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A frequency–duty cycle equation for the ACGIH hand activity level

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A new equation for predicting the hand activity level (HAL) used in the American Conference for Government Industrial Hygienists threshold limit value® (TLV®) was based on exertion frequency (*F*) and percentage duty cycle (*D*). The TLV® includes a table for estimating HAL from *F* and *D* originating from data in Latko et al. (Latko WA, Armstrong TJ, Foulke JA, Herrin GD, Rabourn RA, Ulin SS, Development and evaluation of an observational method for assessing repetition in hand tasks. *American Industrial Hygiene Association Journal*, 58(4):278–285, 1997) and *post hoc* adjustments that include extrapolations outside of the data range. Multimedia video task analysis determined *D* for two additional jobs from Latko's study not in the original data-set, and a new nonlinear regression equation was developed to better fit the data and create a more accurate table. The equation, $\mathrm{HAL} = 6.56 \ln D[F^{1.31}/1 + 3.18\,F^{1.31}]$, generally matches the TLV® HAL lookup table, and is a substantial improvement over the linear model, particularly for $F > 1.25$ Hz and $D > 60\%$ jobs. The equation more closely fits the data and applies the TLV® using a continuous function.

Practitioner Summary: The original HAL lookup table is limited in resolution, omits values and extrapolates values outside of the range of data. A new equation and table were developed to address these issues.

Keywords: repetitive motion; work-related musculoskeletal disorders; exposure assessment

1. Introduction

The American Conference for Government Industrial Hygienists (ACGIH) hand activity level (HAL) was developed for use with normalised peak hand force (NPF) to estimate the threshold limit value® (TLV®), which is a measure of the risk of work-related distal upper extremity musculoskeletal disorders (ACGIH Worldwide 2001). The TLV® is limited to mono-task jobs that can be characterised as repeated exertions separated by periods of rest and that are performed for four or more hours daily.

The HAL scale was first introduced by Latko et al. (1997) and incorporated into the TLV®. Up to the time of the Latko et al. (1997) study, repetitive work was characterised in terms of cycle time or exertion frequency (Luopajärvi et al. 1979; Silverstein, Fine, and Armstrong 1987). Latko et al. (1997) proposed a 10-point visual-analog scale that ranged from idle most of the time/no regular exertions to rapid, steady motion/difficulty keeping up or continuous exertion. The observers consider exertion frequency, rest pauses and speed of motion according to specified guideline descriptions.

Latko et al. (1997) reported a coefficient of determination of $R^2 = 0.88$ for repeated ratings by the same observers after 79–118 weeks to show that ratings were consistent over time. Ebersole and Armstrong (2002) analysed 410 jobs at an automotive assembly plant using two observers recording initial and final rating. Before discussion, HAL reliability was rated as moderate and after discussion, HAL κ values were rated as good (i.e. 0.75). Ebersole and Armstrong (2006) reported that inter-rater reliability for repetition was high with an interclass correlation coefficient value of 0.71 prior to discussion and 0.87 after discussion. Paulsen et al. (2014) recently reported that HAL inter-rater reliability was a reliable exposure assessment method for 858 cyclic ($\bar{r} - \mathrm{bar}_w = 0.69$) and non-cyclic work tasks ($\bar{r} - \mathrm{bar}_w = 0.68$).

Previous studies have shown that a cycle time less than 30 s was associated with risk of carpal tunnel syndrome (CTS) and tendinitis (Silverstein, Fine, and Armstrong 1987; Roquelaure et al. 1997). Latko et al. (1997) reported that HAL ratings were not strongly related to cycle time but were more closely related to hand exertion frequency ($R^2 = 0.58$) and duty cycle ($R^2 = 0.53$). They argued that frequency and duty cycle were better indicators of the biomechanical burden than cycle time. When the TLV® was proposed by the ACGIH, a need for a lookup table was identified for objectively determining HAL based on job descriptions, and exertion time and frequency measurements.

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A linear regression model for HAL as a function of frequency and duty cycle was developed by the ACGIH Physical Agents Committee using the data from 31 of 33 jobs in Latko et al. (1997). The equation was then used to develop a lookup table for estimating HAL. The 2001 TLV® guideline HAL look-up table (reproduced in Table 1) gives approximate HAL values of given estimates for exertion frequency F and duty cycle D, where

$$F = \left(\frac{\text{exertions}}{\text{work time}}\right) \quad \text{and} \quad D = 100\left(\frac{\text{work time}}{\text{work time} + \text{rest time}}\right).$$

Cells in the table that corresponded to D and F below the range of the observed data were left blank or set to one if the predicted value was less than one. When applying the TLV guidelines, practitioners can ascertain frequency and duty cycle information using instruments, video frame-by-frame analysis or other means.

Although it offers objective measures of HAL, the look-up table provided in the TLV® (Table 1) has several limitations. The HAL values are rounded to the nearest integer and the table includes only five frequency and five duty cycle values. In addition, HAL values are provided for frequency duty cycle combinations outside the range in the experts' data. An equation that continuously and accurately predicts HAL values along with appropriate ranges for its use would overcome these limitations.

Since its introduction, numerous studies have been published for quantifying repetitive hand motion or for evaluating the efficacy of the TLV® for estimating risk using the HAL scale based on observational or table look-up methods. Observational methods for measuring HAL were employed by Latko et al. (1999), Franzblau et al. (2005), Gell et al. (2005), Violante et al. (2007), Harris et al. (2011), Garg et al. (2012), Bonfiglioli et al. (2013) and Kapellusch et al. (2013). Video frame-by-frame analysis was used by Bao et al. (2006). Both observational and video methods were employed by Wurzelbacher et al. (2010) and Burt et al. (2011).

Whether estimating HAL using the observational rating scale or the TLV® lookup table, a positive relationship between HAL and risk of hand and wrist musculoskeletal disorders was established. Significant relationships were found between the TLV® action limit (AL) and elbow/forearm tendonitis and CTS in a cross-sectional study of 908 workers from seven different job sites (Franzblau et al. 2005). Werner et al. (2005) investigated predictors of upper extremity discomfort in a longitudinal study involving 501 industrial and clerical workers over 5.4 years, and found that significant increases in musculoskeletal pain were associated with exceeding the TLV® (odds ratio = 2.14). A longitudinal study of workers from 10 diverse manufacturing facilities and followed monthly for 6 years found that the TLV®, when treated as a continuous variable, was predictive of increased risk of CTS (Garg et al. 2012), predicted increased risk for CTS while controlling for obesity and job strain (Burt et al. 2013), and that the TLV® showed a statistical trend of association with increased risk of flexor tendon entrapment of the digits using the ACGIH limits (Kapellusch et al. 2013). Armstrong et al. (2006) suggested that the TLV® AL might be lowered, particularly for surveillance purposes or if other risk factors are observed.

Recent advances allow HAL to be calculated directly using automated video analysis that employs semi-automatic marker-less tracking to measure frequency and duty cycle (Chen et al. 2013). The video-based direct exposure assessment method was demonstrated as promising in a simple laboratory simulation of a hand load transfer task. Such an approach is objective, unobtrusive and does not require attaching sensors to the body of workers, and suitable for a real-time, direct reading exposure assessment instrument for HAL. Automated methods for measuring HAL would benefit from a continuous and accurate equation for calculating HAL directly from the measured parameters.

The Latko et al. (1997) data are reproduced in Table 2 for the 33 jobs that were rated by a team of expert raters. These jobs are described in Latko et al. (1997) for HAL ranging from 1 to 9. Latko had each job rated by the observers (HAL rating time 1), and again by the same team a week later (HAL rating time 2). These ratings and their average are shown for each job in Table 2.

Latko et al. (1997) averaged the observable recovery time across five or more cycles. The time spent in recovery was defined as time in which the busiest hand in the cycle 'was not holding, manipulating, triggering, pushing, pulling or

Table 1. HAL look-up table published in the TLV® document (2001).

Frequency (exertions/s)	Period (s/exertion)	Duty cycle (%)				
		0–20	20–40	40–60	60–80	80–100
0.125	8.0	1	1	–	–	–
0.25	4.0	2	2	3	–	–
0.5	2.0	3	4	5	5	6
1.0	1.0	4	5	5	6	7
2.0	0.5	–	5	6	7	8

Table 2. Data used for calculations in Latko et al. (1997).

Job	Description	Industry	HAL rating time 1	HAL rating time 2	Average HAL	Frequency (exertions/s) F	Duty cycle (%) D	Cycle time (s)
1	Inspection	Appliance manufacturing	0.8	0.4	0.6	0.125	26	8.0
2	Milacron	Fibre drum manufacturing	1.0	2.0	1.5	0.167	11	30.0
3	Marriage load	Auto components	1.0	1.0	1.0	0.281	54	71.3
4	Auto edge wrap	Auto components	1.8	3.5	2.65	0.338	45	80.0
5	Water jet	Auto components	2.0	2.25	2.13	0.376	55	122.5
6	Transfer task	Laboratory	2.2	2.5	2.35	0.167	32	6.0
7	Line stack	Fibre drum manufacturing	2.5	4.5	3.5	0.740	31	7.0
8	Ground wire	Appliance manufacturing	3.4	6.25	4.83	0.820	71	12.2
9	DC inspection	Glass/mirror manufacturing	4.2	4.25	4.21	0.385	26	13.0
10	Silkscreen	Auto components	4.2	5.25	4.73	0.769	86	7.8
11	Rotary	Fibre drum manufacturing	4.4	6.0	5.2	0.500	74	4.0
12	Hanging parts	Appliance manufacturing	4.4	4.5	4.45	0.555	59	9.0
13	Bulkhead	Appliance manufacturing	4.6	4.0	4.3	0.320	47	53.0
14	Panel upholstery	Office furniture manufacturing	4.9	4.75	4.83	0.550	83	150.0
15	Fabric wrap	Auto components	5.2	6.75	5.98	1.330	74	40.5
16	Transfer task	Laboratory	5.2	5.25	5.23	0.333	43	3.0
17	Securing fan	Appliance manufacturing	5.7	6.75	6.23	1.080	95	12.0
18	Wiring heat box	Appliance manufacturing	5.8	6.75	6.28	0.730	84	12.3
19	Upper back panel	Appliance manufacturing	6.0	6.5	6.25	0.870	100	11.5
20	Rear console	Appliance manufacturing	6.4	5.5	5.95	0.667	87	12.0
21	Securing top panel	Appliance manufacturing	6.5	6.75	6.63	0.833	100	12.0
22	Shape cutter	Glass/mirror manufacturing	6.6	6.75	6.68	1.050	88	42.0
23	Paint – visors	Auto components	7.2	7.5	7.35	1.260	90	30.0
24	Paint – armrest	Auto components	7.2	7.75	7.48	1.110	91	19.0
25	Lid assembly	Auto components	7.2	7.0	7.1	0.917	95	24.0
26	CAN sewing	Auto components	7.2	8.75	7.98	1.580	93	48.0
27	Deck sewing	Auto components	7.4	7.5	7.45	0.568	96	95.0
28	Cup assembly	Auto components	7.6	7.75	7.68	0.800	92	125.0
29	Ergo. upholstery	Office furniture manufacturing	7.9	8.0	7.95	0.814	90	214.0
30	Curler	Fibre drum manufacturing	8.0	8.25	8.13	1.429	71	3.5
31	Hand operation 2	Fibre drum manufacturing	8.0	9.0	8.5	1.430	81[a]	1.4
32	Hand operation 1	Fibre drum manufacturing	8.0	9.0	8.5	1.670	82[a]	1.2
33	Transfer task	Laboratory	8.2	8.5	8.35	0.667	61	1.5
	Min		0.8	0.4	0.6	0.125	11	1.2
	Max		8.2	9	8.5	1.670	100	214
	Median		5.7	6.5	6.0	0.740	74	12.3

Note: Shaded region in the table contains data and statistics not originally published in Table II in Latko et al. (1997).
[a]Values obtained for this analysis. Not included in Table II in Latko et al. (1997).

otherwise handling an object'. The average recovery time was divided by the average time spent 'performing operations' on one unit of product (the cycle time) to yield an average percentage of time spent in recovery. The remaining integer percentage (100-R) was reported as duty cycle D.

This paper first determines D estimates for two additional jobs from Latko's study that were not included in the original data-set. Next an equation is developed that more accurately predicts the 33 Latko et al. (1997) HAL values as a function of F and D. Finally the equation is compared with the TLV® HAL table and a new look-up table is presented.

2. Methods

Using the 33 job descriptions in Latko's study, corresponding to figures in Latko et al. (1997), jobs numbered 31 and 32 without duty cycle information were identified as the two handle assembly; riveting jobs in a fibre drum manufacturer both of which have an average HAL of 8.5. These jobs have high frequencies (1.43, 1.67) and low cycle times (1.4, 1.2 s). Digital methods were required to find the percentage recoveries for both jobs.

The Latko videos of jobs 31 and 32 were digitised and single frame analysis was conducted utilising multimedia video task analysis (MVTA, Yen and Radwin 1995) in order to obtain the previously unavailable recovery time data. The video frame-rate was 30 fps. This allowed frame-by-frame identification and analysis of hand load for the short cycle time jobs. The analyst looked at a sequence of frames to determine whether it was an active exertion.

The motion classifications and definitions from Latko et al. (1997) were used to label active and recovery segments for both jobs. Hand exertions of the most active hand were observed for at least five cycles of the job and averaged. Recovery time was defined as periods when the hand was not holding, manipulating, triggering, pushing, pulling or otherwise handling an object, and included times when the hand was completely idle, resting upon an object for voluntary support, moving freely or reaching for an object. These values were divided by cycle time to obtain percentage recovery time within the cycle. After confirming the frequency across various cycles throughout the entire video, nine cycles of each job were used to calculate duty cycle. These values appear in Table 2.

A new model for predicting HAL from *F* and *D* was developed by fitting candidate three- and four-parameter asymptotic growth models using *F* as the '*x*' variable and allowing the asymptote and growth rate to vary by various functions of *D* (Ratkowsky 1990). A broken line model (two-segment linear spline) was also considered. All models were fit using nonlinear least squares, a generalisation of linear least squares used for fitting models that are nonlinear in their parameters. This minimisation is an iterative process as there is no closed form solution for nonlinear models. The ability of the models to fit the data was evaluated using residual plots.

A model that fits the data well will produce a residual plot with residuals evenly scattered around zero. The models that produced good fits to the data were then compared using likelihood ratio tests for nested models (models where one is a version of the other with one or more parameters set to zero) and Akaike information criterion (AIC) (Akaike 1974) for non-nested models. AIC is a measure of the distance between the fitted values and the data penalised for the number of parameters in the model. We also sought to find a model that produces fitted HAL values reasonably consistent with the values in the TLV® table in order to provide continuity with previous research and applications that used that table.

3. Results and discussion

The newly calculated duty cycle for jobs 31 and 32 is included in Table 2. The complete 33 job Latko data-set is shown in Figure 1. Only two of the 33 jobs exhibited frequencies >1.50 exertions/s, and no job exceeded 1.70 exertions/s. Jobs with high frequencies tended to have long duty cycles (Spearman correlation $= 0.66$). Summary statistics for the job parameters for the full data-set was computed and provided in Table 2.

Overlays of the Latko frequency of exertions and duty cycle data (33 jobs) and the TLV® table HAL ranges are shown in Figure 2. Some of the HAL values in the TLV® table are for frequency and duty cycle combinations not covered by the data, especially for high frequencies that were extrapolated outside of the range of the observed data. The regions corresponding to these table cells are in grey in Figure 2. Eight of the HAL predictions are outside the range of the observed frequencies and duty cycles in the original data. In general, predictions from a model that are outside the range of the data are unreliable since there is no way to know whether the model is accurate in these regions. Given the lack of data above 1.5 exertions/s, it

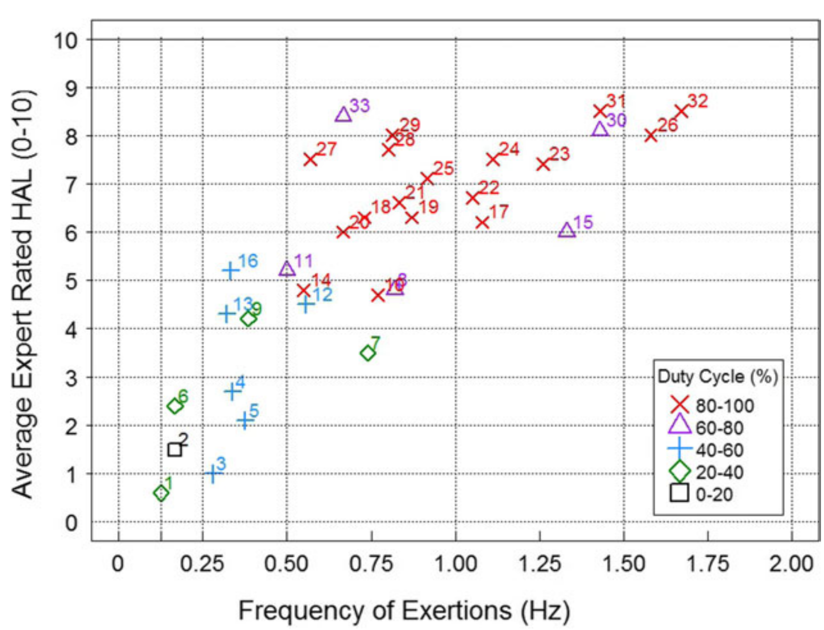

Figure 1. Complete 33 job data-set. Job numbers are shown next to plotted values (including jobs 31 and 32).

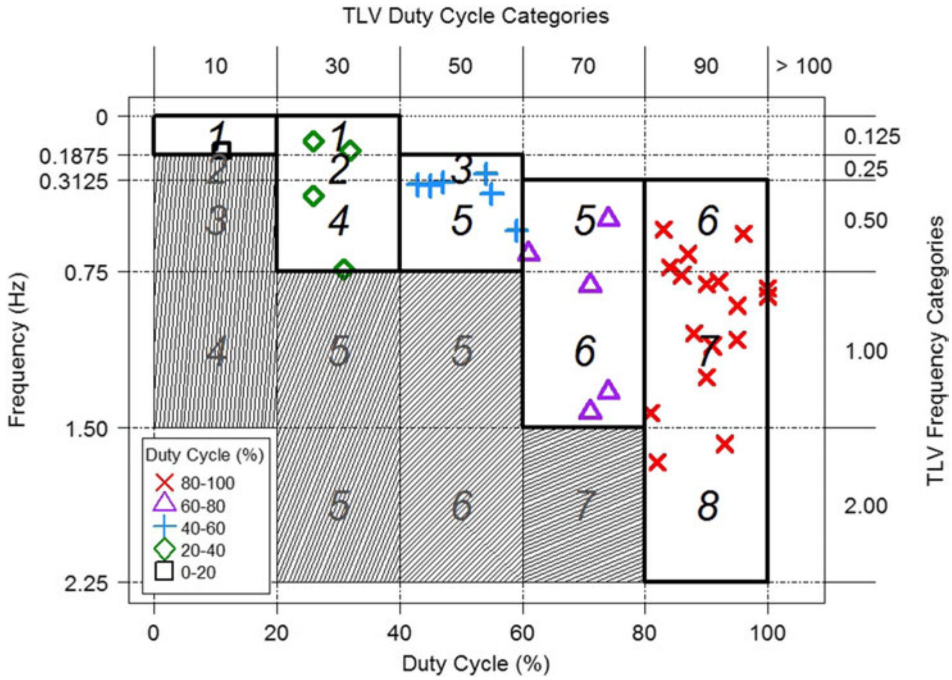

Figure 2. The Latko data (33 observations) are compared against the HAL values in the TLV Table 1. The plot is oriented similar to the HAL table and areas where table values are provided without data are shaded in grey.

is proposed that the frequency row labelled 2 exertions/s in the TLV® table should more accurately be labelled 1.5 exertions/s.

3.1. Linear regression model

The linear regression model for average rated HAL as a function of period and duty cycle used to populate the TLV table (ACGIH Worldwide 2005) was reproduced using the Latko et al. (1997) data shown in Table 2 (omitting jobs 31 and 32). That model is

$$\mathrm{HAL} = 4.31 - 0.636\frac{1}{F} + 0.0339D, \tag{1}$$

where F is frequency in exertions/s, D is percentage duty cycle and HAL is average HAL. The HAL values predicted by Equation (1) for the five duty cycle values in the TLV table are shown in Figure 3 as curves. The HAL values from the TLV® table are shown as symbols.

It is apparent that the TLV® table HAL values for the higher frequencies and duty cycles have been adjusted from the values predicted by the linear regression equation (Equation (1)). The TLV® table values were adjusted upwards from the regression model predictions for $F = 2$ and $D \geq 50\%$ (as described in the TLV® documentation). The TLV® table also specifies HAL = 1 when Equation (1) predicts negative HAL values (i.e. $F \leq 0.125$, $D < 50$). Consequently Equation (1) is not useful as a continuous representation of HAL for measured values of F and D.

The linear regression model in Equation (2) was estimated using the complete 33 job data-set:

$$\mathrm{HAL} = 4.69 - 0.709\frac{1}{F} + 0.0321D. \tag{2}$$

The addition of jobs 31 and 32 to the data-set increased the fitted values at higher frequencies slightly, but the model was still not a good fit to the data. The residuals from this fit are shown in Figure 4(a). The residuals for small and large predicted HAL values are all larger than zero, indicating that the linear curve under-predicts very small and very large HAL values.

3.2. Nonlinear regression model

We considered other linear and nonlinear functions of frequency and duty cycle to see whether a better model could be developed for HAL. The model shown in Equation (3) is the simplest model found that provided both a good fit to the data

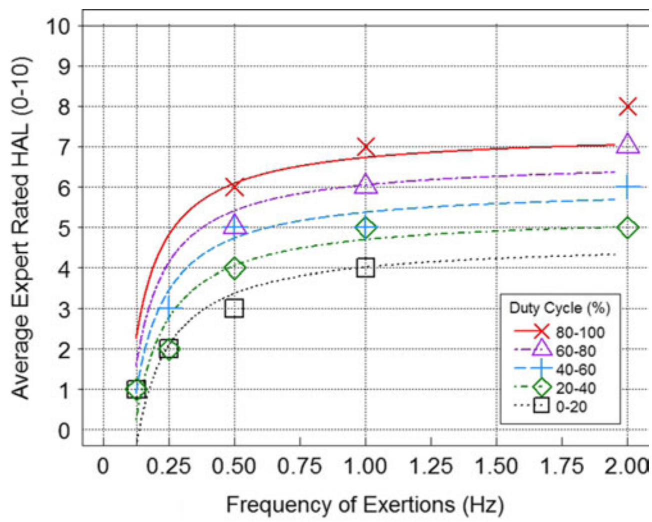

Figure 3. HAL values predicted by Equation (1) from Table 1 of the TLV. The smooth curves are the fitted values for duty cycles of 10, 30, 50, 70 and 90 as a function of frequency. The symbols are the values from the TLV® Table 1.

and closely matched the HAL table (Table 1) values from the Latko et al. (1997) data that are within the range of the data. The predictions from the model are plotted with the Latko data in Figure 5(b) and a residual plot is shown in Figure 4(b). The residuals for this model indicate a better fit to the data than Equation (2), the estimated residual standard deviation (the typical distance from the data to the fitted model) is smaller for the nonlinear model (1.18 vs. 1.31) and the AIC is lower (109.3 vs. 116.2).

$$\mathrm{HAL} = 6.56 \ln D \left[\frac{F^{1.31}}{1 + 3.18F^{1.31}}\right]. \tag{3}$$

The nonlinear model in Equation (3) closely follows the original TLV® table (Table 1). Differences between Equation (3) predictions and the original TLV® table are plotted in Figure 6. The adjustments for 90% duty cycle made for the original TLV® table are captured by Equation (3).

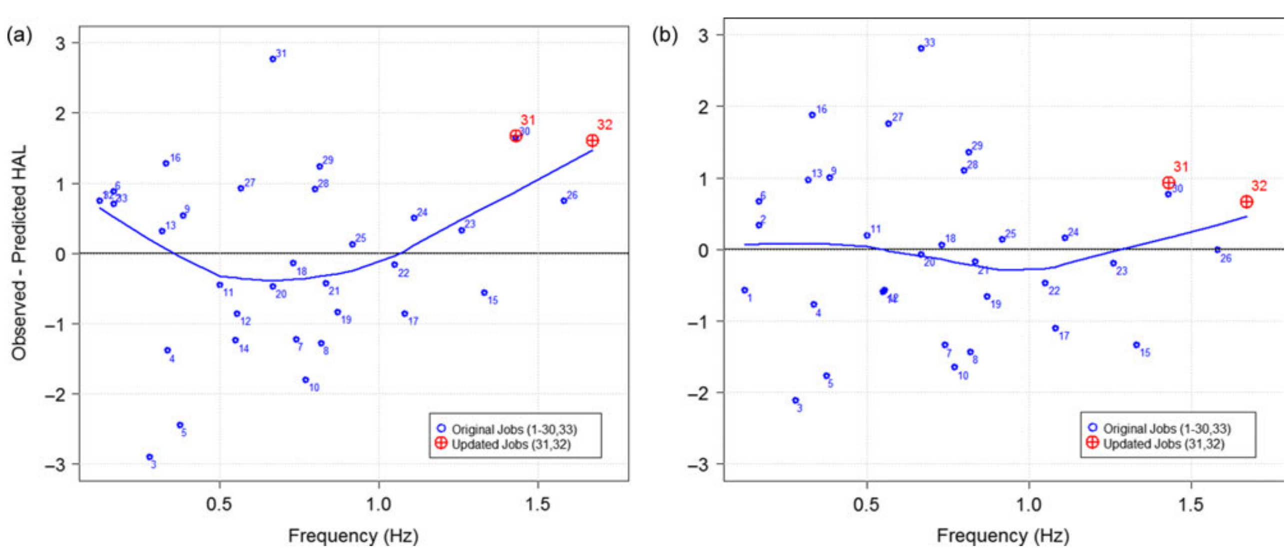

Figure 4. Residual plot (observed value − predicted value) for the linear model (a) in Equation (2) and the nonlinear regression model (b) in Equation (3). The numbers adjacent to data points correspond to the job numbers in Table 2. The curves indicate the trend of the residuals. Ideally these would lie exactly on the residual equal zero line.

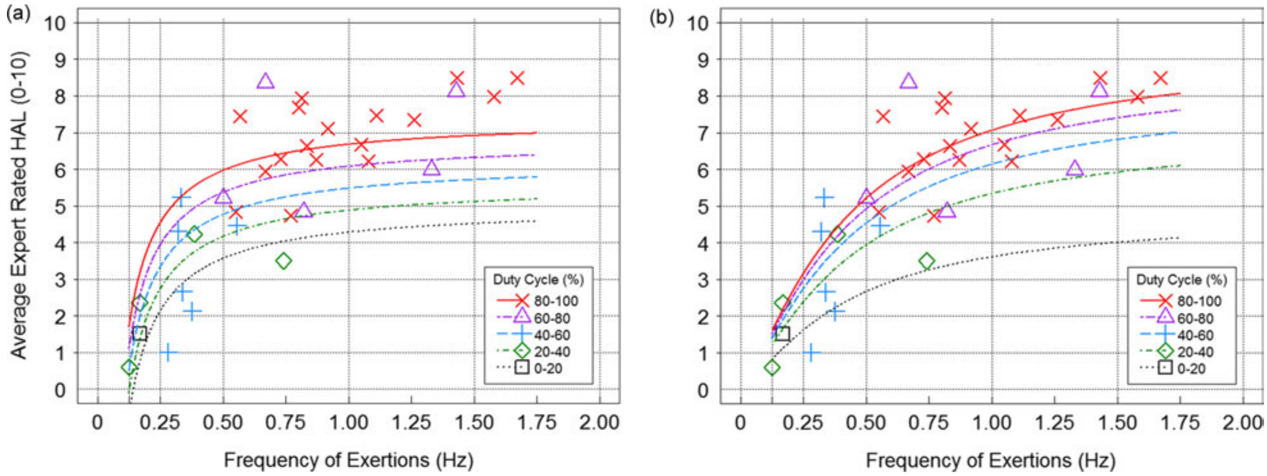

Figure 5. Linear (a) and nonlinear (b) regression models with complete Latko et al. (1997) data. The smooth curves are the fitted values for duty cycles of 10, 30, 50, 70 and 90 as a function of frequency.

The TLV® table corresponding to Equation (3) is shown in Table 3. Values that differ from the current TLV® table (Table 1) are indicated by an asterisk. Ebersole and Armstrong (2002) found that observers were in agreement within one point of the scale 91% of the time. We have reported the predicted HAL values to one decimal place so that these values can be used in calculations such as means and differences and for comparison.

Once calculations are complete, HAL values should be rounded to integer values. HAL values were rounded off to the nearest whole number because it was believed that even single decimal values implied greater accuracy and precision than could be supported by the data (ACGIH 2001). In light of recent studies (e.g. Ebersole and Armstrong 2002; Bao et al. 2006; Paulsen et al. 2014), single decimal values may facilitate comparing ratings and jobs. Also, single decimal accuracy helps provide insight into the analyst about how much exertion frequency needs to be decreased or recovery time needs to be increased to achieve compliance with the TLV®. It can help the analyst decide whether the value should be rounded up or down due to other exposure factors such as posture. A mathematical expression providing estimates of HAL to the nearest 0.1 units will be useful for practitioners.

The TLV® was based on epidemiological and fatigue studies that were available at the time the TLV® was first proposed in 2000 (ACGIH 2001) for estimating combinations of peak force and HAL associated with elevated risk of hand,

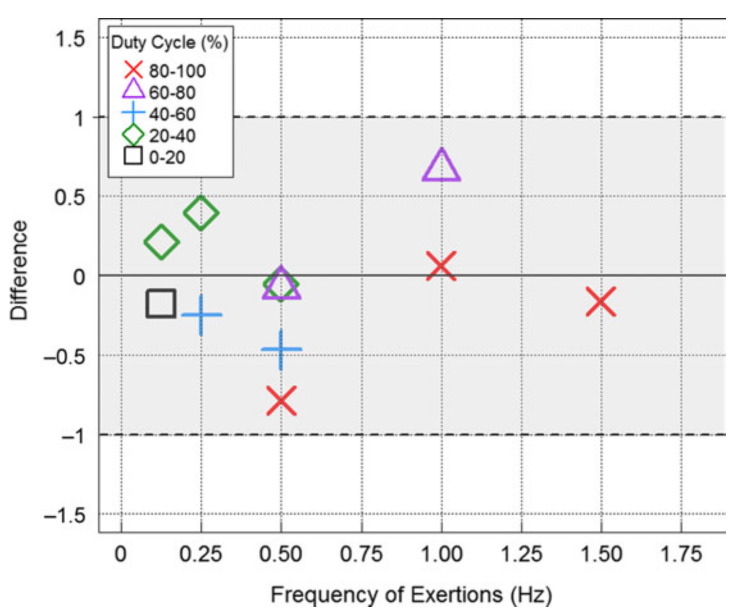

Figure 6. Differences between the nonlinear model predictions and values in the original TLV® table which are within the range of the data.

Table 3. HAL look-up table based on Equation (3).

Frequency (exertions/s)	Period (s/exertion)	Duty cycle (%)				
		0–20	20–40	40–60	60–80	80–100
0.125	8.0	0.8	1.2			
0.25	4.0		2.4	2.8		
0.5	2.0		4	4.5	4.9	5.2[a]
1.0	1.0				6.7[a]	7.1
1.5[b]	0.67[b]				7.4[b]	7.8[b]

Note: Shaded region: Outside the range of the data.
[a]Differs from the TLV® table.
[b]Entries not included in the original TLV® table.

wrist and forearm work-related musculoskeletal disorders. The TLV® for hand, wrist and forearm work-related musculoskeletal disorders recommended an AL that should trigger a control program that includes risk factor identification, health surveillance, education and appropriate control measures, as well as a threshold limit that should also trigger a control program as well as immediate attention to the jobs that exceed the TLV® and to workers performing them.

The availability of an accurate equation for HAL makes it possible to visualise the TLV® guidelines graphically and analytically. The TLV® NPF can be expressed as an equation:

$$\mathrm{NPF_{TLV}} = 7.8 - 0.78\,\mathrm{HAL}.$$

Using the expression for HAL given in Equation (3), we obtain the following equation for the TLV:

$$\mathrm{NPF_{TLV}} = 7.8 - 0.78\left(6.56\ln D\left[\frac{F^{1.31}}{1+3.18\,F^{1.31}}\right]\right),$$

$$= 7.8 - 5.12\ln D\left[\frac{F^{1.31}}{1+3.18\,F^{1.31}}\right].$$

This limit is shown as a function of frequency for a number of duty cycle values in Figure 7. Similarly, the AL linear equation for NPF is

$$\mathrm{NPF_{AL}} = 5.56 - 0.556\left(6.56\ln D\left[\frac{F^{1.31}}{1+3.18\,F^{1.31}}\right]\right)$$

and is displayed in Figure 7 as a function of frequency and duty cycle.

The utility of using this equation in practice may be illustrated in the following example. Consider a task having a frequency $F = 0.5$ Hz and duty cycle $D = 90\%$. Under the HAL look-up table (Table 1) published in the TLV® Document

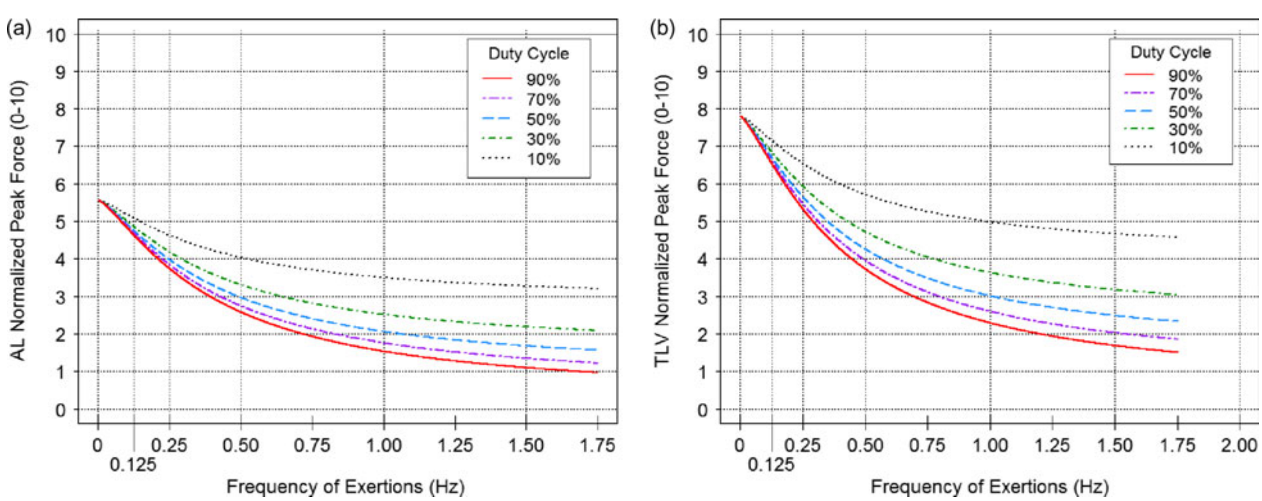

Figure 7. AL (a) and TLV (b) for NPF plotted against frequency and duty cycle values of 10, 30, 50, 70 and 90, according to Equation (3) and tthe specified AL and TLV functions.

(2001), the job would have a HAL = 6. Correspondingly, Equation (3) yields HAL = 5.2. Rounding HAL to 5 would result in a difference in NPF for the TLV of 0.78 on a 0 to 10 scale, and consequently over-estimate the TLV using the original Table 1.

The current HAL scales, equations and tables are all based on a relatively small number of observed data that were used in the original studies by Latko et al. (1997). While the proposed equations appear to provide reasonable extrapolations beyond the range of observed data – they are still extrapolations and should not be relied on beyond the range of the original data. Theoretical models are needed that account for the tradeoff between force, frequency and recovery time. This is a complex multi-factorial relationship involving both short-term and long-term biomechanical and physiological processes that will most likely prove to be nonlinear. Future research may further optimise the equation and complete gaps in the table. Observations of additional jobs over the range of forces and frequencies of the jobs shown in Table 1 should be used to validate the proposed equations until theoretical models are developed and accepted.

3.3. Equation validation

The nonlinear equation for HAL (Equation (3)) was validated against a set of 30 job video segments (tasks) from Harris et al. (2011). Tasks were selected at random and deemed eligible for inclusion if the video contained no breaks, corruptions or jumps, had unambiguous task descriptions and had corresponding expert HAL ratings. Five tasks were excluded from the initial random selection due to video recording jumps or incomplete task depiction in the video record. The resulting random selection included 30 different subjects performing 24 unique tasks, and had expert-rated HAL values ranging between 2 and 8.

MVTA single frame video analysis was performed to measure frequency and duty cycle for each task. Exertion time and rests periods in these segments were consistent with those in Latko et al. (1997). Exertions were considered a unique application of force by a loaded hand, while rest was marked only when the hand was unloaded. At least 10 cycles of exertions and rest periods for each video segment were marked using MVTA software and the subsequent frequencies and duty cycles were calculated directly.

The resulting linear regression (with intercept set to zero) between the equation-predicted HAL and the observed HAL values had a slope of 1.04 ($p < 0.001$) and $R^2 = 0.95$, and is plotted in Figure 8. Residual analysis for this regression (equation fit-observed HAL) compared against table-predicted HAL values from Table 1 (table value-observed HAL) suggested an improvement for Equation (3) over the original HAL table, especially for high and low HAL values. Table residual values ranged between −3.5 and 2, while all residual values from Equation (3) were contained within the range −2.2 and 2.2. The equation to predict HAL was more randomly distributed and reduced the tendency to under-predict HAL for high frequency and high duty cycle combinations.

Although the equation to predict HAL offers a better estimate than a look-up table, the nonlinear regression model contained residuals for some data points that exceeded HAL = 2 (Figure 5(b)), indicating that the model did not account for some of the variance. A companion paper (Akkas et al. 2014) explores substituting tracked RMS hand speed for F to automatically estimate HAL using video tracking, and compares the fit when modelling HAL based on F or speed.

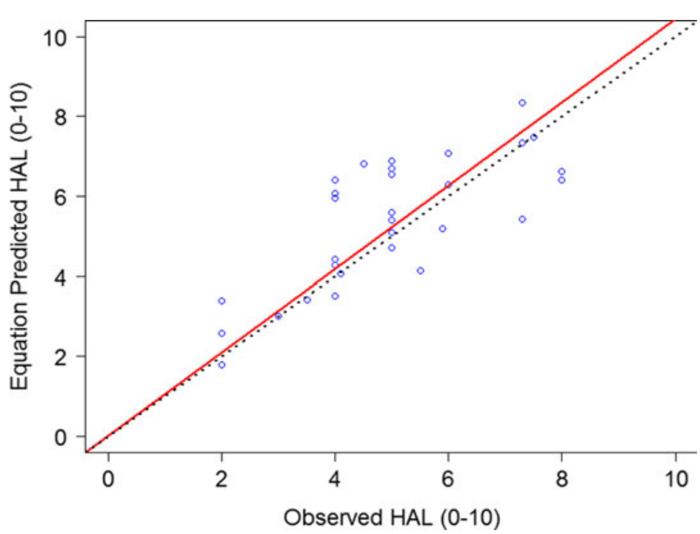

Figure 8. Validation ($N = 30$) between expert-observed HAL and equation-predicted HAL (by Equation (3)).

4. Summary and conclusions

This paper reviewed the origin of the table for calculating HAL from objective measures of *F* and *D*, used in the calculation of the repetitive motion TLV®, examined its limitations and developed a new equation that provides a continuous HAL scale and allows an improved table. We have arrived at the following observations and conclusions.

1. Some of the HAL values in the ACGIH TLV® table are for frequency and duty cycle combinations not covered by the original Latko et al. (1997) data, especially for high frequencies.
2. The Latko et al. (1997) data omitted duty cycle for two high frequency jobs (Nos 31 and 32), which were not used in creating the TLV® HAL table. We digitised the original videos and calculated the duty cycles for these jobs. The percentage recovery for jobs 31 and 32 was 81% and 82%, respectively.
3. We observed that when the TLV® HAL table was created, the values for low frequencies and short duty cycles were set to 1, HAL for frequencies of 2 exertions/s was adjusted one unit greater than the original linear model actually predicted, and extrapolated outside the range of the available data.
4. A new equation was developed that provides HAL predictions for all values of duty cycle and frequency within the range of the Latko et al. (1997) data.
5. Given the lack of data above 1.5 exertions/s, it is proposed that the frequency row labelled 2 exertions/s in the ACGIH TLV® table should more accurately be labelled 1.5 exertions/s.

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