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# The Composite Strain Index (COSI) and Cumulative Strain Index (CUSI): methodologies for quantifying biomechanical stressors for complex tasks and job rotation using the Revised Strain Index

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**ABSTRACT**
The Composite Strain Index (COSI) quantifies biomechanical stressors for complex tasks consisting of exertions at different force levels and/or with different exertion times. The Cumulative Strain Index (CUSI) further integrates biomechanical stressors from different tasks to quantify exposure for the entire work shift. The paper provides methodologies to compute COSI and CUSI along with examples. Complex task simulation produced 169,214 distinct tasks. Use of average, time-weighted average (TWA) and peak force and COSI classified 66.9, 28.2, 100 and 38.9% of tasks as hazardous, respectively. For job rotation the simulation produced 10,920 distinct jobs. TWA COSI, peak task COSI and CUSI classified 36.5, 78.1 and 66.6% jobs as hazardous, respectively. The results suggest that the TWA approach systematically underestimates the biomechanical stressors and peak approach overestimates biomechanical stressors, both at the task and job level. It is believed that the COSI and CUSI partially address these underestimations and overestimations of biomechanical stressors.

**Practitioner Summary:** COSI quantifies exposure when applied hand force and/or duration of that force changes during a task cycle. CUSI integrates physical exposures from job rotation. These should be valuable tools for designing and analysing tasks and job rotation to determine risk of musculoskeletal injuries.

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## Introduction

Physical exposure is commonly described in terms of force, repetition, posture, duration of exertion and/or duration of exposure per day. The Strain Index (SI) (Moore and Garg 1995) and the Revised Strain Index (RSI) (Garg, Moore and Kapellusch 2016) are designed to combine these job physical factors to evaluate risk of distal upper extremity disorders (DUE MSDs) for simple, mono-task jobs where: (i) the constituent variables (e.g. force, duration per exertion, hand/wrist posture) do not change substantially between different exertions during a task cycle and (ii) the worker does not rotate between different tasks during a work shift (Moore and Garg 1995). Often, in modern industry, workers' jobs consist of more than one task (i.e. multi-task jobs; referred to in industry as 'job rotation') and practically all modern tasks consist of several subtasks – where a subtask is defined as a unique combination of magnitude of force, duration of force, frequency of exertion and hand–wrist posture. To determine exposure at the job (i.e. worker) level, subtask level measures of force, duration of force, repetition and posture must be integrated and summarised at their respective task levels and then biomechanical stressors from each task need to be integrated and summarised at the job level.

Currently used approaches to quantify varying physical exposures to determine risk of musculoskeletal symptoms and disorders, either from a multi-subtask task or from a multi-task job, include: (i) using average values for exposure variables (NIOSH 1981; Marras et al. 1999; Lu et al. 2014), (ii) time-weighted average exposure (TWA) (Frazer et al. 2003; Bao et al. 2009; Garg and Kapellusch 2009a; Harris-Adamson, You, and Eisen 2014), (iii) cumulative exposure (Norman et al. 1998; Kerr et al. 2001; Frazer et al. 2003; Seidler et al. 2011; Marras et al. 2014), (iv) peak exposure, or using the highest values of exposure variables (Herrin, Jaraiedi, and Anderson 1986; Marras et al. 1993; Norman et al. 1998; ACGIH 2002; Frazer et al. 2003; Bao et al. 2009; Garg, Boda, et al. 2014; Garg, Kapellusch, Hegmann, Moore, et al. 2014; Ferguson et al. 2014; Lu et al. 2014) and (v) typical exposure (Garg et al. 2012; Garg, Kapellusch,

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Hegmann, Thiese, et al. 2014; Kapellusch, Garg, Hegmann, et al. 2014). Each of these approaches is unsatisfactory as they tend to result in exposure misclassification (Dempsey 1999; Garg and Kapellusch 2016). Averaging approaches – such as simple average, TWA, frequency-weighted average (FWA) and cumulative exposure – tend to dilute the effects of high force exertions (Dempsey 1999; Callaghan, Salewytsch, and Andrews 2001; Frazer et al. 2003; Waters, Lu, and Occhipinti 2007; Garg and Kapellusch 2009a, 2009b, 2016; Coenen et al. 2012). Use of the highest values of physical exposure may overestimate that exposure, for example, use of peak force assumes that all exertions are performed at the peak force level (Dempsey 1999; Garg and Kapellusch 2009a, 2009b). Similarly, using peak task exposure to represent multi-task job exposure ignores all other tasks performed by the worker and assumes that the peak task is performed for the entire work shift.

Using concepts similar to those of the Revised NIOSH Lifting Equation (Waters et al. 1993; Garg and Kapellusch 2016), Garg and colleagues developed the Composite Strain Index (COSI) and the Cumulative Strain Index (CUSI) to integrate biomechanical stressors from multiple subtasks at the task level and multiple tasks at the job level (Garg 2006; Garg and Kapellusch 2009b) to determine risk of DUE MSDs. These algorithms were first developed as a part of a NIOSH sponsored research project in 2002 (U01 OH007917) and modified over the subsequent years. They were later shared with researchers, some of whom used these algorithms for laboratory (Stephens 2006) and epidemiological studies (Drinkaus et al. 2005; Silverstein et al. 2006; Gerr et al. 2014; Meyers, Gerr, and Fethke 2014). These referenced epidemiological studies have reported associations between risk of upper limb pain and/or musculoskeletal disorders and the biomechanical stressors determined using the earlier versions of the algorithms designed for the 1995 SI (Moore and Garg 1995). Unfortunately, the 1995 SI had certain limitations, such as categorical variables and multipliers (Garg, Moore, and Kapellusch 2016), that reduced the practical utility of the prior COSI and CUSI algorithms. The COSI and CUSI, described in this paper, are designed for the recently developed RSI, which addresses many of the limitations of the 1995 SI (Garg, Moore, and Kapellusch 2016).

The objectives of this research were to propose: (i) a task-level COSI to integrate biomechanical stressors from multiple subtasks determined using the RSI, and (ii) a CUSI to integrate biomechanical stressors from different tasks (COSIs) performed during a work shift into a single, job-level exposure using an incremental approach.

## Subtask, task and job

A subtask is defined by a unique combination of magnitude of force, duration of that force, hand/wrist posture during application of that force and number of exertions at that force level. The biomechanical stressors from a subtask are determined using the RSI (Garg, Moore, and Kapellusch 2016). A task is defined as a sequence of one or more subtasks that are repeated within a task cycle and are performed for a certain duration (h) in a work shift. A job consists of one or more tasks performed during a work shift (Kapellusch et al. 2013). Biomechanical stressors from a task with two or more subtasks are determined using the COSI. For a task consisting of a single subtask, COSI = RSI. Biomechanical stressors from a job are determined using the CUSI. For a job consisting of a single task, CUSI = COSI.

## Composite Strain Index (COSI) and Cumulative Strain Index (CUSI)

The following are the procedures to calculate COSI and CUSI:

### *COSI*

(1) Calculate RSI for each subtask and arrange them in a descending order such that,

$$RSI_1 \geq RSI_2 \geq RSI_3 \geq \cdots \geq RSI_n \quad (1)$$

where $n$ is the total number of subtasks in the task.

(2) Calculate the COSI score. The COSI score is $RSI_1$ (peak exposure subtask) plus an incremental increase in physical exposure, $\Delta RSI$, as each subsequent subtask is added to the peak subtask,

$$COSI = RSI_1 + \sum_2^n \Delta RSI_i \quad (2)$$

where $RSI_1$ is the RSI for the peak exposure subtask; $\Delta RSI_i$ is the incremental increase in physical exposure associated with each of the remaining subtasks, in the order determined by in Equation (1); and $\Delta RSI_i$ is calculated using Equations (3–5) below.

(3) Calculate $\Delta RSI$ for subtasks 2 to $n$, using Equation (3), by first determining the frequency independent RSI, (FIRSI), see Equation (4), for each subtask and then multiplying it by the delta efforts per minute multiplier (EM) associated with that subtask, see Equation (5). FIRSI ignores the frequency of the subtask and is conceptually similar to the Frequency Independent Lifting Index (FILI) used in the Revised NIOSH Lifting Equation (Waters et al. 1993). $\Delta EM_i$ is the differential increase in frequency multiplier when the $i$th subtask's frequency is added to the cumulative frequency of the prior subtasks. The equations for $\Delta RSI$, and FIRSI are:

$$\Delta RSI_i = (FIRSI_i \times \Delta EM_i) \quad (3)$$

$$FIRSI_i = RSI_i \div EM_i \quad (4)$$

where $RSI_i$ is the RSI for the $i$th subtask, and $EM_i$ is the efforts per minute (i.e. frequency) multiplier for subtask $i$, and the equation for ΔEM is:

$$\Delta EM_i = EM_{(\sum_1^i E_j)} - EM_{(\sum_1^{i-1} E_j)} \quad (5)$$

where $E_j$ is the exertions per minute for subtask $j$.

## *CUSI*

(1) Calculate COSI for each task and arrange them in descending order such that

$$COSI_1 \geq COSI_2 \geq COSI_3 \geq \cdots \geq COSI_m \quad (6)$$

where $m$ is the total number of tasks performed in a work shift.

(2) Calculate the CUSI score. The CUSI score is $COSI_1$ (i.e. COSI from peak exposure task) plus an incremental increase in physical exposure as each subsequent task is added to the peak task.

$$CUSI = COSI_1 + \sum_2^m \Delta COSI_k \quad (7)$$

where $COSI_1$ is the COSI for the peak exposure, calculated using Equation (2), and $\Delta COSI_k$ is the incremental increase in physical exposure associated with each of the remaining tasks, in the order determined by Equation (6). $\Delta COSI_k$ is calculated using Equations (8–10) below.

(3) Calculate ΔCOSI for tasks 2 to $m$, using the equation:

$$\Delta COSI_k = (HICOSI_k \times \Delta HM_k) \quad (8)$$

where $HICOSI_k$ is the hours independent COSI, defined by the equation:

$$HICOSI_k = COSI_k \div HM_k \quad (9)$$

where $COSI_k$ is the COSI for the $k$th task and $HM_k$ is the hours per day multiplier for task $k$ (Garg, Moore, and Kapellusch 2016). $HM_k$ is calculated is the equation:

$$\Delta HM_k = HM_{(\sum_1^k H_j)} - HM_{(\sum_1^{i-k} H_j)} \quad (10)$$

where $H_j$ is the hours per day for task $j$. The HICOSI ignores the hours per day that the task is performed (in a manner similar to the FIRSI that ignores frequency of exertion). $\Delta HM_k$ is the differential increase in the hours per day multiplier when the $k$th task's hours per day is added to the cumulative hours per day of the prior tasks.

Tentatively, similar to RSI, a score ≤ 10.0 for COSI and CUSI is considered safe, and a score > 10.0 is considered hazardous.

## Example of COSI and CUSI calculations

As a simple example, consider a worker who performs the job of 'assembler'. This job consists of two tasks: assembly of transformers, performed for four hours/day (task A = transformer assembly) and operating a grinding machine for four hours/day (task B = operating machine). Transformer assembly requires subtasks of cutting wire, wrapping wire and driving screws using a powered screwdriver; each subtask requires a different force, duration of force and number of exertions (Table 1). Similarly, operating machine consists of multiple subtasks. The COSI is used to integrate biomechanical stressors from the multiple subtasks (e.g. cutting wire, wrapping wire and driving screws) and summarise them at the task level (i.e. transformer assembly). The CUSI is used to integrate biomechanical stressors from the multiple tasks (i.e. transformers assembly and operating machine) and summarise them at the job level (i.e. assembler).

Table 1 also shows the calculations for RSI and FIRSI (Equation 4) for each of the three subtasks. According to Equation (1), the subtasks are arranged in decreasing order from the highest to the lowest RSI, and assigned the corresponding index values of one to three (i.e. driving

**Table 1.** Summary of subtask parameters used to calculate RSI score and FIRSI for the example task of 'transformer assembly'.

| Subtask | Intensity of exertion (%MVC) | Intensity multiplier (IM) | Efforts per min | Efforts per min multiplier (EM) | Duration per exertion (s) | Duration per exertion multiplier (DM) | Hours per day multiplier[a] (HM) | RSI[b] | FIRSI (RSI ÷ EM) |
|---|---|---|---|---|---|---|---|---|---|
| Cutting wire | 70 | 11.51 | 1.0 | .35 | 1.0 | .76 | .77 | 2.36 | 6.74 |
| Wrapping wire | 40 | 5.02 | 2.6 | .75 | 1.2 | .82 | .77 | 2.39 | 3.19 |
| Driving screws | 20 | 2.61 | 5.0 | 1.35 | 3.0 | 1.38 | .77 | 3.75 | 2.78 |

[a]Task is performed for 4 h per day.
[b]RSI = IM × EM × DM × PM × HM, where PM = Posture Multiplier and PM is assumed to be 1.0.

Table 2. Summary of parameters used to calculate the COSI for the example task of 'transformer assembly'.

| Subtask (name) | Subtask (Index, $i$) | RSI | FIRSI | $\Sigma E_i$ | $\Sigma E_{(i-1)}$ | $EM_i$ | $EM_{i-1}$ | $\Delta EM_i$ | $\Delta RSI_i$ |
|---|---|---|---|---|---|---|---|---|---|
| Driving screws | 1 | 3.75 | N/A | 5.0 | N/A | N/A | N/A | N/A | N/A |
| Wrapping wire | 2 | 2.39 | 3.19 | 7.6 | 5.0 | 2.00 | 1.35 | .65 | 2.07 |
| Cutting wire | 3 | 2.36 | 6.74 | 8.6 | 7.6 | 2.25 | 2.00 | .25 | 1.69 |

COSI = 3.75 + 2.07 + 1.69 = 7.51.

Table 3. Summary of parameters used to calculate the CUSI for the combined tasks of A, 'transformer assembly' and B, 'operate machine'.

| Task | Index ($i$) | COSI | HICOSI[a] | $\Sigma H_i$ | $\Sigma H_{i-1}$ | $HM_i$ | $HM_{i-1}$ | $\Delta HM_i$ | $\Delta COSI_i$ |
|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 7.51 | 9.75 | 4 | N/A | N/A | N/A | N/A | N/A |
| B | 2 | 5.20 | 6.75 | 8 | 4 | 1.00 | .77 | .23 | 1.55 |

[a]HICOSI based on 4 h per day for each task, Hours multiplier (HM) for 4 h = .77, HM for 8 h = 1.00. CUSI = 7.51 + 1.55 = 9.06.

Table 4. Sample comparisons of average force RSI, TWA force RSI, peak force RSI and COSI scores.

| Task # | Subtask | %MVC | Duration per exertion (s) | Efforts per min | RSI subtask | RSI task: Avg. force | RSI task: TWA force | RSI task: Peak force | $\Sigma RSI_i$[a] | COSI |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 70 | 2 | 2 | 7.4 | 7.9 | 7.9 | 30.0 | 10.9 | 10.8 |
| | B | 10 | 2 | 8 | 3.5 | – | – | – | – | – |
| 2 | A | 50 | 2 | 2 | 4.3 | 6.7 | 6.7 | 18.6 | 7.8 | 7.7 |
| | B | 10 | 2 | 8 | 3.5 | – | – | – | – | – |
| 3 | A | 40 | 1 | 6 | 6.1 | 10.4 | 7.8 | 16.7 | 9.6 | 9.4 |
| | B | 10 | 3 | 6 | 3.5 | – | – | – | – | – |
| 4 | A | 40 | 3 | 6 | 11.1 | 10.4 | 13.3 | 16.7 | 13.0 | 12.9 |
| | B | 10 | 1 | 6 | 1.9 | – | – | – | – | – |
| 5 | A | 50 | 3 | 2 | 5.5 | 11.1 | 9.3 | 22.7 | 12.3 | 11.0 |
| | B | 40 | 2 | 1 | 1.9 | – | – | – | – | – |
| | C | 30 | 2 | 1 | 1.4 | – | – | – | – | – |
| | D | 10 | 5 | 4 | 3.5 | – | – | – | – | – |
| 6 | A | 20 | 3 | 2 | 2.2 | 8.4 | 7.2 | 17.0 | 9.0 | 7.6 |
| | B | 40 | 2 | 1 | 1.9 | – | – | – | – | – |
| | C | 30 | 2 | 1 | 1.4 | – | – | – | – | – |
| | D | 10 | 5 | 4 | 3.5 | – | – | – | – | – |
| 7 | A | 100 | 3 | 1 | 12.4 | 9.0 | 5.8 | 65.1 | 14.7 | 14.4 |
| | B | 5 | 7 | 3 | 2.3 | – | – | – | – | – |

[a]Simple sum of subtask RSI scores. Provided for comparative and discussion purposes.

screws = subtask (index) #1, wrapping wire = subtask (index) #2 and cutting wire = subtask (index) #3, see Table 2). For calculating incremental RSI from subtask #2 (i.e. wrapping wire), the cumulative frequency of subtasks #1 and #2 is 7.6 (i.e. 5.0 + 2.6) and the corresponding effort multiplier (EM) is 2.00 (Table 2) as specified by the EM equation from the RSI (Garg, Moore, and Kapellusch 2016). The frequency of subtask #1 is 5.0 and the corresponding EM is 1.35. Thus, from Equation (5) the ΔEM is .65 (i.e. 2.00 – 1.35). ΔRSI (Equation 3) is 2.07 and is the product of FIRSI for subtask #2 (i.e. 3.19) and the ΔEM for subtask #2 (i.e. .65) (Table 2). Similarly, the ΔRSI for subtask #3 (i.e. driving screws) is 1.69 (the cumulative frequency for subtasks #1, #2 and #3 is 8.6, and for subtasks #1 and #2 is 7.6; the corresponding frequency multipliers are 2.25 and 2.00, respectively; the ΔEM is .25; and the FIRSI for subtask #3 is 6.74; see Table 2). Using Equation (2), the COSI for task A (i.e. transformer assembly) is 7.51, which is equal to the RSI for subtask #1 (i.e. 3.75) plus ΔRSI for subtask #2 (i.e. 2.07) plus ΔRSI for subtask #3 (i.e. 1.69). Similarly, the COSI for task B (machine operator) is 5.20 (subtasks and calculations not shown).

The CUSI for the job is calculated by first ordering the tasks performed in decreasing order of COSI score (Equation 6), thus the task order for this example is task A (i.e. transformer assembly) followed by task B (i.e. operating machine) (Table 3), with COSI of 7.51 and 5.20, respectively. Each task is performed for 4 h per day, and has a corresponding hours per day multiplier (HM) of .77. The CUSI for this job is 9.06 (i.e. COSI for task A, 7.51) plus ΔCOSI from task B (i.e. 1.55). The ΔCOSI for task B is calculated by multiplying the HICOSI for task B by the ΔHM for task B. The HICOSI for task B is 6.75 (i.e. 5.20 ÷ .77, Equation 9). The ΔHM for task B is .23, and is calculated by taking the HM for cumulative hours per day of task A plus task B (i.e. 1.00, for 8 h) minus the HM for task A (i.e. .77, for 4 h). Thus, the ΔCOSI for task B is 1.55 (i.e. 6.75 × .23). The combined daily exposure from performing task A and task B (i.e. CUSI) is 9.06 and would be classified as 'safe'.

## Comparison of COSI with other approaches for estimating task level physical exposures

To demonstrate how the COSI differs from some other approaches to estimate task-level physical exposures using RSI, consider the tasks shown in Table 4. For simplicity we have considered only three of the five constituent variables in the RSI: intensity of exertion (%MVC), duration per exertion and efforts per minute (i.e. we assumed neutral hand/wrist posture and a task duration of 8 h for all subtasks and tasks in Table 4). The COSI for each task was calculated using Equation (2) shown above. Additionally, RSI for each task was calculated using: (i) average force for all exertions (Avg. Force, based on frequency of exertions), (ii) time-weighted average force (TWA force, based on frequency and duration of exertions) for all exertions and (iii) peak force for all exertions (peak force). We have also provided the simple sum of subtask RSI scores, for comparison (Table 4).

For example, for Task #1, subtasks A and B have RSI scores of 7.4 and 3.5, and the COSI = 10.8 (hazardous). The average force and TWA force in this example are both 22% MVC and the RSI score is 7.9 (safe) for both average and TWA force. The peak force is 70% of MVC producing a RSI score of 30.0 (hazardous). If we reduce the %MVC for subtask A from 70 to 50% and everything else remains unchanged (see Task #2 in Table 4), the COSI decreases from 10.8 (hazardous) to 7.7 (safe). However, the RSI using the peak force of 50% MVC remains elevated (RSI = 18.6, hazardous). The RSI scores for Task #2 using average and TWA forces remain relatively unchanged (Table 4).

Similarly, both Task #3 and #4 consist of subtasks A and B requiring six exertions per minute each at 40 and 10% MVC. The difference is in the durations of exertions for subtasks A and B, where Task #3 requires 1 and 3 s at 40 and 10%, respectively, and, conversely, Task #4 requires 3 and 1 s at 40 and 10%, respectively (Table 4). Note that duty cycles for tasks #3 and #4 are identical (duty cycle = 40%). The COSIs for Tasks #3 and #4 are 9.4 (safe) and 12.9 (hazardous), respectively. Use of peak force produces identical RSI scores of 16.7 (hazardous) for both tasks and thus is unable to identify the important increase in duration of the higher force (40% MVC) exertion in task #4. For tasks #3 and #4 the TWA force provides more consistent results with the COSI scores (Table 4). Conversely, for tasks #5 and #6, average force RSI agrees with COSI on risk classifications, whereas TWA force RSI does not. Peak force RSI classifies both tasks #5 and #6 as hazardous, despite a reduction in force for subtask A from 50% of MVC to 20% of MVC. For task #7, which requires a very high force subtask and a very low force subtask, both the average force RSI and TWA force RSI classify the task as safe, even though subtask A would be classified as hazardous were it performed alone.

For tasks consisting of only two subtasks the COSI was comparable to the sum of subtask RSIs. For tasks with more than two subtasks, the difference between the simple sum of subtask RSIs and the COSI was larger (Table 4). Similarly, tasks with cumulative subtask frequencies greater than 90 efforts per minute (i.e. into the non-linear range of the efforts per minute multiplier) would tend to result in large differences between the simple sum of subtask RSI and COSI scores.

For a comprehensive comparison of the average, TWA and peak force and COSI techniques, we performed a simulation of tasks consisting of two subtasks. Possible intensities of exertion for subtasks were 1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 75, 90 and 100% MVC. Frequencies of exertion were .2, .5, 1.0–10.0 in increments of 1, 12–20 in increments of 2 and 25 efforts per minute. Durations per exertion were .5, 1, 2, 3, 5, 7, 9, 12, 15 and 20 s. The preceding parameters were factorially combined to create each of the two subtasks. We removed from the simulation those combinations of subtasks: (i) that produced duty cycles > 100%, (ii) where the two subtasks were identical or factorial duplicates, (iii) where both subtasks had RSI score > 10.0 (all methods will classify task as hazardous), (iv) where physiologic demands of the task (i.e. combinations of frequency and average duration per exertion even at 1%MVC) exceeded RSI score > 10.0 (i.e. no matter what the %MVC is used the task is hazardous) and (v) where the combined exertions of subtasks #1 and #2 at the peak force of subtasks #1 and #2 produced an RSI score < 10.0 (i.e. all methods will classify the task as safe). After these exclusions the simulation produced 169,214 usable tasks. Average force, TWA force and peak force classified 56.9, 28.2 and 100% of tasks as hazardous, while COSI classified 38.9% tasks as hazardous. Among the four approaches TWA force and COSI had the best agreement. However, the agreement between these two approaches in hazard classification decreased as the difference in %MVC between the two subtasks increased. For example, the average agreement was 83.1, 78.8 and 75.4% when the difference in %MVC between the two subtasks was 20, 40 and 60%, respectively.

## Comparison of CUSI with other approaches for calculating job-level physical exposures

To demonstrate how the CUSI differs from some other approaches to compute job-level biomechanical stressors using COSI, consider a few selected jobs shown in Table 5. The CUSI for each job was calculated using Equation (7) shown above. Additionally, physical exposure from each job was calculated using: (i) time-weighted average COSI (TWA COSI) and (iii) peak task COSI (which assumes that the task was performed for 8 h per day). We have also provided the simple sum of task COSI scores, for comparison

Table 5. Sample comparisons of TWA COSI, peak task COSI and CUSI scores.

| Job no. | Task A hours | Task A COSI | Task B hours | Task B COSI | TWA COSI | Peak task COSI[a] | $\Sigma COSI_i$[b] | CUSI |
|---|---|---|---|---|---|---|---|---|
| 1 | 6.0 | 3.0 | 2 | 7.5 | 4.1 | 12.0 | 10.5 | 8.8 |
| 2 | 6.0 | 3.0 | 2 | 11.0 | 5.0 | 17.6 | 14.0 | 12.3 |
| 3 | 4.0 | 3.0 | 4 | 8.5 | 5.8 | 11.0 | 11.5 | 9.4 |
| 4 | 4.0 | 3.0 | 4 | 12.0 | 7.5 | 15.6 | 15.0 | 12.9 |
| 5 | 3.0 | 3.0 | 5 | 8.5 | 6.4 | 10.2 | 11.5 | 9.2 |
| 6 | 3.0 | 3.0 | 5 | 11.0 | 7.5 | 13.2 | 14.0 | 11.7 |

[a]Assumes peak task is performed for 8 h.
[b]Simple sum of task COSI scores. Provided for comparative and discussion purposes.

(Table 5). For all the examples shown in Table 5, the TWA COSI will classify the job as safe, and the peak task COSI will classify the job as hazardous. CUSI will classify some jobs as safe and others as hazardous, depending on the composition of task COSIs and their durations. The simple sum of task COSI scores will consistently produce higher, and sometimes much higher job scores than the corresponding CUSI.

For example, for job #1, tasks A and B have COSI scores of 3.0 and 7.5 calculated using task durations of 6 and 2 h, respectively. The TWA COSI in this example is 4.1 (i.e. when combined, task A COSI score dilutes the task B score). The peak task COSI is 12.0, which is the COSI for task B if it were performed for 8 h. The CUSI is 8.6, higher than the TWA COSI, and lower than the peak force COSI. In this case, using peak task COSI will classify the job as hazardous, and TWA COSI, and CUSI will classify the job as safe. If we change the COSI score for Task B from 7.5 to 11.0 (see job #2 in Table 5), the job would be classified as hazardous using peak task COSI and CUSI, and safe using TWA COSI.

To compare the differences between the above three approaches we performed a simulation consisting of two tasks. For each task COSI ranged from .5 to 20.0 in increments of .5 and duration of each task ranged from 1 to 7 h/day in increments of 1 h. Those jobs having duration > 8 h/day as well as identical and factorial duplicate tasks were removed. The simulation produced 10,920 jobs. Peak task COSI, TWA COSI and CUSI classified 78.1, 36.5 and 66.6% jobs as hazardous, respectively. For job rotation (i.e. multiple tasks), CUSI showed better agreement with the peak task COSI approach, a noteworthy change in tendency compared to complex tasks (i.e. multiple subtasks) where the COSI had better agreement with the TWA COSI approach.

## Discussions

### *Complex tasks-COSI*

Engineers, ergonomists and health and safety professionals are interested in designing safe and productive jobs. At present the scientific literature does not provide clear guidance on how to analyse a task when different exertions are performed at different force levels (%MVCs) during a task cycle. Current options include using average force, time-weighted average force and peak force for all exertions. These approaches often lead to different estimates of physical exposure, and thus different conclusions regarding hazard classification. Similarly, the lack of guidance for acceptable durations per exertion, especially at different force levels (%MVCs), remains problematic. One option is to use average duration per exertion calculated from all exertions. However, this approach may lead to underestimation of stresses when a small number of exertions in a task have long duration time that may lead to localised muscle fatigue (e.g. two subtasks performed at 25% MVC each, one with one exertion of 13 s and the other with seven exertions of 1 s would be treated as eight exertions of 2.5 s each at 25% MVC, when combined). As an alternative to the above approaches we propose the COSI for calculating task-level physical exposure. Unlike the above approaches, the COSI integrates biomechanical stressors from exertions at different force levels with different durations per exertion, and/or requiring different hand/wrist postures by treating them as separate subtasks. Thus, it accounts for the combination of force of exertion, duration of that exertion and hand/wrist posture used to perform that exertion(s) in determining biomechanical stressors from each subtask. Then, it uses an incremental approach to integrate biomechanical stressors from all subtasks to estimate the physical exposure from the complete task. In this regard, the proposed COSI is similar in concept to the Composite Lifting Index used for the Revised NIOSH Lifting Equation (Waters et al. 1993). Further, the COSI is able to differentiate physical exposure from two tasks that have identical subtask force levels (%MVCs), task duty cycle and task frequency of exertion but differ in duration per exertion across subtasks (see Table 4, Tasks 3 and 4).

Structurally, and confirmed by simulation results presented in this paper, it is clear that different approaches (average force, TWA force, peak force and COSI) used to calculate physical exposure for a task will result in different RSI or COSI scores. From a hazard classification perspective, if all the subtasks have RSI scores > 10.0, all four methods to calculate task-level biomechanical stressors will classify the task as hazardous. If one of the subtasks has a RSI score > 10.0, biomechanically the task must be classified as hazardous. Under this scenario, while peak force RSI and COSI will classify the task as hazardous average force RSI and TWA force RSI will classify some of these tasks as safe. Similarly, when all the subtasks have RSI scores < 10.0, the task as a whole may still be hazardous. Under this scenario, as compared to COSI, peak force RSI tends to classify more tasks as hazardous and average force and TWA force methods tend to classify more tasks as safe. Based on the task simulation presented in this paper while the TWA force and COSI showed good agreement, they differed in hazard classifications for about one out of eight tasks. This level of disagreement might be acceptable for surveillance and epidemiological studies, but is unacceptable for the assessment and design of individual tasks.

Lastly, from task design and analysis perspectives COSI offers more insight by breaking a task into subtasks and examining RSI scores for each subtask. Ergonomists and engineers can determine which aspects of a task (subtask) are the most stressful as well as what changes (force, duration of exertion, number of exertions, etc.) are needed in to make the task safe.

It should be noted that for a task consisting of two subtasks the COSI and the simple sum of subtask RSIs will typically be comparable because currently the frequency of exertion multiplier is a linear function of frequency of exertion up to 90 exertions per minute. However, as the number of subtasks increases, the difference between the simple sum of RSIs and the COSI also increases. Similarly, tasks with frequencies > 90 exertions per minute may result in large differences between these two methods. Further, the COSI algorithm enables a non-linear relationship between the frequency of exertion and its multiplier, should future research suggest such a relationship is warranted. In that case, the differences between COSI and the simple sum of RSIs scores would be much more pronounced.

### *Job rotation-CUSI*

The proposed CUSI provides an estimate of total physical exposure to each worker from an entire work shift by integrating biomechanical stressors from multiple tasks (COSIs). It is believed that for these multi-task jobs, the CUSI will provide more precise physical exposure estimates compared to TWA exposure and peak exposure approaches. Effectiveness of CUSI for predicting risk of DUE MSDs needs to be determined from epidemiological studies.

Epidemiological studies using time-weighted average exposure to represent an entire work shift have shown associations with increased risk of DUE MSDs (Silverstein et al. 2010; Burt et al. 2011; Bonfiglioli et al. 2012; Gerr et al. 2014; Kapellusch, Gerr et al. 2014; Fan et al. 2015; Harris-Adamson et al. 2015). However, with TWA approach low exposure task(s) dilutes the effect of high exposure task(s) (Waters et al. 2006; Garg and Kapellusch 2009a, 2009b). Studies using peak task exposure have shown associations with low-back pain outcomes(Herrin, Jaraiedi, and Anderson 1986; Marras et al. 1993; Norman et al. 1998; Kerr et al. 2001; Garg, Boda, et al. 2014; Garg, Kapellusch, Hegmann, Moore, et al. 2014; Kapellusch, Garg, Boda, et al. 2014) but, to our knowledge, there are no epidemiological studies on peak task exposure and risk of DUE MSDs. From the construct of peak exposure, it is clear that assigning exposure from peak task for the entire work shift will often tend to overestimate worker exposure. From the simulation reported in this study, TWA exposure classified about 63% jobs as safe, CUSI 33% and peak exposure 22%. Thus, it appears that, as compared to CUSI, the TWA approach may systematically tend to classify more jobs as 'safe' and peak exposure more jobs as 'unsafe'. Regarding absolute scores, TWA will result in lower COSI scores and peak exposure higher scores as compared to COSI. Thus, the choice of methodology used to assign worker exposure for the entire work shift may have a major impact on job design, job modification and in determining appropriate job rotation.

We did not compare cumulative and typical exposures to CUSI. Each of these has limitations. Cumulative exposure assumes that a unit increase in force has the same effect on risk of DUE MSDs as a unit increase in time (e.g. applying 10% MVC for 3 s 10 times/min has the same effect as applying 100% MVC for 3 s once per min; 300%MVC-s/min) (Garg and Kapellusch 2009a, 2009b). Typical exposure (Garg et al. 2012) considers only the task performed for the largest proportion of the shift and ignores exposures from all other tasks even though one or more of those tasks may be hazardous by themselves.

## Conclusions

We propose the COSI and the CUSI to estimate physical exposures from complex tasks and multi-task jobs (i.e. job rotation), respectively. The COSI integrates biomechanical stressors when a task consists of exertions that are performed at different force levels and/or have different durations of exertion. The CUSI further integrates physical exposures from different tasks using an incremental approach to determine daily physical exposure to a worker with job rotation. We believe that the COSI and CUSI partially address the systematic underestimation and over estimation of job physical exposure at the task and job levels associated with the time-weighted average and the peak exposure approaches, respectively. Comprehensive simulations presented in this paper support these conclusions.

## Key points

- Use of average force and time-weighted average force underestimate and peak force overestimates physical exposures from complex tasks (i.e. a task consisting of exertions at different force levels and/or with different exertion times).
- Similarly, time-weighted average and peak exposure approaches underestimate and overestimate job physical exposures to workers exposed to job rotation.
- Methodologies to estimate physical exposures from complex tasks and job rotation are provided. These are called COSI and CUSI.
- Both the COSI and CUSI integrate biomechanical stressors at the task and job level, respectively, using an incremental approach conceptually similar to the methods used in the Revised NIOSH Lifting Equation.
- It is believed that the COSI and CUSI will provide more accurate estimates of distal upper extremity physical exposures for workers exposed to complex tasks and job rotation, respectively.

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