \bullet 2. \qquad (8)$$

c. Using SISW rating and SIIE (both normalized to 10) in place of both the HAL and the NPF, respectively:

$$\text{SISW} \bullet 2 \text{ vs. SIIE} \bullet 2. \qquad (9)$$

2.3. Establishing Job Level Risk From Task Level ACGIH HAL TLV Outputs

Several methods were explored to determine if the ACGIH HAL TLV, developed for single-task jobs lasting 4 or more hours a day, can be modified to estimate the risk of multi-task jobs to the upper extremities.

2.3.1. Method 1

Taking the average distance from the TLV for each task across the job. If this average is negative, then the job is predicted to be a control job.

$$\text{Average Distance}_i = \frac{\sum_{i=1}^{N} \text{Distance Task}_{i_i}}{N}. \qquad (10)$$

2.3.2. Method 2

Taking the maximum difference for each task across the job. That is, taking the largest difference (largest positive number, or, if all the distances are negative, the smallest negative number) between the allowable NPF and the actual NPF to determine if the job is hazardous or not. This method is analogous to taking the maximum (riskiest) task as the metric for the job. If this maximum distance is negative, then the job is predicted to be a control job.

2.3.3. Method 3

Modify the TLV equation, the difference, or the ratio by the Busy Weighted Ratio (BWR) or the Effort Weighted Ratio (EWR).

i. Independent variables, HAL, and the distance and ratio task outputs are multiplied by the busy ratio. Note: Busy ratio is a job level variable:

$$\text{Busy Weighted Ratio}_{Ti} = \text{BWR}_{Ti}$$
$$= \frac{\text{Time Busy}_{Ti}\ (s)}{\text{Cycle Time (s)}}. \qquad (11)$$

This ratio was incorporated into the NPFTLV equation:

$$\text{NPFTLV}_{TiBWR}$$
$$= -\frac{7}{9} \bullet (\text{HAL}_{Ti} \bullet \text{BWR}_{J}) + 7\frac{7}{9}. \qquad (12)$$

The busy ratio was used to modify the distance. That is,

$$\text{Distance}_{TiBWR}$$
$$= (\text{NPFACT}_{Ti} - \text{NPFTLV}_{Ti}) \bullet \text{BWR}_{Ti} \qquad (13)$$
$$= \text{Distance}_{Ti} \bullet \text{BWR}_{Ti}.$$

The busy ratio was used to modify the ratio of NPF actual to NPF TLV. That is,

$$\text{Ratio}_{TiBWR} = \frac{\text{NPFACT}_{Ti}}{\text{NPFTLV}_{Ti}} \bullet \text{BWR}_{Ti}$$
$$= \text{Ratio}_{Ti} \bullet \text{BWR}_{Ti}. \qquad (14)$$

ii. Using the amount of time that the task requires effort.

$$\text{Effort Weighted Ratio}_{Ti} = \text{EWR}_{Ti}$$
$$= \frac{\text{Effort Duration}_{Ti}(s)}{\text{Cycle Time (s)}}. \qquad (15)$$

This effort ratio was incorporated into the NPFTLV equation:

$$NPFTLV_{TiEWR} = -\frac{7}{9} \bullet (HAL_{Ti} \bullet EWR_{Ti}) + 7\frac{7}{9}.$$

(16)

The effort ratio was used to modify the distance. That is,

$$Distance_{TiEWR}$$
$$= (NPFACT_{Ti} - NPFTLV)_{Ti} \bullet EWR_{Ti} \quad (17)$$
$$= Distance_{Ti} \bullet EWR_{Ti}.$$

The effort ratio was used to modify the distance. That is,

$$Ratio_{TiEWR} = \frac{NPFACT_{Ti}}{NPFTLV_{Ti}} \bullet EWR_{Ti} \quad (18)$$
$$= Ratio_{Ti} \bullet EWR_{Ti},$$

where T*i*—task *i*, BWR—Busy Weighted Ratio, EWR—Effort Weighted Ratio, L—left, R—right.

Using the vertical distances and these weighted average methods, the sum of the differences from the allowable TLV for the tasks within the job was calculated. If the sum was less than zero, the job was predicted to be a control job. If the sum was zero or greater, the job was predicted to be a case job.

Similarly, when the ratio outputs were also modified by the busy ratio or the effort ratio, if the output was less than one, the job was predicted to be a control job. If the output was greater than, or equal to one, then the job was predicted to be a case job.

It was also desirable to determine if a modification of the ACGIH TLV line would improve the results. For this study, it was assumed that the anchor point of a HAL of 10 and an NPF of 0 was appropriate. That is, at the most busy or continuous HAL a worker cannot exert force. The slope and the *y* intercept were modified so that each line would go through the point (10, 0). This is similar to creating new cut points, or a cut point "line".

The equations for each line were:

$$y = -\frac{7}{9} \bullet x + 7\frac{7}{9} \text{ (TLV)}, \quad (19a)$$
$$y = -0.7 \bullet x + 7, \quad (19b)$$
$$y = -0.6 \bullet x + 6, \quad (19c)$$
$$y = -\frac{5}{9} \bullet x + 5\frac{5}{9} \text{ (AL)}, \quad (19d)$$
$$y = -0.5 \bullet x + 5, \quad (19e)$$
$$y = -0.4 \bullet x + 4, \quad (19f)$$
$$y = -0.3 \bullet x + 3, \quad (19g)$$
$$y = -0.2 \bullet x + 2, \quad (19h)$$
$$y = -0.1 \bullet x + 1. \quad (19i)$$

Note: the *y* intercept was decreased by about 1 for each equation (except for the original TLV and the AL). These equations were used in a similar fashion as indicated in the example calculations and are illustrated in Figure 3.

Figures 4 and 5 illustrate the permutations explored in this pilot study for the task analyses and the job level calculations, respectively.

2.3.4. Statistics

For each method and approach, 2×2 matrices were created and sensitivities, specificities, negative predictive values, positive predictive values, odds ratios and Fisher's Exact Tests were calculated for each of the 900 variations.
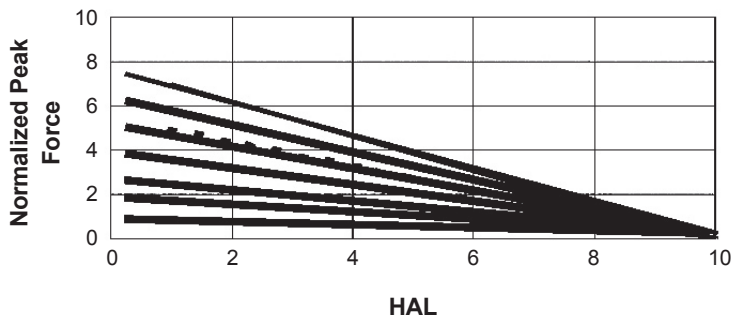

Figure 3. Illustration of alternative TLV lines investigated. *Notes*. TLV— threshold limit value.
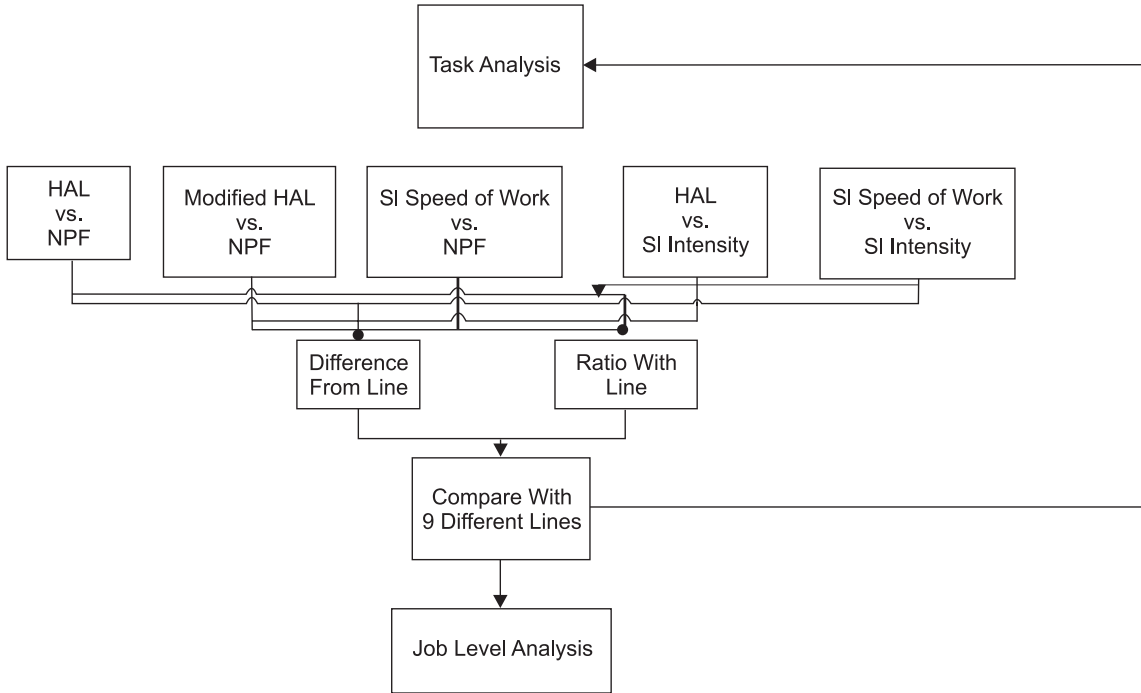
Figure 4. Flow chart of task analysis. *Notes.* HAL—Hand Activity Level, NPF—normalized peak force, SI—Strain Index
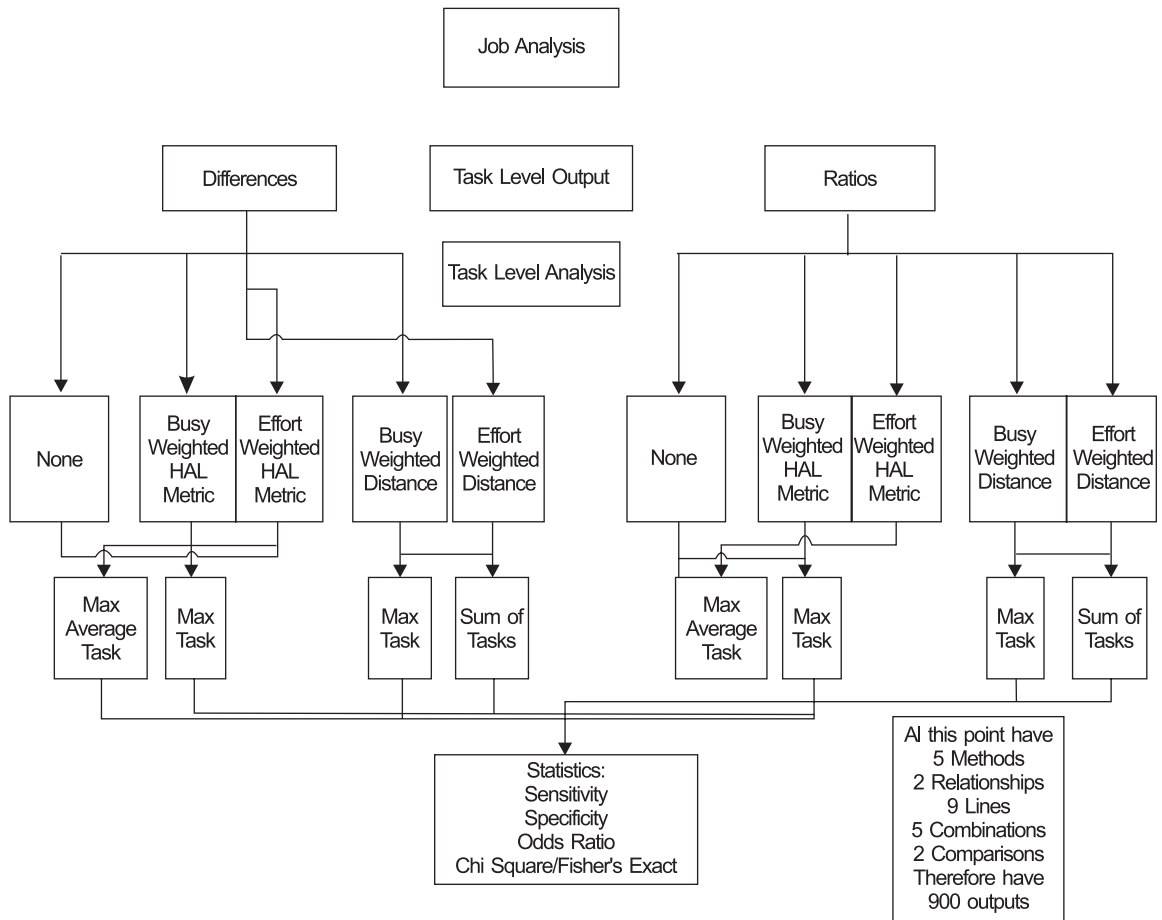

Figure 5. Flow chart of job level analysis. *Notes.* HAL—Hand Activity Level.

3. RESULTS

The results included here are examples of the outputs from the two methodologies (distance from and ratio between the intersection and the TLV line) and cut point lines that provided the largest significant odds ratios.

The results with the best odds ratio for the distance methodology used the SISW, SIIE and Equation 19b,

$$\text{NPFTLV} = -0.7 \bullet \text{SISW} \bullet 2 + 7, \qquad (21b)$$

where NPF is calculated using SIIE $\bullet$ 2.

That is,

$$\text{Distance}_i \bullet \text{BR}_i = (\text{SII}_i \bullet 2 - \text{NPFTLV}_i) \bullet \text{BR}_i$$

$$= (\text{SII}_i \bullet 2 - (-0.7 \bullet \text{SISW}_i \bullet 2 + 7)) \bullet \frac{\text{TimeBusy}_i}{\text{CT}}.$$

Therefore the job score is calculated:

$$\sum_{i=1}^{j} \text{Distance}_i \bullet \text{BR}_i$$

$$= \sum_{i=1}^{j} (\text{SII}_i \bullet 2 - \text{NPFTLV}_i) \bullet \text{BR}_i$$

$$= \sum_{i=1}^{j} (\text{SII}_i \bullet 2 - (-0.7 \bullet \text{SISW}_i \bullet 2 + 7)) \bullet \frac{\text{TimeBusy}_i}{\text{CT}}.$$

This method achieved sensitivity = 0.6, specificity = 0.9, odds ratio = 18.0 (95% CI 1.8–172) and Fisher's Exact Test; $p < .05$.

The results with the largest odds ratio using the ratio methodology and Equation 19h of the line,

$$\text{NPFTLV} = -0.2 \bullet \text{SISW} \bullet 2 + 2. \qquad (19h)$$

That is,

$$\text{Ratio}_i \bullet \text{BR}_i = \frac{\text{SII}_i \bullet 2}{\text{NPFTLV}_i} \bullet \text{BR}_i$$

$$= \frac{\text{SII}_i \bullet 2}{-0.7 \bullet \text{SISW}_i \bullet 2 + 7} \bullet \frac{\text{BusyTime}_i}{\text{CT}}.$$

Therefore the job score is calculated:

$$\sum_{i=1}^{j} \text{Ratio}_i \bullet \text{BR}_i = \sum_{i=1}^{j} \frac{\text{SII}_i \bullet 2}{\text{NPFTLV}_i} \bullet \text{BR}_i$$

$$= \sum_{i=1}^{j} \frac{\text{SII}_i \bullet 2}{-0.7 \bullet \text{SISW}_i \bullet 2 + 7} \bullet \frac{\text{BusyTime}_i}{\text{CT}}.$$

This method achieved: sensitivity = 0.5, specificity = 0.9, odds ratio = 12.0 (95% CI 1.2–120) and Fisher's Exact Test; $p < .04$.

4. DISCUSSION

All of the significant results used alternative metrics for NPF and HAL (SIIE and SISW, respectively). That only a few of the 900 combinations were significant may not be surprising because the ACGHI HAL TLV was originally developed for mono-task jobs that last over 4 hrs a day. If an employee, working an 8-hr day, has evenly divided tasks, the highest number of 4-hr mono-tasks would be two. Only one of our multi-task jobs was limited to two tasks.

There are a number of possible explanations why alternative metrics for HAL and NPF appeared to better predict risk than those proposed in the original ACGIH HAL TLV. The first explanation is that the observers were not trained properly in the application of the observer ratings prescribed for HAL and the NPF in the ACGIH HAL TLV. While this may be true, every attempt was made to learn not only the letter of the ACGIH TLV but also its spirit. Discussions with the original authors were initiated to ensure that the ACGIH TLV was interpreted and applied correctly.

However, using the biomechanical approach to determine NPF did not seem to improve the outcomes, whereas using the SIIE did. It is difficult to get grip strengths for non-neutral grips. As stated in the TLV documentation "Professional judgment should be used to recommend TLV reductions when exposures include work-related risk factors of musculoskeletal disorders such as... sustained non-neutral postures such as flexion, extension, or forearm rotation" (p. 112) [5]. That is, ergonomists must make qualitative judgments about how much NPF should be modified for extreme postures. This is not trivial, nor do ergonomists necessarily agree on the magnitude of the modification. Because non-neutral postures are often required of automotive industry workers, appropriate population strengths for non-neutral postures must be determined to properly apply the biomechanical approach of estimating the NPF.

TABLE 2. Acronyms Used in This Paper

ACRONYM	Full Name
ACGIH	American Conference of Governmental Industrial Hygienists
ACGIH HAL TLV	American Conference of Governmental Industrial Hygienists hand activity level threshold limit value
AL	Action limit
BWR	Busy weighted ratio
EWR	Effort weighted ratio
FTOV	First time office visit
HAL	Hand activity level
HAL TLV	Hand activity level threshold limit value
MSD	Musculoskeletal disorders
NIOSH	National Institute for Occupational Safety and Health
NPF	Normalized peak force
NPFACT	NPF actually observed
NPFTLV	NPF allowable as predicted using the TLV equation
OHMDs	Occupational medicine doctors
OHNS	Occupational health nurses
RULA	Rapid upper limb assessment
SI	Strain index
SIIE	Strain index intensity of exertion
SISW	Strain index speed of work
TLV	Threshold limit value
UECTDs	Upper extremity cumulative trauma disorders

Modifying the HAL ratings when a tool or part was held did not increase the significance of the results. The method using the SISW in place of HAL appeared to provide the best results.

This may indicate that our observers need to modify the application of NPF and HAL; however, this does not explain why using the ACGIH HAL TLV as originally intended did not seem to work as well as the ACGIH HAL TLV using the SI metrics. This is made even more confusing because both the SI and ACGIH HAL TLV indicate that the Borg Scale may be used for intensity of work or NPF, respectively.

Both the distance and ratio methods were improved using the busy ratio. This is in agreement with results found in other studies [9]. This suggests that the busy ratio may be useful not only as a modifier of other independent variables, but may be an important variable by itself.

The preliminary results of this pilot study indicate that the methods proposed here for modifying the ACGIH TLV may aid in determining the work-related risk of a multi-task job. Further research should be conducted to determine if there are other, more appropriate methods of modifying this TLV for multi-task jobs.

Table 2 is an overview of the acronyms used in this paper.

5. CONCLUSION

These results indicate that two of the methods, SISW SIIE Busy Ratio and SISW SIIE Busy Ratio Distance, with their respective TLV lines, are able to predict ($p < .05$) which multi-task jobs have an increased risk of injury.

REFERENCES

1. Bureau of Labor Statistics (BLS). Table 3: number and percent of non-fatal occupational injuries and illnesses involving days away from work involving repetitive motion by selected worker and case characteristics. Washington, DC, USA: United States Department of Labor, BLS; 2003.

2. Silverstein B, Welp E, Nelson N, Kalat J. Claims incidence of work-related disorders of the upper extremities: Washington State, 1987 through 1995. Am J Public Health 1998;88(12):1827–33.

3. National Research Institute (NRI). Musculoskeletal disorders and the

workplace: low back and upper extremities (ES-5). Washington, DC, USA: National Academy Press; 2001.

4. Bernard BP, editor. Musculoskeletal disorders and workplace factors: a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back (Publication No.: 97-141). Atlanta, GA, USA: U.S. Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH); 1997.

5. American Conference of Governmental Industrial Hygienists (ACGIH). Threshold Limit Values for chemical substances and physical agents & Biological Exposure Indices. 2001; Cincinnati, OH, USA: ACGIH.

6. McAtamney L, Corlett EN. RULA: a survey method for the investigation of work-related upper limb disorders. Appl Ergon 1993;24(2):91–9.

7. Moore JS, Garg A. The strain index: a proposed method to analyze jobs for risk of distal upper extremity disorders. Am Ind Hyg Assoc J 1995;56(5):443–58.

8. Kee D, Karwowski W. LUBA: an assessment technique for postural loading on the upper body based on joint motion discomfort and maximum holding time. Appl Ergon 2001;32(4):357–66.

9. Drinkaus P, Bloswick D, Sesek R, Mann C, Bernard T. Job level risk assessment using task level strain index scores: a pilot study. International Journal of Occupational Safety and Ergonomics (JOSE) 2005;11(2):141–52.

10. Latko W. Development and evaluation of an observational method for quantifying exposure to hand activity and other physical stressor in manual work [doctoral dissertation]. Ann Arbor, MI, USA: University of Michigan, Department of Mechanical Engineering; 1997.

11. Latko W, Armstrong TJ, Foulke JA, Herrin GD, Raboum RA, Ulin SS. Development and evaluation of an observational method for assessing repetition in hand tasks. Am Ind Hyg Assoc J 1997;58(4):278–85.

12. Slverstien B, Fine L, Armstrong T. Occupational factors and Carpal Tunnel Syndrome. Am J of Industrial Med 1987;11:343–58.

APPENDIX: SAMPLE CALCULATIONS

The information in Table SC 1 is from a hypothetical two-task job that will be used to illustrate the calculations for each of these methods. Note: only the calculations for the difference method are presented. The ratio outputs were treated in a similar way. To determine the job level ratio outputs, just substitute the task difference with the task ratio.

TABLE SC 1. Independent Variables for the Sample Calculation of a Hypothetical Two-Task Job

Task Number	Side	Cycle Time	Busy Time	Effort Time	Force (N)	HAL	SI Speed of Work	SI Intensity	Grip	Modified HAL	Modified HAL
1	Right	40	10	5	8.9	10	3	2	g	4	4
	Left	40	15	7	4.4	3	2	2	p		3
2	Right	40	20	15	44.5	5	2	3	g		5
	Left	40	10	3	22.2	6	3	3	p		6

Notes. HAL—Hand Activity Level, SI—Strain Index, g—grip, p—pinch.

Normalized Peak Force (NPF)

Using the average grip (342.1 N) and pinch (41.8 N) strengths, NPF is calculated as follows:

$$NPF = \frac{Object\ Weight\ (N)}{Population\ Average\ (N)} \bullet 10,$$

$$NPF_{T1L} = \frac{4.44\ N}{41.8\ lbs} \bullet 10 = 1.1, \qquad NPF_{T1R} = \frac{8.9\ N}{342.1\ N} \bullet 10 = 0.3,$$

$$NPF_{T2L} = \frac{22.2\ N}{41.8\ N} \bullet 10 = 5.3, \qquad NPF_{T2R} = \frac{8.9\ N}{342.1\ N} \bullet 10 = 1.3.$$

This is the same for all methods and represents biomechanical NPF for each hand for each task.

Method 1: HAL

Determine the NPF TLV, given the observed HAL. In this example the observed HALs are 3, 6, 10, 5, for left and right, respectively.

$$NPFTLV = -\frac{7}{9} \bullet HAL + 7.78,$$

$$NPFTLV_{T1L} = -\frac{7}{9} \bullet 3 + 7.78 = 5.4, \qquad NPFTLV_{T1R} = -\frac{7}{9} \bullet 10 + 7.78 = 0,$$

$$NPFTLV_{T2L} = -\frac{7}{9} \bullet 6 + 7.78 = 3.1, \qquad NPFTLV_{T2R} = -\frac{7}{9} \bullet 5 + 7.78 = 3.9.$$

Determine the difference between the NPFACT and the NPFTLV. If the difference is less than zero, then the task is below the TLV; if the difference is positive, then the task is above the TLV.

$$NPFACT - NPFTLV = Difference,$$

$$Diff_{T1L} = 1.1 - 5.4 = -4.3, \qquad Diff_{T1R} = 0.3 - 0 = 0.3,$$

$$Diff_{T2L} = 5.3 - 3.1 = 2.2, \qquad Diff_{T2R} = 1.3 - 3.9 = -2.6.$$

Method 2: HAL based upon speed of work alone

For this job, only task 1 right side (T1R) is changed.

$$NPFTLV = -\frac{7}{9} \bullet HAL + 7.78,$$

$$NPFTLV_{T1L} = -\frac{7}{9} \bullet 3 + 7.78 = 5.4, \qquad NPFTLV_{T1R} = -\frac{7}{9} \bullet 4 + 7.78 = 4.7,^*$$

$$NPFTLV_{T2L} = -\frac{7}{9} \bullet 6 + 7.78 = 3.1, \qquad NPFTLV_{T2R} = -\frac{7}{9} \bullet 5 + 7.78 = 3.9.$$

$$NPFACT - NPFTLV = Difference,$$

$$Diff_{T1L} = 1.1 - 5.4 = 4.3, \qquad Diff_{T1R} = 0.3 - 4.7 = -4.4,^*$$

$$Diff_{T2L} = 5.3 - 3.1 = 2.2, \qquad Diff_{T2R} = 1.3 - 3.9 = -2.6.$$

*Note: only $Diff_{T1R}$ changed.

Method 3i: Use Strain Index's speed of work (SISW) rating multiplied by 2 in lieu of the HAL rating

$$NPFTLV = -\frac{7}{9} \bullet SISW \bullet 2 + 7.78,$$

$$NPFTLV_{T1L} = -\frac{7}{9} \bullet 2 \bullet 2 + 7.78 = 4.7, \qquad NPFTLV_{T1R} = -\frac{7}{9} \bullet 3 \bullet 2 + 7.78 = 3.1,$$

$$NPFTLV_{T2L} = -\frac{7}{9} \bullet 3 \bullet 2 + 7.78 = 3.1, \qquad NPFTLV_{T2R} = -\frac{7}{9} \bullet 2 \bullet 2 + 7.78 = 4.7.$$

$$NPFACT - NPFTLV = Difference,$$

$$Diff_{T1L} = 1.1 - 4.7 = -3.6, \qquad\qquad Diff_{T1R} = 0.3 - 3.1 = -2.8,$$

$$Diff_{T2L} = 5.3 - 3.1 = 2.2, \qquad\qquad Diff_{T2R} = 1.3 - 4.7 = -3.4.$$

Method 3ii: Use Strain Index's intensity of effort rating (SIIE) multiplied by 2 in lieu of the NPFACT rating

Calculate NPFTLV:

$$NPFTLV = -\frac{7}{9} \bullet HAL + 7.78,$$

$$NPFTLV_{T1L} = -\frac{7}{9} \bullet 3 + 7.78 = 5.4, \qquad NPFTLV_{T1R} = -\frac{7}{9} \bullet 4 + 7.78 = 4.7,$$

$$NPFTLV_{T2L} = -\frac{7}{9} \bullet 6 + 7.78 = 3.1, \qquad NPFTLV_{T2R} = -\frac{7}{9} \bullet 5 + 7.78 = 3.9.$$

Calculate Difference using SIIE $\bullet$ 2:

$$SII \bullet 2 - NPFTLV = Difference,$$

$$Diff_{T1L} = 2 \bullet 2 - 5.4 = -1.4, \qquad\qquad Diff_{T1R} = 2 \bullet 2 - 4.7 = -0.7,$$

$$Diff_{T2L} = 3 \bullet 2 - 3.1 = 2.9, \qquad\qquad Diff_{T2R} = 3 \bullet 2 - 3.9 = 2.1.$$

Method 3iii: Use Strain Index's speed of work (SISW) rating multiplied by 2 to replace HAL score and use Strain Index's intensity rating multiplied by 2 to replace NPF

$$NPFTLV = -\frac{7}{9} \bullet SISW \bullet 2 + 7.78,$$

$$NPFTLV_{T1L} = -\frac{7}{9} \bullet 2 \bullet 2 + 7.78 = 4.7, \qquad NPFTLV_{T1R} = -\frac{7}{9} \bullet 3 \bullet 2 + 7.78 = 3.1,$$

$$NPFTLV_{T2L} = -\frac{7}{9} \bullet 3 \bullet 2 + 7.78 = 3.1, \qquad NPFTLV_{T2R} = -\frac{7}{9} \bullet 2 \bullet 2 + 7.78 = 4.7,$$

$$SII \bullet 2 - NPFTLV = Difference$$

$$Diff_{T1L} = 2 \bullet 2 - 4.7 = -0.7, \qquad\qquad Diff_{T1R} = 2 \bullet 2 - 3.1 = 0.9,$$

$$Diff_{T2L} = 3 \bullet 2 - 3.1 = 2.9, \qquad\qquad Diff_{T2R} = 3 \bullet 2 - 4.7 = 1.3.$$

Estimation of job level work-related risk

Several methods for combining the estimated risk of each task onto a
job level risk estimate were investigated in this study.

1. The average distance from the TLV for the left and right side.
2. The maximum distance from the TLV for the left and right side.
3. The sum of the time weighted task level ratios or distances weighted by busy time for the left and right side.
4. The sum of the time weighted task level risks weighed by effort time for the left and right side.

Methods 1 and 2 are described first.

Method 1: HAL

$$\text{Average Distance} = \frac{\sum_{i=1}^{j} \text{Distance Task}_i}{J}, \text{where } J \text{ is the number of tasks for that job.}$$

$$\text{Average Distance}_L = \frac{-4.3 + 2.2}{2} = -1.0,$$

$$\text{Average Distance}_R = \frac{0.3 - 2.6}{2} = -1.2,$$

Maximum Average Distance $= -1.0,$

Maximum Difference $= 2.2.$

Method 2: Modified HAL (based on speed of work alone)

$$\text{Average Distance} = \frac{\sum_{i=1}^{j} \text{Distance Task}_i}{J}, \text{where } J \text{ is the number of tasks for that job.}$$

$$\text{Average Distance}_L = \frac{-4.3 + 2.2}{2} = -1.0,$$

$$\text{Average Distance}_R = \frac{-4.4 - 2.6}{2} = -3.5,$$

Maximum Average Distance $= -1.0,$

Maximum Task Distance $= 2.2.$

Method 3i: SISW vs. NPF

$$\text{Average Distance} = \frac{\sum_{i=1}^{j} \text{Distance Task}_i}{J}, \text{where } J \text{ is the number of tasks for that job.}$$

$$\text{Average Distance}_L = \frac{-3.6 + 2.2}{2} = -0.7,$$

$$\text{Average Distance}_R = \frac{-2.8 - 3.4}{2} = -3.1,$$

Maximum Average Distance $= -0.7,$

Maximum Task Distance $= 2.2.$

Method 3ii: HAL vs. SIIE

$$\text{Average Distance} = \frac{\sum_{i=1}^{j}\text{Distance Task}_i}{J}, \text{ where } J \text{ is the number of tasks for that job.}$$

$$\text{Average Distance}_L = \frac{-1.4 + 2.9}{2} = 0.8,$$

$$\text{Average Distance}_R = \frac{-0.7 + 2.1}{2} = 0.7,$$

Maximum Average Distance = 0.8,

Maximum Task Distance = 2.9.

Method 3iii: Use Strain Index's speed of work (SISW) rating multiplied by 2 to replace HAL score and use Strain Index's intensity rating multiplied by 2 to replace NPF

$$\text{Average Distance} = \frac{\sum_{i=1}^{j}\text{Distance Task}_i}{J}, \text{ where } J \text{ is the number of tasks for that job.}$$

$$\text{Average Distance}_L = \frac{-0.7 + 2.9}{2} = 1.1,$$

$$\text{Average Distance}_R = \frac{0.9 + 1.3}{2} = 1.1,$$

Maximum Average Distance = 1.1,

Maximum Task Distance = 2.9.

The following method is used for the time weighted averages (busy and effort). First the busy (or effort) ratio is determined. The appropriate multiplication is computed for each task for the right and left sides. Then the sum of these products is calculated for the right and left side.

Determine the Busy Ratio for each task.

$$\text{Busy Ratio}_{Ti} = \frac{\text{Time Busy Task}_i \text{ (s)}}{\text{Cycle Time (s)}}, \qquad \text{Effort Ratio}_{Ti} = \frac{\text{Time Effort Task}_i \text{ (s)}}{\text{Cycle Time (s)}},$$

$$\text{Busy Ratio}_{T1L} = \frac{15\,(S)}{40\,(s)} = 0.38, \qquad \text{Effort Ratio}_{T1L} = \frac{5\,(S)}{40\,(s)} = 0.12,$$

$$\text{Busy Ratio}_{T1R} = \frac{10\,(s)}{40\,(s)} = 0.25, \qquad \text{Effort Ratio}_{T1R} = \frac{7\,(s)}{40\,(s)} = 0.18,$$

$$\text{Busy Ratio}_{T2L} = \frac{10\,(s)}{40\,(s)} = 0.25, \qquad \text{Effort Ratio}_{T2L} = \frac{3\,(s)}{40\,(s)} = 0.08,$$

$$\text{Busy Ratio}_{T2R} = \frac{20\,(s)}{40\,(s)} = 0.5, \qquad \text{Effort Ratio}_{T2R} = \frac{3\,(s)}{40\,(s)} = 0.08.$$

Method 3 (the sum of the time-weighted task level risks weighted by busy time by side) and method 4 (the sum of the time-weighted task level risks weighted by effort time by side) previously mentioned are now described.

There are two possible approaches using this weighting system. The first multiplies the metric for HAL and then inserts this product into the difference equation. The second method multiplies the differences

for each task by the ratio. In this way, the distance from the TLV is modified by the ratio. Both methods are explored in this paper. Only the calculations for the distance busy ratio are shown here. The sample calculations that follow all use the NPF calculated using biomechanics (force and grip type).

Determine the distance using the HAL metric multiplied by the busy ratio then determine the average or the maximum for the right and left side. The maximum of each was used as the risk metric for the entire job.

Determine $\text{NPFTLV}_{Ti\text{BWR}}$ given.

Method 1: HAL

$$\text{Diff}_{Ti} = \text{NPFACT}_{Ti} - \text{NPFTLV}_{Ti\text{BWRTI}} = \text{NPFACT}_{Ti} - (-\frac{7}{9} \bullet \text{HAL}_{Ti} \bullet \text{BWR}_{Ti} + 7.78),$$

$$\text{Diff}_{\text{BWRT1L}} = 1.1 - (-\frac{7}{9} \bullet 3 \bullet 0.38 + 7.78) = -5.9, \qquad \text{Diff}_{\text{BWRT1R}} = 0.3 - (-\frac{7}{9} \bullet 10 \bullet 0.25 + 7.78) = -5.8,$$

$$\text{Diff}_{\text{BWRT2L}} = 5.3 - (-\frac{7}{9} \bullet 6 \bullet 0.25 + 7.78) = -1.3, \qquad \text{Diff}_{\text{BWRT2R}} = 1.3 - (-\frac{7}{9} \bullet 5 \bullet 0.5 + 7.78) = -4.5,$$

$$\text{Ave}_{\text{BWRJL}} = \frac{-5.9 - 1.3}{2} = -3.6, \qquad\qquad \text{Ave}_{\text{BWRJR}} = \frac{-5.8 - 4.5}{2} = -5.2,$$

$$\text{Max}_{\text{BWRJL}} = -1.3, \qquad\qquad \text{Max}_{\text{BWRJR}} = -4.5,$$

$$\text{MaxAve}_{J} = -3.6,$$

$$\text{Max}_{J} = -1.3.$$

Method 2: Modified HAL (based on speed of work alone)

In this job only task 1 right side (T1R) is changed.

$$\text{Diff}_{Ti} = \text{NPFACT}_{Ti} - \text{NPFTLV}_{Ti\text{BWRTI}} = \text{NPFACT}_{Ti} - (-\frac{7}{9} \bullet \text{HAL}_{Ti} \bullet \text{BWR}_{Ti} + 7.78),$$

$$\text{Diff}_{\text{BWRT1L}} = 1.1 - (-\frac{7}{9} \bullet 3 \bullet 0.38 + 7.78) = -5.9, \qquad \text{Diff}_{\text{BWRT1R}} = 0.3 - (-\frac{7}{9} \bullet 4 \bullet 0.25 + 7.78) = -6.7,^{*}$$

$$\text{Diff}_{\text{BWRT2L}} = 5.3 - (-\frac{7}{9} \bullet 6 \bullet 0.25 + 7.78) = -1.3, \qquad \text{Diff}_{\text{BWRT2R}} = 1.3 - (-\frac{7}{9} \bullet 5 \bullet 0.5 + 7.78) = -4.5,$$

$$\text{Ave}_{\text{BWRJL}} = \frac{-5.9 - 1.3}{2} = -3.6, \qquad\qquad \text{Ave}_{\text{BWRJR}} = \frac{-6.7 - 4.5}{2} = -5.6,$$

$$\text{Max}_{\text{BWRJL}} = -1.3, \qquad\qquad \text{Max}_{\text{BWRJR}} = -4.5,$$

$$\text{MaxAve}_{J} = -3.6,$$

$$\text{Max}_{J} = -1.3.$$

*Note: only Diff_{T1R} changed.

Method 3i: Use Strain Index's Speed of Work Rating (SISW) multiplied by 2 in lieu of the HAL rating

$$\text{Diff}_{Ti} = \text{NPFACT}_{Ti} - \text{NPFTLV}_{Ti\text{BWRTI}} = NPFACT_{Ti} - (-\frac{7}{9} \bullet \text{SISW}_{Ti} \bullet 2 \bullet \text{BWR}_{Ti} + 7.78),$$

$$\text{Diff}_{\text{BWRT1L}} = 1.1 - (-\frac{7}{9} \bullet 2 \bullet 2 \bullet 0.38 + 7.78) = -3.6, \qquad \text{Diff}_{\text{BWRT1R}} = 0.3 - (-\frac{7}{9} \bullet 3 \bullet 2 \bullet 0.25 + 7.78) = -2.8,$$

$$\text{Diff}_{\text{BWRT2L}} = 5.3 - (-\frac{7}{9} \bullet 3 \bullet 2 \bullet 0.25 + 7.78) = 2.2, \qquad \text{Diff}_{\text{BWRT2R}} = 1.3 - (-\frac{7}{9} \bullet 2 \bullet 2 \bullet 0.5 + 7.78) = -3.4,$$

$$\text{Ave}_{\text{BWRJL}} = \frac{-3.6 + 2.2}{2} = -0.7, \qquad\qquad \text{Ave}_{\text{BWRJR}} = \frac{-2.8 - 3.4}{2} = -3.1,$$

$$\text{Max}_{\text{BWRJL}} = 2.2, \qquad\qquad \text{Max}_{\text{BWRJR}} = -2.8,$$

$$\text{MaxAve}_{J} = -0.7,$$

$$\text{Max}_{J} = 2.2.$$

Method 3ii: Use Strain Index's Intensity Rating (SIIE) multiplied by 2 in lieu of the NPFACT rating

$$\text{Diff}_{\text{T}i} = SII_{\text{T}i} \bullet 2 - \text{NPFTLV}_{\text{T}i\text{BWRTI}} = SII_{\text{T}i} \bullet 2 - (-\frac{7}{9} \bullet \text{HAL}_{\text{T}i} \bullet \text{BWR}_{\text{T}i} + 7.78),$$

$$\text{Diff}_{\text{BWRT1L}} = 2 \bullet 2 - (-\frac{7}{9} \bullet 3 \bullet 0.38 + 7.78) = -2.8, \qquad \text{Diff}_{\text{BWRT1R}} = 2 \bullet 2 - (-\frac{7}{9} \bullet 4 \bullet 0.25 + 7.78) = -3.0,$$

$$\text{Diff}_{\text{BWRT2L}} = 3 \bullet 2 - (-\frac{7}{9} \bullet 6 \bullet 0.25 + 7.78) = -0.6, \qquad \text{Diff}_{\text{BWRT2R}} = 3 \bullet 2 - (-\frac{7}{9} \bullet 5 \bullet 0.5 + 7.78) = -0.1,$$

$$\text{Ave}_{\text{BWR/L}} = \frac{-2.8 - 0.6}{2} = -1.7, \qquad\qquad \text{Ave}_{\text{BWR/R}} = \frac{-3.0 - 0.1}{2} = -1.6,$$

$$\text{Max}_{\text{BWR/L}} = -0.6, \qquad\qquad\qquad\qquad \text{Max}_{\text{BWR/R}} = -0.1,$$

$$\text{MaxAve}_J = -1.6,$$

$$\text{Max}_J = -0.1.$$

Method 3iii: Use Strain Index's Speed of Work (SISW) Rating multiplied by 2 to replace HAL score and use Strain Index's Intensity rating multiplied by 2 to replace NPF

$$\text{Diff}_{\text{T}i} = SII_{\text{T}i} \bullet 2 - \text{NPFTLV}_{\text{T}i\text{BWR}} = SII_{\text{T}i} \bullet 2 - (-\frac{7}{9} \bullet \text{SISW}_{\text{T}i} \bullet 2 \bullet \text{BWR}_{\text{T}i} + 7.78),$$

$$\text{Diff}_{\text{BWRT1L}} = 2 \bullet 2 - (-\frac{7}{9} \bullet 2 \bullet 2 \bullet 0.38 + 7.78) = -2.5, \qquad \text{Diff}_{\text{BWRT1R}} = 2 \bullet 2 - (-\frac{7}{9} \bullet 3 \bullet 2 \bullet 0.25 + 7.78) = -2.6,$$

$$\text{Diff}_{\text{BWRT2L}} = 3 \bullet 2 - (-\frac{7}{9} \bullet 3 \bullet 2 \bullet 0.25 + 7.78) = -0.6, \qquad \text{Diff}_{\text{BWRT2R}} = 3 \bullet 2 - (-\frac{7}{9} \bullet 2 \bullet 2 \bullet 0.5 + 7.78) = -0.2,$$

$$\text{Ave}_{\text{BWR/L}} = \frac{-2.5 - 0.6}{2} = -1.6, \qquad\qquad \text{Ave}_{\text{BWR/R}} = \frac{-2.6 - 0.2}{2} = -1.4,$$

$$\text{Max}_{\text{BWR/L}} = -0.6, \qquad\qquad\qquad\qquad \text{Max}_{\text{BWR/R}} = -0.2,$$

$$\text{MaxAve}_J = -1.4,$$

$$\text{Max}_J = -0.2.$$

Determining the distance modified by the busy ratio (BR)
Method 1: HAL BR

$$\text{Difference}_{\text{T}i} \bullet \text{BR}_{\text{T}i} = (\text{NPFACT}_{\text{T}i} - \text{NPFTLV}_{\text{T}i}) \bullet \text{BR}_{\text{T}i},$$

$$\text{Diff}_{\text{T1L}} \bullet \text{BR}_{\text{T1L}} = -4.4 \bullet 0.38 = -1.7, \qquad\qquad \text{Diff}_{\text{T1R}} \bullet \text{BR}_{\text{T1R}} = 0.3 \bullet 0.25 = 0.1,$$

$$\text{Diff}_{\text{T2L}} \bullet \text{BR}_{\text{T2L}} = 2.2 \bullet 0.25 = 0.6, \qquad\qquad \text{Diff}_{\text{T2R}} \bullet \text{BR}_{\text{T2R}} = -2.6 \bullet 0.5 = -1.3,$$

$$\text{Sum}_{\text{BWR/L}} = -1.7 + 0.6 = -1.2, \qquad\qquad \text{Sum}_{\text{BWR/R}} = 0.1 - 1.3 = -1.2,$$

$$\text{Max}_{\text{BWR/L}} = 0.55, \qquad\qquad\qquad\qquad \text{Max}_{\text{BWR/R}} = 0.1,$$

$$\text{MaxSum}_J = -1.2,$$

$$\text{Max}_J = 0.6.$$

Method 2: Modified HAL BR

$$\text{Difference}_{\text{T}i} \bullet \text{BR}_{\text{T}i} = (\text{NPFACT}_{\text{T}i} - \text{NPFTLV}_{\text{T}i}) \bullet \text{BR}_{\text{T}i},$$

$$\text{Diff}_{\text{T1L}} \bullet \text{BR}_{\text{T1L}} = -4.4 \bullet 0.38 = -1.7, \qquad\qquad \text{Diff}_{\text{T1R}} \bullet BR_{\text{T1R}} = -4.4 \bullet 0.25 = -1.1,$$

$$\text{Diff}_{\text{T2L}} \bullet \text{BR}_{\text{T2L}} = 2.2 \bullet 0.25 = 0.6, \qquad\qquad \text{Diff}_{\text{T2R}} \bullet \text{BR}_{\text{T2R}} = -2.6 \bullet 0.5 = -1.3,$$

$$\text{Sum}_{\text{BWR/L}} = -1.7 + 0.55 = -1.2, \qquad\qquad \text{Sum}_{\text{BWRJR}} = -1.1 - 1.3 = -2.4,$$

$$\text{Max}_{\text{BWR/L}} = 0.5, \qquad\qquad\qquad\qquad \text{Max}_{\text{BWRJR}} = -1.1,$$

$$\text{MaxSum}_J = -1.2,$$

$$\text{Max}_J = 0.6.$$

Method 3i: Use SISW • 2 in lieu of HAL

$$\text{Difference}_{Ti} \bullet \text{BR}_{Ti} = (\text{NPFACT}_{Ti} - \text{NPFTLV}_{Ti}) \bullet \text{BR}_{Ti},$$

$\text{Diff}_{T1L} \bullet \text{BR}_{T1L} = -3.7 \bullet 0.38 = -1.4,$ $\qquad \text{Diff}_{T1R} \bullet \text{BR}_{T1L} = -2.8 \bullet 0.25 = -0.7,$

$\text{Diff}_{T2L} \bullet \text{BR}_{T1L} = 2.2 \bullet 0.25 = 0.6,$ $\qquad \text{Diff}_{T2R} \bullet \text{BR}_{T1L} = -3.4 \bullet 0.5 = -1.8,$

$\text{Sum}_{BWR/L} = -1.4 + 0.6 = -0.8,$ $\qquad \text{Sum}_{BWR/R} = -0.7 - 1.8 = -2.5,$

$\text{Max}_{BWR/L} = 0.6,$ $\qquad \text{Max}_{BWR/R} = -0.7,$

$\text{MaxSum}_J = -0.8,$

$\text{Max}_J = 0.6.$

Method 3ii: Use SIIE • 2 in lieu of NPF

$$\text{Difference}_{Ti} \bullet \text{BR}_{Ti} = (\text{SII}_{Ti} \bullet 2 - \text{NPFTLV}_{Ti}) \bullet \text{BR}_{Ti},$$

$\text{Diff}_{T1L} \bullet \text{BR}_{T1L} = -1.4 \bullet 0.38 = -0.5,$ $\qquad \text{Diff}_{T1R} \bullet \text{BR}_{T1R} = -0.7 \bullet 0.25 = -0.2,$

$\text{Diff}_{T2L} \bullet \text{BR}_{T2L} = 2.9 \bullet 0.25 = 0.7,$ $\qquad \text{Diff}_{T2R} \bullet \text{BR}_{T2R} = 2.1 \bullet 0.5 = 1,$

$\text{Sum}_{BWR/L} = -0.5 + 0.7 = 0.2,$ $\qquad \text{Sum}_{BWR/R} = -0.2 + 1.0 = 0.8,$

$\text{Max}_{BWR/L} = 0.7,$ $\qquad \text{Max}_{BWR/R} = 1.0,$

$\text{MaxSum}_J = 0.8,$

$\text{Max}_J = 1.0.$

Method 3iii: Use SIIE • 2 in place of NPF, and SISW • 2 in place of HAL to determine NPFTLV

$$\text{Difference}_{Ti} \bullet \text{BR}_{Ti} = (\text{SIIE}_{Ti} \bullet 2 - \text{NPFTLV}_{Ti}) \bullet \text{BR}_{Ti},$$

$\text{Diff}_{T1L} \bullet \text{BR}_{T1L} = -0.7 \bullet 0.38 = -0.3,$ $\qquad \text{Diff}_{T1R} \bullet \text{BR}_{T1L} = 0.9 \bullet 0.25 = 0.2,$

$\text{Diff}_{T2L} \bullet \text{BR}_{T1L} = 2.9 \bullet 0.25 = 0.7,$ $\qquad \text{Diff}_{T2R} \bullet \text{BR}_{T1L} = 1.3 \bullet 0.5 = 0.6,$

$\text{Sum}_{BWR/L} = -0.3 + 0.7 = 0.4,$ $\qquad \text{Sum}_{BWRJR} = 0.2 + 0.6 = 0.8,$

$\text{Max}_{BWR/L} = 0.7,$ $\qquad \text{Max}_{BWRJR} = 0.6,$

$\text{MaxSum}_J = 0.8,$

$\text{Max}_J = 0.7.$

The results from each of these methods are presented in Table SC 2.

TABLE SC 2. Outputs of the Sample Calculation for Distance Modified by the Busy Ratio

Method	Task	Left	Right	Sum Left	Sum Right	Max Sum	Max Task
HAL	1	−1.7	0.1				
	2	0.6	−1.3	−1.2	−1.2	−1.2	0.6
Mod. HAL	1	−1.7	−1.1				
	2	0.6	−1.3	−1.2	−2.4	−1.2	0.6
3i	1	−1.4	−0.7				
	2	0.6	−1.8	−0.9	−2.5	−0.9	0.6
3ii	1	−0.5	−0.2				
	2	0.7	1.0	0.2	0.8	0.8	1.0
3iii	1	−0.3	0.2				
	2	0.7	0.6	0.4	0.8	0.8	0.7

Notes. HAL—Hand Activity Level, mod.—modified.