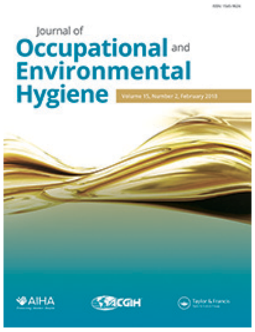

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

Risk assessments using the Strain Index and the TLV for HAL, Part II: Multi-task jobs and prevalence of CTS

Jay M. Kapellusch, Barbara A. Silverstein, Stephen S. Bao, Mathew S. Thiese, Andrew S. Merryweather, Kurt T. Hegmann & Arun Garg

To cite this article: Jay M. Kapellusch, Barbara A. Silverstein, Stephen S. Bao, Mathew S. Thiese, Andrew S. Merryweather, Kurt T. Hegmann & Arun Garg (2018) Risk assessments using the Strain Index and the TLV for HAL, Part II: Multi-task jobs and prevalence of CTS, Journal of Occupational and Environmental Hygiene, 15:2, 157-166, DOI: 10.1080/15459624.2017.1401709

To link to this article: https://doi.org/10.1080/15459624.2017.1401709

Accepted author version posted online: 20 Nov 2017.
Published online: 20 Nov 2017.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2018, VOL. 15, NO. 2, 157–166
https://doi.org/10.1080/15459624.2017.1401709

Taylor & Francis
Taylor & Francis Group

Risk assessments using the Strain Index and the TLV for HAL, Part II: Multi-task jobs and prevalence of CTS

Jay M. Kapellusch [a], Barbara A. Silverstein[b], Stephen S. Bao [b], Mathew S. Thiese [c], Andrew S. Merryweather [c], Kurt T. Hegmann [c], and Arun Garg[a]

[a]Department of Occupational Science & Technology, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin; [b]SHARP Program, Washington State Department of Labor and Industries, Olympia, Washington; [c]Rocky Mountain Center for Occupational and Environmental Health, University of Utah, Salt Lake City, Utah

ABSTRACT

The Strain Index (SI) and the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value for hand activity level (TLV for HAL) have been shown to be associated with prevalence of distal upper-limb musculoskeletal disorders such as carpal tunnel syndrome (CTS). The SI and TLV for HAL disagree on more than half of task exposure classifications. Similarly, time-weighted average (TWA), peak, and typical exposure techniques used to quantity physical exposure from multi-task jobs have shown between-technique agreement ranging from 61% to 93%, depending upon whether the SI or TLV for HAL model was used. This study compared exposure-response relationships between each model-technique combination and prevalence of CTS.

Physical exposure data from 1,834 workers (710 with multi-task jobs) were analyzed using the SI and TLV for HAL and the TWA, typical, and peak multi-task job exposure techniques. Additionally, exposure classifications from the SI and TLV for HAL were combined into a single measure and evaluated. Prevalent CTS cases were identified using symptoms and nerve-conduction studies. Mixed effects logistic regression was used to quantify exposure-response relationships between categorized (i.e., low, medium, and high) physical exposure and CTS prevalence for all model-technique combinations, and for multi-task workers, mono-task workers, and all workers combined.

Except for TWA TLV for HAL, all model-technique combinations showed monotonic increases in risk of CTS with increased physical exposure. The combined-models approach showed stronger association than the SI or TLV for HAL for multi-task workers.

Despite differences in exposure classifications, nearly all model-technique combinations showed exposure-response relationships with prevalence of CTS for the combined sample of mono-task and multi-task workers. Both the TLV for HAL and the SI, with the TWA or typical techniques, appear useful for epidemiological studies and surveillance. However, the utility of TWA, typical, and peak techniques for job design and intervention is dubious.

KEYWORDS

Job rotation; risk classifications; exposure-response; MSDs; Strain Index; TLV for HAL

Introduction

It is generally accepted that combinations of biomechanical stressors such as force, repetition, and posture interact to create increased risk for distal upper extremity (DUE) musculoskeletal disorders (MSDs).[1,2] In North America, the threshold limit value (TLV) for hand activity level (HAL)[3] and the Strain Index (SI)[4] are commonly used models to combine two or more DUE biomechanical stressors into a single measure of physical exposure. However, there is a poor correlation (Spearman's Rho = 0.50) between exposure scores from the two models, and less than 50% agreement (Kappa = 0.28) between DUE MSD exposure classifications using each model's a priori low, medium, and high exposure categories.[5] Results from part one of this paper[5] showed that for 16% of 3,647 tasks one of the models classified a task as low exposure while the other classified the task as high exposure. Despite these differences, recent epidemiological studies have reported that the two models have relatively comparable ability to predict risk of DUE MSDs and, in particular, carpal tunnel syndrome (CTS).[6–9]

CONTACT Jay M. Kapellusch kap@uwm.edu Department of Occupational Science & Technology, College of Health Sciences, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201.

We postulate that the SI and TLV for HAL might be measuring different aspects of DUE MSD exposure[5] because the two models: (i) have different constituent variables (e.g., both models include "force" but the definition of force is considerably different between the two), (ii) combine and penalize those variables differently, and (iii) have been shown to have comparable association with MSDs. An implication of this assertion is that combining the exposure classifications from the two models into a single exposure estimate might provide stronger exposure-response relationships than either of the two models could alone.

Regardless of the model used, another complication in quantifying physical exposure is the widespread use of job rotation or job enrichment strategies in industry (i.e., multi-task jobs where each worker performs at least two or more, but typically several unique tasks per day). Both the SI and the TLV for HAL were developed to analyze mono-task jobs[3,4] and, thus, there are no predefined techniques within either of the original models to quantify physical exposure from multi-task jobs. Nonetheless, a few techniques are commonly used to aggregate the physical exposures from multiple tasks into a single measure of physical exposure for a job. These are: (1) time-weighted average (TWA) of tasks; (2) "Peak" exposure that assumes the most stressful task is performed for the shift; and (3) "Typical" exposure that assumes that the longest duration task represents the exposure from the shift.[5] In part one of this study, we compared exposure classifications using these three techniques and found good to very good between-technique exposure classification agreement for SI scores (Kappa $>= 0.78$), but poor between-technique agreement for TLV for HAL scores (i.e., Kappa $= 0.19$ and 0.16 when comparing TWA to typical and peak TLV for HAL, respectively).[5] Since the two models (the SI and the TLV for HAL) and the three techniques (TWA, peak, and typical exposure) differ in exposure classifications, it is reasonable to question whether one model-technique combination provides superior exposure-response relationships. Similarly, combining the exposure classifications for the SI and TLV for HAL may produce the stronger result.

The objectives of this study were to: (i) compare exposure-response relationships for CTS prevalence using the SI and TLV for HAL, quantified with each of three daily physical exposure techniques: (a) TWA exposure, (b) Peak exposure, and (c) Typical exposure; and (ii) determine whether a single exposure estimate, produced by combining exposure classifications from the SI and the TLV for HAL, provides stronger exposure-response relationships than either of the two models alone.

Methods

This study combined physical exposure and health outcome data from three large-scale, occupational studies of CTS. These studies were approved by the institutional review boards (IRB) of the University of Wisconsin – Milwaukee, the University of Utah, and the State of Washington. All workers enrolled in these studies provided written informed consent. The methods used to enroll workers, determine health status, and quantify physical exposures have been discussed in detail elsewhere.[5] The following is a summary of those methods.

Workers were recruited from 35 facilities representing 25 industries in the U.S. states of Illinois, Utah, Washington, and Wisconsin. Workers' ages and genders were recorded. Heights and weights were measured at the time of enrollment and subsequently used to calculate body mass index (BMI), a convenient and widely used, though modestly inaccurate, proxy for obesity.[10]

Dominant hand physical exposures were quantified for each task performed by each worker. Peak[3] and overall hand forces[4,9,11] were rated by trained ergonomists using the Borg CR-10 scale.[12] Hand activity level (HAL) was rated by trained analysts using the HAL verbal anchor scale.[13] Frequency of exertion, duty cycle (% duration of exertion), hand/wrist posture, and speed of work were quantified from video recordings and subsequently categorized using the Strain Index rating scales.[4] Frequency of exertion and duty cycle computations were based upon only those exertions that occurred at an analyst estimated force level of one or more on the Borg CR-10 scale (i.e., Force rating ≥ 1, "very light" or harder).[5] For cyclic tasks with cycle times of 2 min or less, a minimum of 10 task cycles were randomly analyzed. If cycles times were very short (i.e., < 30 s), a minimum of 5 min of cycles were randomly analyzed. For longer duration tasks, a minimum of three representative task cycles were analyzed.[5]

Tasks below the TLV for HAL action limit (AL) were classified as "low" exposure. Similarly, tasks at or above the AL and up to and including the threshold limit value (TLV) were classified as "medium" exposure, and tasks above the TLV were classified as "high" exposure.[3] SI scores for each task were calculated using: (i) overall force, (ii) frequency of exertion, (iii) duty cycle, (iv) hand/wrist posture, (v) speed of work, and (vi) hours of exposure per day as described by Moore and Garg[4] and Garg et al.[9] SI scores were then classified into exposure categories of "low" (SI ≤ 3.0), "medium" ($3.0 <$ SI ≤ 6.1), and "high" (SI > 6.1) using the recommended limits of Moore and Garg.[14]

For those workers with job rotation, exposures were summarized at the job-level (i.e., daily exposure) using three previously reported techniques: (i) TWA of tasks

Table 1. Descriptive statistics of cohort (N = 1,834).

Variable	Mean	SD	Min	Max	Median	IQR[a]	N	%
Entire cohort (N = 1,834)								
Age	41.1	11.3	18	72	42	32–50		
BMI	28.7	6.5	16.0	58.6	27.5	23.9–32.1		
Gender								
Female							1096	59.8
Male							738	41.2
Mono-Task cohort (N = 1,124)								
Age	40.8	11.3	18	72	41	32–50		
BMI	28.8	6.6	16.0	58.6	27.5	23.9–32.2		
Gender								
Female							618	55.0
Male							506	45.0
Multi-task cohort (N = 710)								
Age	41.6	11.4	18	68	42	33–50		
BMI	28.5	6.4	16.6	55.0	27.4	23.9–32.1		
Gender								
Female							478	67.3
Male							232	32.7

[a]IQR: inter-quartile-range.

based on task hours per day,[15–18] (ii) Typical exposure defined as the task performed for the largest proportion of the work shift,[8,9] and (ii) Peak exposure defined as the task with the highest (i.e., worst) physical exposure.[15,19] Multi-Task job physical exposures were classified into each model's low, medium, and high exposure categories in the same manner as previously described.

Workers were determined to be prevalent cases for CTS in their dominant hand if they had both (i) symptoms consistent with CTS and (ii) abnormal median nerve conduction. Symptoms consistent with CTS included pain, numbness, tingling, and/or burning with no acute or traumatic onset, in two or more of the first four digits of the dominant hand for greater than one week, or three or more times in the prior year.[20] Workers had abnormal nerve conduction if the following combined criteria were met for the dominant hand: (i) median motor latency > 4.5 ms at 8 cm, or median sensory latency > 3.5 ms at 14 cm, or midpalmar latency > 2.2 ms at 8 cm; AND (ii) ulnar sensory latency < 3.7 ms at 14 cm, or medium-ulnar sensory latency difference > 0.5 ms, or midpalmar median-ulnar difference > 0.3 ms.[20]

Three sets of workers were created for this study's analyses. The main set consisted of all eligible workers. The second set was a subset of the main, and consisted of only those workers performing mono-task jobs (i.e., no job rotation). For these workers, there was no difference between the results of TWA, Peak, and Typical job exposure summary techniques as the jobs they performed consisted of only a single task. The last set, also a subset of the main, consisted of only those workers performing multi-task jobs (i.e., workers *with* job rotation).

To test the assertion that the SI and TLV for HAL measure different aspects of DUE MSD exposure and, thus, their combined exposure classifications might be superior predictors of risk than each model's individual exposure classifications, we combined the classifications from the two models' as follows: (1) if both models agreed that the job was low exposure, the job was classified as "low"; (2) if both models agreed that the job was high exposure, the job was classified as 'high"; and (3) all remaining combinations were classified as "medium."

Mixed effects logistic regression was used to determine odds ratios and 95% confidence intervals for: (i) the TLV for HAL, (ii) the SI, and (iii) the combined models approach for each of the three sets of workers (i.e., all workers, mono-task workers only, and multi-task workers only). All models were a-priori adjusted for age, gender, and BMI, and included research site (UT, WA, WI) as a random effect. A separate model, including only the a priori adjustment factors (i.e., no physical exposure), was built to estimate the associations between age, gender and BMI, and prevalence of CTS for the cohort of all workers.

Results

The three studies had combined, total enrollment of 2,020 workers who represented a diverse group of manufacturing and service industries.[5] Of those 2,020 workers, 1,834 (90.8%) completed both health and physical exposure baseline assessments. Multi-task jobs were performed by 710 of the workers (i.e., workers had job rotation), while the remaining 1,124 worked mono-task jobs (i.e., performed only one task for their entire work shift).

The point prevalence of dominant hand CTS was 16.3%. Total prevalence of CTS for the entire eligible cohort was 18.4% (347 participants with CTS in the right, left, or both hands). Right hand, left hand, and bilateral prevalence were 16.9%, 6.5%, and 4.4%, respectively. Age, gender and BMI of the entire sample, and for the mono-task and multi-task subsets of workers are summarized in Table 1. Age and BMI were comparable between

Table 2. Physical exposure summary for entire cohort (N = 1,834).

Variable	Mean	SD	Min	Max	Median	IQR[a]	N	%
Strain Index - TWA	5.1	7.8	0.2	80.8	2.5	0.8–6.5		
≤ 3							955	52.1
3 < SI ≤ 6.1							409	22.3
> 6.1							470	25.6
Strain Index - Typical	6.8	10.5	0.3	117.0	3.0	0.8–9.0		
≤ 3							839	45.7
3 < SI ≤ 6.1							463	25.2
> 6.1							532	29.1
Strain Index - Peak	7.3	10.8	0.3	117.0	3.0	0.8–9.0		
≤ 3							804	43.8
3 < SI ≤ 6.1							461	25.1
> 6.1							569	31.1
TLVHAL - TWA	0.44	0.41	0.00	5.00	0.38	0.20–0.57		
< AL							1363	74.3
AL ≤ score ≤ TLV							229	12.5
> TLV							242	13.2
TLVHAL - Typical	0.55	0.56	0.00	5.00	0.44	0.25–0.67		
< AL							1182	64.4
AL ≤ score ≤ TLV							326	17.8
> TLV							326	17.8
TLVHAL - Peak	0.58	0.49	0.00	5.00	0.49	0.25–0.71		
< AL							1156	63.0
AL ≤ score ≤ TLV							332	18.1
> TLV							346	18.9

[a]IQR: inter-quartile-range.

the mono-task and multi-task worker sets ($t = -1.465$, $p = 0.14$, and $t = 0.751$, $p = 0.45$, respectively). However, the multi-task workers consisted of a larger proportion of female workers than the mono-task (67.3% vs. 55.0%, chi-square = 27.051, $p < 0.01$).

For the set of all workers, females, older workers, and obese workers had higher prevalence of CTS. Dominant hand prevalence for females was 20.1% as compared to 10.7% for males (OR = 1.74, 95% CI = 1.30–2.31), 22.7% for those classified as obese (i.e., BMI ≥ 30 kg/m^2) as compared to 13.0% for nonobese (OR = 1.06/unit BMI, 95% CI =1.04–1.08), and 21.4% for those older than 42 years of age (median age) vs. 11.7% for younger workers (OR = 1.03/year, 95% CI =1.02–1.04).

Physical exposure estimates using the SI and TLV for HAL, and the TWA, peak and typical techniques

Table 2 summarizes the descriptive statistics of physical exposures using the SI and the TLV for HAL, and each of the three job physical exposure aggregation techniques (i.e., TWA, typical, and peak exposure). Overall, physical exposures ranged from very low to very high (Table 2). A majority of workers (N = 1,124, 61.3%) performed mono-task jobs, and thus their SI and TLV for HAL estimated physical exposure was constant regardless of whether the TWA, typical, or peak technique was used to summarize their job exposure. The TWA technique resulted in the lowest physical exposure estimate (see Part I for details).[5] On average, typical and peak SI scores were 1.7 and 2.2 units (33 to 43%) higher, and TLV for HAL scores were 0.11 and 0.14 units (25 to 32%) higher, respectively, than the TWA exposures ($t > 14.8$, $p < 0.001$). Peak exposures were statistically higher than typical exposures for both the SI and the TLV for HAL ($t > 5.4$, $p < 0.01$), but the magnitude differences were relatively small (0.5 units, 7% higher for the SI and 0.03 units, 5% higher for the TLV for HAL).

Table 3 summarizes physical exposures for those workers performing multi-task jobs and mono-task jobs, separately. When only those workers with multi-task jobs were examined, the relative difference in physical exposure magnitude between the TWA and the typical and peak techniques was more apparent. The average SI score was 6.0, 10.4 and 11.7 for the TWA, typical and peak exposures, respectively, and the corresponding TLV for HAL score was 0.49, 0.77 and 0.85, respectively. Regardless of the technique used, multi-task workers had higher average physical exposure than mono-task workers (mean SI score of 4.5 for mono-task versus 6.0–11.7 for multi-task [$t > 4.2$, $p < 0.001$], and mean TLV for HAL score of 0.41 for mono-task vs. 0.49–0.84 for multi-task [$t > 4.2$, $p < 0.0001$]; Table 3).

Exposure-response relationships between the SI and the TLV for HAL, and for the TWA, peak and typical techniques, and prevalence of CTS

Exposure-response relationships between prevalence of CTS and SI, TLV for HAL, and the combined exposure classification for each of the three multi-task physical exposure aggregation techniques applied to all workers

Table 3. Physical exposure summary for multi-task and mono-task cohorts.

Variable	Mean	SD	Min	Max	Median	IQR[a]	N	%
Multi-Task job cohort (N = 710 workers)								
Strain Index - TWA	6.0	6.9	0.3	68.3	3.8	1.7–7.5		
≤ 3							302	42.5
$3 < SI \leq 6.1$							149	21.0
> 6.1							259	36.5
Strain Index - Typical	10.4	12.4	0.3	117.0	6.0	2.3–13.5		
≤ 3							233	32.8
$3 < SI \leq 6.1$							156	22.0
> 6.1							321	45.2
Strain Index - Peak	11.7	12.7	0.3	117.0	6.8	3.0–18.0		
≤ 3							195	27.5
$3 < SI \leq 6.1$							157	22.1
> 6.1							358	50.4
TLVHAL - TWA	0.49	0.35	0.00	5.00	0.41	0.40–0.80		
$<$ AL							504	71.0
AL $\leq$ score $\leq$ TLV							90	12.7
$>$ TLV							116	16.3
TLVHAL - Typical	0.77	0.66	0.00	5.00	0.60	0.28–0.63		
$<$ AL							323	45.5
AL $\leq$ score $\leq$ TLV							187	26.3
$>$ TLV							200	28.2
TLVHAL - Peak	0.84	0.73	0.00	5.00	0.60	0.40–0.83		
$<$ AL							297	41.8
AL $\leq$ score $\leq$ TLV							193	27.2
$>$ TLV							220	31.0
Mono-Task job cohort (N = 1,124 workers)								
Strain Index	4.5	8.3	0.3	81.0	1.5	0.4–6.0		
≤ 3							660	58.7
$3 < SI \leq 6.1$							253	22.5
> 6.1							211	18.8
TLV for HAL	0.41	0.43	0.00	5.00	0.33	0.11–0.50		
$<$ AL							859	76.4
AL $\leq$ score $\leq$ TLV							139	12.4
$>$ TLV							126	11.2

[a]IQR: inter-quartile-range.

(i.e., both multi-task and mono-task workers, N = 1,834) are provided in Table 4. Regardless of model and technique, there was a generally increasing trend in risk of CTS as the physical exposure classification increased.

Table 4. Odds ratios, (95% confidence intervals), and [model p-values] for the SI, TLV for HAL, and the combined models approach for the total cohort (N = 1,834).

N = 1,834 workers		SI	TLV for HAL	Combined
TWA Exposure	Low	1.00 [p = 0.08]	1.00 [p = 0.42]	1.00 [p = 0.13]
	Medium	1.34 (0.95–2.01)	1.39 (0.93–2.08)	**1.57** (1.16–2.13)
	High	**1.65** (1.19–2.30)	1.33 (0.88–1.99)	**1.84** (1.14–2.95)
Typical Exposure	Low	1.00 [p = 0.09]	1.00 [p = 0.18]	1.00 **[p = 0.03]**
	Medium	1.25 (0.85–1.84)	1.32 (0.92–1.88)	**1.54** (1.12–2.14)
	High	**1.66** (1.19–2.30)	**1.48** (1.03–2.12)	**1.99** (1.30–3.04)
Peak Exposure	Low	1.00 [p = 0.18]	1.00 [p = 0.18]	1.00 [p = 0.08]
	Medium	1.12 (0.76–1.17)	1.28 (0.90–1.83)	**1.43** (1.03–1.99)
	High	**1.48** (1.06–2.06)	1.37 (0.96–1.95)	**1.71** (1.12–2.61)

Categories in **bold** were significant at the $p < 0.05$ level.

Both the SI and the TLV for HAL appeared to exhibit monotonic increases in risk of CTS for the Typical and the Peak Techniques (although the high exposure category for peak TLV for HAL was not significant, $p > 0.05$). For the TWA technique, the SI showed a monotonic increase in risk whereas the TLV for HAL showed essentially the same OR estimate for both medium and high exposure jobs as compared to low exposure jobs (OR = 1.39, and OR = 1.33, respectively).

When analyses were restricted to only those workers performing multi-task jobs, no monotonic increases in risk of CTS were observed for the TLV for HAL or the SI models with the exception of TWA technique for the SI model (Table 5). All three techniques showed modest increases in risk for high exposure categories for both the SI and TLV for HAL, with the typical and TWA exposure SI showing statistically significant increases ($p \leq 0.05$). However, medium exposure categories for the SI and TLV for HAL showed no statistically significant increase in risk for any of the three techniques (Table 5).

The opposite trend was seen when the analyses were restricted to only those workers with mono-task jobs (Table 5). Medium-exposures had modest elevated risk for both the SI and TLV for HAL (OR = 1.43 and

Table 5. Odds ratios, (95% confidence intervals), and [model p-values] for the SI, TLV for HAL, and the combined models approach for the multi-task and mono-task cohorts.

Multi-Task job cohort (N = 710 workers)		SI	TLV for HAL	Combined
	Low	1.00 [p = 0.09]	1.00 [p = 0.29]	1.00 [p = 0.07]
TWA Exposure	Medium	1.26 (0.71–2.23)	1.03 (0.53–2.00)	1.43 (0.90–2.28)
	High	**1.69** (1.06–2.72)	1.43 (0.83–2.45)	**2.08** (1.11–3.89)
	Low	1.00 [p = 0.33]	1.00 [p = 0.25]	1.00 [p = 0.12]
Typical Exposure	Medium	1.00 (0.55–1.83)	1.08 (0.64–1.80)	1.38 (0.80–2.37)
	High	**1.64** (1.01–2.68)	1.57 (0.96–2.56)	**2.13** (1.16–3.92)
	Low	1.00 [p = 0.35]	1.00 [p = 0.33]	1.00 [p = 0.27]
Peak Exposure	Medium	0.74 (0.40–1.39)	1.00 (0.59–1.67)	1.05 (0.61–1.84)
	High	1.23 (0.75–2.01)	1.33 (0.82–2.16)	1.47 (0.79–2.70)
Mono-Task job cohor (N = 1,124 workers)				
	Low	1.00 [p = 0.28]	1.00 [p = 0.93]	1.00 [p = 0.74]
Exposure	Medium	1.43 (0.88–2.34)	**1.67** (1.00–2.77)	**1.65** (1.13–2.41)
	High	1.47 (0.93–2.34)	1.08 (0.57–2.04)	1.26 (0.57–2.80)

Categories in **bold** were significant at the $p < 0.05$ level.

OR = 1.67, respectively), although the OR for SI was not statistically significant ($p > 0.05$). The OR for the SI for high exposure was essentially the same as that for medium-exposure (OR = 1.47 for high vs. OR = 1.43 for medium) and the OR for TLV for HAL was reduced to OR = 1.08. Neither the SI nor the TLV for HAL high exposure category ORs were statistically significant ($p > 0.05$).

Exposure-response relationships for the combined exposure classification, and the TWA, peak and typical techniques

Also shown in Tables 4 and 5 are the exposure-response relationships between the combined exposure classifications from the SI and TLV for HAL models (i.e., combined approach) and prevalence of CTS. For the all workers and multi-task workers sets, the combined approach exhibited monotonic increases in CTS risk with increases in physical exposure, regardless of which of the three job exposure aggregation techniques was used. The only exception was peak exposure technique for multi-task workers where the medium exposure category showed no increase in risk (OR = 1.05). For the set consisting of all workers, the ORs were statistically significant ($p < 0.05$) for both medium and high exposure categories. For the set with only multi-task workers, the high exposure ORs for TWA and Typical exposure were statistically significant. For mono-task workers, the combined approach showed a statistically significant increased risk of CTS for the medium-exposure classification (OR = 1.65, $p \leq 0.05$), and an elevated, but relatively lower and statistically nonsignificant OR for high exposure classification (Table 5).

In general, the combined approach of determining exposure level by combining exposure classifications from the SI and TLV for HAL models showed stronger (i.e., higher ORs and lower p-values) exposure-response relationships with CTS prevalence than either the SI or TLV for HAL alone (Tables 4 and 5). This observation was true for all three job physical exposure aggregation techniques (TWA, typical and peak). Furthermore, there was a greater trend toward monotonic increases in CTS risk for the combined approach as compared to either of the SI or the TLV for HAL. This was especially true for the typical exposure technique, in the context of all workers (Table 4), where the increase in risk was nearly linear (Low OR = 1.00, Medium OR = 1.54, and High OR = 1.99).

An exception to the trend of the combined approach being superior was among mono-task workers, where the SI showed nonstatistically significant elevated risk for both medium and high exposures whereas the combined approach showed a statistically significant increase in risk for the medium exposure classification, but a markedly reduced and nonsignificant increase for the high exposure classification (Table 5).

Discussion

Consistent with the findings of prior studies, these results show an association between level of physical exposure and risk of CTS as quantified by the TLV for HAL and the SI. To our knowledge, this is the first study to examine how commonly used techniques to estimate physical exposure for multi-task jobs (i.e., TWA, typical, and peak), affect exposure-response relationships between the TLV for HAL and the SI, and risk of CTS.

Prevalence of CTS in this cohort

Our data suggest that nearly one in five workers have findings consistent with CTS. This prevalence is at the high end of the 5–21% range previously reported for manufacturing and meat-packing workers,[21] and nearly four times the upper limit of the 1–5% range reported for the general population.[21] The case definition for this study is similar to those of other recent epidemiological studies.[9,15,19–21] This suggests that our observed prevalence is not simply an artifact of an overly sensitive case-definition, although it is likely driven by the careful surveillance of a workforce.

The high prevalence observed in these workers may be magnified by the types of jobs studied (i.e., manufacturing and service industries with a high proportion of hand intensive work) and many years of exposure to this type of work prior to the study's inception. It is interesting to note that, while CTS is generally considered a serious musculoskeletal disorder, these prevalent workers were continuing to perform hand intensive work at the time of enrollment.[22]

Risk prediction differences between the SI and TLV for HAL

The SI and the TLV for HAL were designed to quantify DUE physical exposure and, therefore risk of DUE MSDs. However, while the physical exposure domains of force and repetition are present in both the SI and the TLV for HAL, the models share no constituent variables within those domains. This led to exposure classification differences between the two models for nearly half of the jobs in this study.[5] Nevertheless, the exposure-response relationships between each of the two models and prevalence of CTS were broadly similar. The SI achieved statistical significance for more exposure categories, but the OR differences were generally small between the two models.

A possible explanation for comparable exposure-response performance, despite large exposure classification differences, is that neither the SI nor the TLV for HAL captured a complete representation of a task's exposure. For example, applied force has been shown to be a strong risk factor for CTS.[23] The SI relies on overall force[4,11] while the TLV for HAL uses peak force.[11] It is possible that both peak and overall force are relevant to quantifying the true stress posed by a task, but neither the SI nor the TLV for HAL addresses both simultaneously.

To test whether the SI and TLV are essentially providing orthogonal estimates of DUE physical exposure, we combined their low, medium and high exposure classifications into a single estimate (i.e., combined approach). For all three sets of workers and regardless of the job physical exposure aggregation technique used, the combined approach consistently showed relatively stronger exposure-response relationships than either the SI or the TLV for HAL (Tables 4 and 5). The only exception was for the mono-task job cohort where the SI showed nonsignificant but elevated risk for both the medium and high exposure categories, whereas the combined approach showed statistically elevated risk for the medium-exposure category but much lower risk for the high exposure category relative to the medium-exposure category (Table 5). It is important to note that, on average, the mono-task workers had relatively lower physical exposure than the multi-task cohort workers (Table 3). This might explain the somewhat poor exposure-response performance of the models when applied to mono-task workers only.

Exposure-response differences between the TWA, typical, and peak techniques for multi-task job exposure quantification

Among the three techniques used in this study, the TWA job physical exposure classification technique worked best for estimating risk of CTS insofar as the SI and the combined approach appeared to show monotonic increases in risk of CTS among the 710 workers performing multi-task jobs. The Typical technique applied to the SI and TLV for HAL showed marked increase in risk only for those workers at high exposure. When using the combined approach, TWA and Typical techniques performed comparably. The Peak technique performed relatively worse than the TWA and Typical techniques, regardless to which model it was applied.

Again, it should be noted that this study's multi-task-job workers had relatively higher physical exposures and higher prevalence of CTS than mono-task-job workers.[24,25] The combined set of all workers (i.e., both mono-task and multi-task workers, N = 1,834) had a wider range of physical exposures. When all workers were considered, the TWA and typical technique worked comparably, whereas the peak technique performed relatively poorly.

From an epidemiological perspective, the differences in exposure classifications resulting from these three techniques appear to have minimal practical effect on quantifying exposure-response relationships insofar as, regardless which of the three techniques was used, the conclusion that medium and high physical exposures are associated with increased prevalence of CTS would remain. The TWA technique includes data from all tasks performed and perhaps for this reason it is widely used in occupational epidemiology despite its obvious mathematical tendency to dilute the effects of high exposures (see Table 3 and Part One[5]). Conversely, the Typical and Peak approaches ignore all but one specific task performed by a worker and thus result in some information loss. However, the constrained focus of the Typical and Peak techniques might also yield results that are more easily or logically translated into practice.

From an ergonomics practitioner perspective, using these three multi-task exposure techniques presents substantive challenges. The TWA technique suggests that high physical exposures from one task can be compensated by low physical exposures on another task; however, this assumption is dubious, particularly when one of the tasks in question would be considered hazardous if performed alone.[17,26–31] Meanwhile, the typical and peak techniques both ignore all but one task and simultaneously considering the effects of typical and peak tasks for a given job would, in many cases, require substantial professional judgment that could lead to poor assessment inter- and intra-rater reliability and, therefore, uncertain intervention strategies.

Limitations

Both the TLV for HAL and the SI were designed to quantify distal upper-limb physical exposures and to predict risk of distal upper-limb injuries and illnesses, in general, and not CTS specifically. While exposure classification disagreement would not change if a DUE MSD other than CTS had been studied, it is possible that exposure-response relationships and predictive ability would. In this regard, DUE MSDs other than CTS are relatively understudied and further investigations are needed to better understand the relative strengths and weaknesses of the TLV for HAL and the SI as tools for job evaluation and design.

Within a given exposure classification, both the TLV for HAL and the SI lack the ability to differentiate between different muscle loading patterns. However, specific muscle loading and recruitment patterns may be important factors for determining risk of MSDs from multi-task jobs. For example, a worker who performs a “high exposure” mono-task job might be at greater risk than a worker performing a job consisting of two “high exposure” tasks that each requires markedly different muscle recruitment patters within the DUE. Neither the SI nor the TLV for HAL, as currently designed, account for these types of exposure differences. Thus, regardless of the technique used to aggregate task exposures into job exposure, it is currently difficult to use mono-task assessment tools such as the SI and TLV for HAL to design safe multi-task jobs and to study the effects of multi-task jobs on risk of MSDs.

The raw data for this study included TLV for HAL and SI scores that are ostensibly continuous variables. However, primarily for two reasons, the analyses of this paper were limited to physical exposure based on a-prior risk categories. First, risk categories are a familiar convention for many MSD researchers and practitioners and therefore easily understood. Second, there are hidden complexities when treating each model’s score as continuous. With regard to the latter, the TLV for HAL numerical score increases in a radial pattern pivoting around the HAL = 10, peak force = 0 intercept, but this implicit trend of increasing stress is somewhat dubious.[32] Similarly, the SI constituent variables are ordinal and thus the SI score is quasi-ordinal with discrete, as opposed to truly continuous, values. Thus, the SI score follows a “saw-tooth” pattern where a one-step, discrete increase in SI score does not necessarily imply increased physical exposure.[33] Nevertheless, based on this paper’s results, treating the scores of the two models as continuous variables and examining the interactions between their constituent variables and model scores appears to be warranted.

This study’s multi-task workers appeared to have higher average physical exposures than its mono-task workers. Similarly, it is likely that mono-task and multi-task workers did not have comparable distributions of physical exposures. This might explain the relatively poorer performance of the SI and TLV for HAL when analyzing the multi-task and mono-task subsets as opposed to when the models were used to analyze all workers combined.

This study analyzed cross-sectional data and the results are subject to the biases and shortcomings of that study design. Recall bias is likely not a meaningful issue in these analyses because elements of both job exposure and CTS (nerve conduction study) were measured objectively. However, there may be recall bias of CTS symptoms. While generally considered superior, use of prospective analyses would add considerable additional complexity because physical exposures tend to change over time. Thus, cross-section analyses were deemed the most logical approach for exploring these comparisons. Regardless, applying these models and techniques to prospective data may lead to different conclusions.

Conclusion

Both the TLV for HAL and SI models showed exposure-response relationships with CTS prevalence despite having differed in exposure classification for 40% of the workers. This disagreement creates uncertainty for job design, job analysis, risk assessments, developing intervention strategies, and other practical applications. Combining the exposure estimates from the SI and TLV for HAL improved exposure-response relationships, particularly for multi-task jobs, perhaps suggesting that the models are quantifying different aspects of the exposure.

For workers performing multi-task jobs, we found that the TWA and Typical task approaches of aggregating physical exposures produced the strongest exposure-response relationships. However, both these techniques have substantial limitations. The TWA technique appears to systematically dilute biomechanical stressors whereas the typical technique ignores exposures from all but one task performed during a work shift. While either technique is useful for epidemiological studies and workforce surveillance where sample sizes are large, both techniques require substantial professional judgment to be successfully used for design of new or revised multi-task jobs and thus may have more limited utility for practitioners.

ORCID

Jay M. Kapellusch http://orcid.org/0000-0003-1016-276X
Stephen S. Bao http://orcid.org/0000-0001-7507-2402
Mathew S. Thiese http://orcid.org/0000-0003-4505-2907
Andrew S. Merryweather http://orcid.org/0000-0002-9048-9473
Kurt T. Hegmann http://orcid.org/0000-0002-0743-1888

References

[1] **NIOSH**: "Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low". National Institute for Occupational Safety and Health, DHHS, Cincinnati, Ohio, 1997.
[2] **National Research Council - Institute of Medicine**: Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities. In Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities, N.R.C.-I.O. Medicine (ed.). National Academy Press, Washington, D.C., 2001.
[3] **ACGIH**: Hand activity level. In *TLVs and BEIs - Threshold Limit Values for Chemical Substances and Physical Agents*. Cincinnati, OH: ACGIH, 2001. pp. 110–112.
[4] **Moore, J.S., and A. Garg**: The Strain Index: A proposed method to analyze jobs for risk of distal upper extremity disorders. *Am. Ind. Hyg. Assoc. J. 56*(5):443–458 (1995).
[5] **Kapellusch, J.M., S.S. Bao, B.A. Silverstein, et al.**: Risk assessments using the strain index and TLV for HAL, Part I: Task and multi-task-job exposure classifications. *J. Occup. Environ. Hygiene. 14*(12):1011–1019 (2017).
[6] **Harris-Adamson, C., E.A. Eisen, A. Neophytou, et al.**: Biomechanical and psychosocial exposures are independent risk factors for carpal tunnel syndrome: Assessment of confounding using causal diagrams. *Occup. Environ. Med. 73*(11):727–734 (2016).
[7] **Fan, Z.J., C. Harris-Adamson, F. Gerr, et al.**: Associations between workplace factors and carpal tunnel syndrome: A multi-site cross sectional study. *Am. J. Ind. Med. 58*(5):509–518 (2015).
[8] **Spielholz, P., S. Bao, N. Howard, et al.**: Reliability and validity assessment of the hand activity level threshold limit value and strain index using expert ratings of mono-task jobs. *J. Occup. Environ. Hyg. 5*(4):250–257 (2008).
[9] **Garg, A., J. Kapellusch, K. Hegmann, et al.**: The strain index (SI) and threshold limit value (TLV) for hand activity level (HAL): Risk of carpal tunnel syndrome (CTS) in a prospective cohort. *Ergonomics. 55*(4):396–414 (2012).
[10] **Burkhauser, R.V., and J. Cawley**: Beyond BMI: The value of more accurate measures of fatness and obesity in social science research. *J. Health. Econ. 27*(2):519–529 (2008).
[11] **Kapellusch, J.M., A. Garg, S.S. Bao, et al.**: Pooling job physical exposure data from multiple independent studies in a consortium study of carpal tunnel syndrome. *Ergonomics 56*(6):1021–1037 (2013).
[12] **Borg, G.**: Psychophysical bases of perceived exertion. *Med. Sc. Spt. Exer. 14*(5):377–381 (1982).
[13] **Latko, W.A., T.J. Armstrong, J.A. Foulke, G.D. Herrin, R.A. Rabourn, and S.S. Ulin**: Development and evaluation of an observation method for assessing repetition in hand tasks. *Am. Ind. Hyg. Assoc. J. 58*(4):278–285 (1997).
[14] **Moore, J.S., and A. Garg**: The Validity and Reliability of the Strain Index. In 16th International Ergonomics Association World Conference Proceedings. The Netherlands: Maastricht, 2006.
[15] **Burt, S., K. Crombie, Y. Jin, S. Wurzelbacher, J. Ramsey, and J. Deddens**: Workplace and individual risk factors for carpal tunnel syndrome. *Occup. Environ. Med. 68*(12):928–933 (2011).
[16] **Fan, Z.J., B.A. Silverstein, S. Bao, et al.**: Quantitative exposure-response relations between physical workload and prevalence of lateral epicondylitis in a working population. *Am. J. Ind. Med. 52*(6):479–490 (2009).
[17] **Frazer, M.B., R.W. Norman, R.P. Wells, and P.W. Neumann**: The effects of job rotation on the risk of reporting low back pain. *Ergonomics. 46*(9):904–919 (2003).
[18] **Drinkaus, P., R. Sesek, D.S. Bloswick, C. Mann, and T. Bernard**: Job level risk assessment using task level ACGIH hand activity level TLV scores: A pilot study. *Int. J. Occup. Saf. Ergon. 11*(3):263–281 (2005).
[19] **Bonfiglioli, R., S. Mattioli, T.J. Armstrong, et al.**: Validation of the ACGIH TLV for hand activity level in the OCTOPUS cohort: A two-year longitudinal study of carpal tunnel syndrome. *Scand. J. Work Environ. Health. 39*(2):155–163 (2013).
[20] **Silverstein, B.A., Z.J. Fan, D.K. Bonauto, et al.**: The natural course of carpal tunnel syndrome in a working population. *Scand. J. Work Environ. Health. 36*(5):384–393 (2010).
[21] **Dale, A.M., C. Harris-Adamson, D. Rempel, et al.**: Prevalence and incidence of carpal tunnel syndrome in US working populations: Pooled analysis of six prospective studies. *Scand. J. Work Environ. Health. 39*(5):495–505 (2013).
[22] **Katz, J.N., R.A. Lew, L. Bessette, et al.**: Prevalence and predictors of long-term work disability due to

carpal tunnel syndrome. *Am. J. Ind. Med. 33*(6):543–550 (1998).

[23] **Harris-Adamson, C., E.A. Eisen, J. Kapellusch, et al.**: Biomechanical risk factors for carpal tunnel syndrome: A pooled study of 2474 workers. *Occup. Environ. Med. 72*(1):33–41 (2015).

[24] **Bao, S.S., J.M. Kapellusch, A.S. Merryweather, et al.**: Relationships between job organisational factors, biomechanical and psychosocial exposures. *Ergonomics. 59*(2):179–194 (2016).

[25] **Bao, S.S., J.M. Kapellusch, A.S. Merryweather, et al.**: Impact of work organizational factors on carpal tunnel syndrome and epicondylitis. *J. Occup. Environ. Med. 58*(8):760–764 (2016).

[26] **Dempsey, P.G.**: Utilizing criteria for assessing multiple-task manual materials handling jobs. *Int. J. Ind. Ergon. 24*(4):405–416 (1999).

[27] **Callaghan, J.P., A.J. Salewytsch, and D.M. Andrews**: An evaluation of predictive methods for estimating cumulative spinal loading. *Ergonomics. 44*(9):825–837 (2001).

[28] **Waters, T.R., M.L. Lu, and E. Occhipinti**: New procedure for assessing sequential manual lifting jobs using the revised NIOSH lifting equation. *Ergonomics. 50*(11):1761–1770 (2007).

[29] **Garg, A., and J.M. Kapellusch**: Applications of biomechanics for prevention of work-related musculoskeletal disorders. *Ergonomics. 52*(1):36–59 (2009).

[30] **Garg, A., and J.M. Kapellusch**: The Cumulative Lifting Index (CULI) for the Revised NIOSH Lifting Equation: Quantifying risk for workers with job rotation. *Hum. Factors. 53*(5):683–694 (2016).

[31] **Coenen, P., I. Kingma, C.R. Boot, P.M. Bongers, and J.H. van Dieen**: The contribution of load magnitude and number of load cycles to cumulative low-back load estimations: A study based on in-vitro compression data. *Clin. Biomech. (Bristol, Avon) 27*(10):1083–1086 (2012).

[32] **Kapellusch, J.M., F.E. Gerr, E.J. Malloy, et al.**: Exposure-response relationships for the ACGIH threshold limit value for hand activity level: Results from a pooled data study of carpal tunnel syndrome. *Scand. J. Work Environ. Health. 40*(6):610–620 (2014).

[33] **Garg, A., J.S. Moore, and J.M. Kapellusch**: The revised strain index: An improved upper extremity exposure assessment model. *Ergonomics. 60*(7):912–922 (2017).