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Cumulative spinal loading exposure methods for manual material handling tasks. Part 2: methodological issues and applicability for use in epidemiological studies

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Objective: The goal of this paper is to review and discuss methodological issues related to cumulative spinal loading exposure assessment methods.
Background: Research has indicated that there likely is an association between integrated spinal loading and lower back pain. A number of studies have been conducted to evaluate cumulative load; however, comparisons between studies is difficult due to the use of different methods for the assessment of cumulative spinal loading.
Methods: A comprehensive electronic search was conducted to locate articles dealing with methods of cumulative spinal loading estimation. The articles were evaluated with respect to methods for obtaining postural data, methods for estimating spinal loads, methods for integrating loads over time and spinal load parameters to be measured.
Results: Thirteen articles were located. A summary of the methods used to estimate cumulative spinal load is described and evaluated.
Conclusions: There is a pressing need for integrated spinal loading methods that are reliable, valid and practical for use in large occupational epidemiological studies. A number of research needs were outlined aimed at improving the ability to use cumulative load to predict risk of low back disorders due to manual material handling.

Keywords: Lower back disorders; Manual material handling; Cumulative spinal loading

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1. Introduction

A previous paper (Waters *et al.* 2005) presented findings from a meta-analysis of cumulative load studies to evaluate whether there was a relationship between cumulative spinal loading and low back pain. That paper reported that it is likely that cumulative spinal loading is associated with lower back pain. Indeed, the meta-odds ratio was 1.66 and was significant at the 0.05 level. That is, workers with lower back pain were almost twice as likely to have been exposed to higher levels of cumulative spinal loading as those not experiencing lower back pain. The results also demonstrated that, without accounting for overall study quality, there were considerable variances among the studies in terms of exposure data. This may be attributed to, among other things, the between-study differences in cumulative spinal loading estimation methods. The purpose of the present paper is to address those methodological issues as they relate to use of cumulative spinal loading in occupational epidemiological research.

The goals of this paper are to systematically review the current scientific exposure methods of cumulative spinal loading and to discuss issues related to their reliability and validity for estimating force distribution and to determine their practicality for use in field studies.

2. Methods

A previous paper (Waters *et al.* 2005) described the strategies employed for the electronic search of relevant articles for this topic. Once the articles were identified and determined relevant, the methodologies used in the documentation of cumulative spinal loading were evaluated in terms of: (1) study population; (2) methods used to estimate, capture or sample postures and hand loads; (3) approaches used to estimate the magnitude of spinal loading; (4) method used to integrate the loads over time due to repeated biomechanical loads; and (5) type of estimated biomechanical parameters produced by the assessment method.

3. Results

3.1. *Overview of studies*

After the initial search and further examination of the titles, abstracts and full text of the papers, 13 articles were identified as relevant and included for review in this paper. The characteristics of cumulative spinal loading exposures methods employed in these studies are summarized in table 1.

Several methods have been developed to assess cumulative exposure to manual object handling activities. A brief description of these methods is given below.

- Kumar (1990) used a recall interview of postures that people were exposed to and then interpolated postures between these recalled positions to produce samples at 0.2 s intervals (5 Hz). A 2-D static biomechanical model was then used with these generated postures to yield a frame-by-frame compression and shear value which was then rectangularly integrated.

Table 1. Summary of cumulative assessment of MMH exposure methods.

Source	Population	Accumulation measurement	Spinal loading measurement	Method of integration (time and amplitude)	Parameters measured
Kumar (1990)	Institutional aides in group homes in Edmonton, Canada 14 males and 147 females Subjects include those with or without pain	Structured questionnaire/interview for measurement of initial/final postures of tasks	2-D static biomechanical model with input variables based on questionnaire Forces calculated for initial and final postures and intermediate positions at 0.2 s intervals for dynamic activities	Sum of loads for stressful tasks (definition of stressful not reported) throughout the shift	Cumulative compressive and shear loads
Norman *et al.* (1998)	Automotive workers in Canadian plant 130 randomly selected controls 104 cases with lower back pain	Video-based posture capture for 2–8 h Trunk movement—unidirectional movement with at least 20 angle and sampled at 30° Hz	Peak static spinal load using 2-D quasi dynamic model (i.e. included effect of acceleration of loads of the hands but not those of body segment accelerations) Hand force measured by a transducer	Sum of product static peak for each task and frequency throughout the day	Cumulative compressive, shear loads and cumulative spine moment
Mientjies *et al.* (1999)	5 male subjects (Canadians) No prior history of disabling lower pain or injury Type of subjects not reported	Posture not needed in this approach	EMG record of erector spinal musculature	Linear normalization of EMG to compressive force modeled by 2-D quasi dynamic model	Time histories of normalized EMG converted into amplitude probability distribution function Compression normalized EMG to eliminate spinal loading

(*continued*)

Table 1. Continued.

Source	Population	Accumulation measurement	Spinal loading measurement	Method of integration (time and amplitude)	Parameters measured
Jäger *et al.* (2000)	Two subjects from each of four groups: construction, metal-processing and refuse collections (Germans)	Video-based posture capture for whole shift Trunk posture classified into several positions Sampling rate not specified	3-D biomechanical model—effects of dynamics due to acceleration of body movement and load handling were neglected	Summation of loading and posture groups and time with different algorithms Linear $=\sqrt{\frac{\sum F_i \times t_i}{T}}$ Squared $=\sqrt{\frac{\sum F_i^2 \times t_i}{T}}$ Tetra powered $=$ $\sqrt[4]{\frac{\sum F_i^4 \times t_i}{T}}$ where t_i = time of i; F_i = disk compression; T = shift duration	Shift dose of cumulative compression (only shown) Could also be developed for cumulative shear load and 3D kinetics
Mirka *et al.* (2000)	28 male and female construction workers 15 form framing/carpentry, 8 masonry, 5 drywall (Americans)	Video-based posture capture of occupational tasks (time per shift not specified) Sampling rate 30 Hz	3-D static biomechanical model LMM NIOSH lifting index	Time weighted histogram of compressive forces and NIOSH lifting indices for manual material handling activities	Time weighted histograms of spine. Compression and NIOSH lifting index and high risk group using LMM

Callaghan *et al.* (2001)	3 male college students (Canadians) No history of lower back pain	Video based posture analysis 30 Hz	2-D static biomechanical model	Five approaches: Rectangular integration of all frames at 30 and 5 Hz Spinal loading at initiation of lift × duration of the task Work-rest: Work, spinal loading at initiation of lift × time duration (while object in hand); Rest, loading during upright standing × remaining time of cycle Work only: Work component only of work-rest	Cumulative compressive and shear loads Cumulative flexion and extension moments
Daynard *et al.* (2001)	36 nursing aides from hospitals (Canadians) Individuals with restricted duties were excluded	Video recording of patient handling activities	2-D and 3-D quasi dynamic model hand force measured by dynamometer	Summation of products of time and peak spinal load for each of its actions	Cumulative compressive and shear load
Kerr *et al.* (2001)	Automotive workers from Canadian plant 137 subjects with lower back pain 244 subjects without lower back pain	Similar to Norman *et al.* (1998)	Similar to Norman *et al.* (1998)	Similar to Norman *et al.* (1998)	Cumulative lumbar disk compression in final regression model

(*continued*)

Table 1. Continued.

Source	Population	Accumulation measurement	Spinal loading measurement	Method of integration (time and amplitude)	Parameters measured
Seidler *et al.* (2001)	229 male patients with osteochondrosis or spondylosis of lumbar spine (Germans) 197 male patients without lumbar diseases	Structured questionnaire/interview supplemented with detailed explanations	Lifting with both arms = $1800\,N + 75\,N\,Kg^{-1}$ * weight of object (kg) Carrying in front or one side of the body = $1000\,N + 85\,N\,Kg^{-1}$ * weight of object (kg) Carrying on both sides, on the shoulder or on the back = $1000\,N +$ $60\,N\,Kg^{-1}$ * weight of object (kg) Extreme forward bending = 1700 N	Sum dose per year = $\text{days} * \sqrt{8h * \sum_i F_i^2 \times t_i}$ where, days = working days per year; t = average daily lifting or carrying duration (h) Cumulative exposure = work years (before diagnosis of lumbar spine disease) × sum dose per year	Cumulative lumbar exposure
Stuebbe *et al.* (2002)	One worker for each of four jobs: punch press, carton stripping, glueing, quality production (Americans)	Video-based posture capture of whole shift 10 s segment of video recording of each work activity at 2 min interval	2-D static biomechanical model Force measurement not described	Cumulative spinal compression per 8 h = summation of spinal compression for all observations taken every 2 min	Cumulative compressive load
Sullivan *et al.* (2002)	5 male and 5 female graduate students (Canadians)	Video-based posture analysis Observers digitized five repeats of 3 occupational lifting tasks with 5–6 s duration	2-D static biomechanical model Weight of external load included	Rectangular integration of spinal loading for tasks with 5–6 s duration at a sampling rate of 2 Hz	Cumulative compressive and shear loads
Seidler *et al.* (2003)	267 male cases with acute lumbar disk herniation (Germans) 197 patients without lumbar diseases	Structured questionnaire/interview	Similar to Seidler *et al.* (2001)	Similar to Seidler *et al.* (2001)	Similar to Seidler *et al.* (2001)
Andrews and Callaghan (2003)	10 healthy male college students (Canadians)	Video-based posture analysis with varying sampling rates (1–30 Hz)	2-D static biomechanical model Weight of external load included	Rectangular integration for tasks analysed at different rates (1–60 Hz)	Cumulative compressive and shear loads

- Norman and coworkers (Norman *et al.* 1998, Daynard *et al.* 2001, Kerr *et al.* 2001) used motion analysis and a 2-D quasi-dynamic model to derive the peak spinal load and multiplied these values by the number of repeats and duration of each task to yield a shift exposure.
- The DOLLY study (Jäger *et al.* 2000) employed a postural sampling approach and a 3-D static biomechanical model to calculate load for an entire shift and then extrapolated the data to yield results for longer time periods. Three weighting systems were used for force relative to exposure time to calculate shift dose. The Mainz-Dortmund dose model (MDD) is based only on the events when the lumbar disk compression force exceeds 3.2 kN and the standardized durations of the lifting process.
- Mirka *et al.* (2000) examined time-weighted histograms of different construction jobs using a 3-D static biomechanical model, NIOSH lifting index and lumbar motion monitor. Their findings indicated that the different techniques yielded different results.
- Callaghan *et al.* (2001) analysed the cumulative spinal loading of selected lifting tasks using six different approaches, including a 'gold standard' and five modified sampling methods. Each of the five methods were compared to the 'gold standard', which consisted of estimating spinal load outputs for each frame for the entire lifting cycle (i.e. all frames at 30 Hz) using a 2-D static rigid link segment model with a single muscle equivalent biomechanical joint model. The authors concluded that there were significant errors (average error between task and subject was 27–69%) for four of the approaches that used discrete measures to represent the time varying cyclic exposure. Sullivan *et al.* (2002) examined inter- and intra-observer reliability of calculating lumbar spine loads. The results showed that compression and moment demonstrated the highest reliability in comparison to joint and reaction shear. Andrews and Callaghan (2003) investigated the minimum sampling rate needed to accurately quantify cumulative spinal loading using a static 2-D biomechanical model. It was found that the mean relative errors with respect to 60 Hz for all cumulative loads and conditions were found to be below 8% at a sampling rate of 1 Hz and less than 3% at a sampling rate of 2 Hz.
- Seidler *et al.* (2001, 2003) investigated the relationship between lumbar spine disease and cumulative occupational exposure to lifting or carrying and to working postures with extreme forward bending using a case-control study design. They employed structured questionnaires/interviews to extract data on postures and loads and used one of the three algorithms described by Jäger *et al.* (2000) for estimating cumulative compressive loading.
- Stuebbe *et al.* (2002) used a work sampling approach to collect postural data for compressive force calculation with a 2D static biomechanical model. The cumulative load was computed as the sum of 10 s samples taken at 2 min intervals.

3.2. *Methods for measuring postural data*

Review of the literature regarding measurement of working postures for cumulative spinal loading revealed that video-based posture capturing were used in nine of these studies (Norman *et al.* 1998, Jäger *et al.* 2000, Mirka *et al.* 2000, Callaghan *et al.* 2001, Daynard *et al.* 2001, Kerr *et al.* 2001, Stuebbe *et al.* 2002, Sullivan *et al.* 2002, Andrews and Callaghan 2003). Three studies used questionnaires/interviews to document the postures (Kumar 1990, Seidler *et al.* 2001, 2003) and one study evaluated the back loading from the EMG record of the erector spinae muscles in comparison to estimates from a biomechanical model (Mientjes *et al.* 1999).

3.3. *Spinal load measurement*

Biomechanical modelling was the most common method used to estimate the spinal loading. Loads were calculated from static 2D modelling (Kumar 1990, Callaghan *et al.* 2001, Sullivan *et al.* 2002, Stuebbe *et al.* 2002, Andrews and Callaghan 2003), quasi-dynamic 2D modelling (Norman *et al.* 1998, Mientjes *et al.* 1999, Daynard *et al.* 2001, Kerr *et al.* 2001) and static 3D modelling (Jäger *et al.* 2000, Mirka *et al.* 2000). These models demand the input of the workers' anthropometric data, the external load or forces applied to the hands, the direction of force application and body posture adopted during the maneouvre. Seidler *et al.* (2001, 2003) used questionnaires to provide estimates of postural and load inputs into regression equations which estimate the spinal loading at work.

3.4. *Method of integrating spinal loads over time*

As pointed out by Stuebbe *et al.* (2002), the quantification of the cumulative spinal stress reported in these studies follows the general principles introduced by Keyserling *et al.* (1987), which state that the cumulative exposure is a summation of the task loading a worker is exposed to over a fixed period of time. Task loading is the product of time spent in each posture, multiplied by the calculated loading in that posture and the number of different postures performed in that task. Kumar (1990) calculated the cumulative daily load, compressive load as:

$$CDC_o = \Sigma(MC_{oi} \times F_i) \quad \text{for } i = 1, n$$

where CDC_o is the daily overall cumulative compression of all tasks combined (N s) (i.e. tasks 1 to n); MC_{oi} is the cumulative spinal compression for load M for task i (N); F_i is the frequency per day for task i and n is the number of different tasks performed. Kumar used a similar approach to calculate the cumulative daily shear load as well. Stuebbe *et al.* (2002) used a similar concept to calculate the cumulative load for an 8-h work shift. Their approach only considered the frequency of the postures (because the work sampling methodology was performed throughout the work shift) but not the duration. Norman *et al.* (1998), Kerr *et al.* (2001) and Daynard *et al.* (2001) all determined the cumulative load exposure by multiplying the peak force of each task by the number of times and duration that each task was performed. Mirka *et al.* (2000) used histograms to document the amount of time spent or the number of lifts performed at different work tasks. The compressive stresses were calculated from the 3D SSPP programme based on the 487 stick figures that represented all the possible work postures. Mientjes *et al.* (1999) used an EMG driven approach to calculate spinal compressive stress at L4/L5. The 2DWATBAK biomechanical model (Norman *et al.* 1998) was first used to calculate the ratio of spinal compression and the EMG record associated with the performance of the task, producing an EMG normalization factor: Newtons of spinal compression per unit of EMG. EMG records were then converted to spinal compression while the subjects performed their tasks.

In addition to the aforementioned, different algorithms for integrating spinal force amplitude, frequency and duration have been evaluated by Jäger *et al.* (2000), Seidler *et al.* (2001, 2003) and Callaghan (2002, 2004). Jäger *et al.* (2000) quantified the cumulative spinal loading by linear, squared and tetra-powered weighting of force and noted that these methods yielded strikingly different cumulative doses for the four work tasks investigated. Seidler *et al.* (2001, 2003), in the Mainz-Dortmund dose model, assessed cumulating damage as a function of summation of the square of force multiplied by duration.

3.5. *Parameters measured*

The cumulative compressive load was investigated in all the studies. Seven studies (Kumar 1990, Norman *et al.* 1998, Jäger *et al.* 2000, Callaghan *et al.* 2001, Daynard *et al.* 2001, Sullivan *et al.* 2002, Andrews and Callaghan 2003) also documented the cumulative shear load. The two dimensional sagittal cumulative moment (flexor/extensor) has also been reported in four studies (Norman *et al.* 1998, Callaghan *et al.* 2001, Sullivan *et al.* 2002, Andrews and Callaghan 2003).

4. Discussion

A number of issues should be considered when evaluating cumulative spinal loading estimation methods. These include: methods for obtaining postural data; methods for estimating biomechanical load; method of integrating the loads over time; and the parameters to be measured. The consideration of all of these issues is essential to progress in the use of cumulative spinal loading as an exposure variable in occupational epidemiological studies.

4.1. *Methods for obtaining postural data*

The predominant method for obtaining postural data in previous studies has been video-based posture analysis. A few studies, however, have used structured-based interviews to capture postural data. Video-based techniques hold the advantage of providing a permanent record of the work tasks in comparison to structured-based questionnaires. On the other hand, these techniques are time intensive, requiring large amounts of effort to estimate cumulative spinal loading. Video-based approaches also present the challenge of acquiring union, plant and individual approval to record images. In comparison, structure-based questionnaires are attractive in that they require much less time than video-based techniques, but they rely heavily on a human operator, which may introduce a significant source of recall bias and error.

Neumann *et al.* (1999) compared peak compression, moment and shear outcomes using video based techniques and questionnaires. On average, compression and moment were slightly higher for questionnaires relative to video methods (2% and 12%, respectively). On the other hand, it was slightly lower for peak shear forces (5%). In addition, the questionnaire based techniques resulted in higher variability than video techniques, as assessed by the coefficient of variation.

In a laboratory study, Andrews *et al.* (1996) found that peak compression was consistently higher for questionnaire methods in comparison to those obtained from video-based techniques. This confirms the findings of Neumann *et al.* (1999). In another investigation by Andrews *et al.* (1997), a comparison was made between questionnaire and video techniques for different spinal measures. Differences were obtained between both methods. Correlations between the video-based and self-reported measures ranged between 0.1–0.4, accounting for relatively small amounts of the explained variance.

It is worth noting that the documentation of work postures by video-based capturing has its own inherent errors, particularly, with respect to non-symmetrical postures and small body segments. For example, Kingma *et al.* (1998) showed that a pelvic rotation of 30° will lead to an error in the estimation of the L5-S1 joint by 7.5 cm. Nonetheless, based on the similarity in the outcomes of studies employing these approaches (Kumar 1990, Norman *et al.* 1998, Seidler *et al.* 2001, 2003), it seems on a preliminary level that the association between integrated spinal loading and lower back pain may be similar for both questionnaire and video-based methods.

Based on a review of the aforementioned studies, it is clear that there are issues about the validity of questionnaire-based methods relative to video techniques that should be explored more fully. Theoretically, from knowledge of the relationship between questionnaire and video-based methods under different handling conditions, it may be possible to come up with correction factors which may assist in the reporting of absolute spinal loading outcomes for questionnaire-based techniques. This may be an extremely important practical issue for large occupational epidemiological studies.

4.2. *Method of estimating spinal loads*

Once the postural information is recorded, spinal loading is estimated using a static, quasi-dynamic or dynamic biomechanical model or regression equations linking postural or task positioning with joint compression. It is likely that dynamic models would provide better estimates of spinal load, with more content validity, than those based on static models, especially when the speed of the lift is high. However, the complexity of dynamic models and the input information they require present major challenges for use in an industrial setting. Static models are much easier to use than dynamic models; but their accuracy may be called into question.

Leskinen (1985) and Leskinen *et al.* (1983) reported that dynamic peak compression forces were higher than those calculated for static forces depending on the type of lift. The percentage increase ranged between 33–60%. Similarly, the compression time integrals were higher for dynamic models than for static models, but the differences were not as pronounced (range: 28–36%). Bernard *et al.* (1999) found that the average dynamic and static moments were in the order of 2.5–14% higher for dynamic models depending on the speed of lift. On the other hand, the differences in terms of the moment time integral were much less pronounced (as depicted from figure 7 in their paper). McGill and Norman (1985) found that peak spinal moments were, on average, 19% higher for the dynamic model relative to the static calculations, with a maximum difference of 52%. De Looze *et al.* (1994) found that static peak lumbar moments were not significantly different from estimates of dynamic moments (9% on average) for slow lifts, but that there was a 42%

difference for fast movements. In contrast, use of a quasi dynamic model, which includes the acceleration of the hand loads only and ignores the body segmental accelerations, resulted in cumulative loading errors of less than 5% compared to a full dynamic analysis, whereas a fully static cumulative load estimate model resulted in errors of ~12% when compared to the full dynamic assessment (Keown *et al.* 2001).

In light of the above, it appears that there are pronounced differences between peak static and dynamic force calculations. The differences, however, become considerably smaller for the integral force time calculations in comparison to peak computations. As such, one should take advantage of this opportunity in the interest of cumulative spinal loading calculations. Perhaps from a practical standpoint, one may develop a monogram to relate the integral force time calculations for both static and dynamic models while accounting for other variables such as speed of lift. Consequently, this could considerably reduce the amount of time for cumulative spinal calculations if one elects to use static techniques.

Another practical approach to estimating spinal loads would be to extract the external mechanical work required by the workers for a particular work activity. This would be especially useful for mixed activities, such as jobs requiring a combination of pushing/pulling, lifting/lowering and carrying.

In summary, research is needed to evaluate the role of individual biomechanical parameters and external mechanical work parameters and how they may be applied to determining cumulative loads for population-based studies.

4.3. *Method of integrating spinal loads over time*

The third issue of significance to the assessment of cumulative loading is the method of integrating spinal loads over time. Several methods have been used to document the load-time components. One approach favours the use of peak loads multiplied by time. Another approach is to give forces a higher weight such as the square of the force. The basic assumption of a simple additive model for this form of integration is that brief exposures to high forces will result in similar magnitudes of damage to the spinal structures as would long duration exposures to low forces. Based on the *in-vitro* cadaver study of vertebrae conducted by Brinckmann *et al.* (1988), Jäger *et al.* (2000) argued that doubling the force produced a more injurious response than the doubling of exposure time. Currently, however, there is no consensus on which method is the most effective in calculating the cumulative dose over time.

Specifically, Jäger *et al.* (2000) evaluated different algorithms for computing cumulative load values for four industrial tasks. These included values resulting from linear, squared and tetra-powered force weighing, relative to time. Results showed that the daily shift dose was ~25% and 50% higher for the squared and tetra-powered algorithms relative to the linear based algorithm, respectively. No explanation was given by Jäger *et al.* as to which is the most preferred algorithm. From a physics standpoint, the algorithms suggested by Jäger *et al.* (2000) (i.e. squared and tetra-powered weightings) do not fit the classic definition of internal dose (e.g. the units are not Newton sec). Therefore, new algorithms or techniques that are more compatible with the physics definition of spinal dose may be needed. Theoretically, for example, rather than using a power formula, the force (F) could be weighted by simply multiplying the force by a constant, such as αF and time (T) such as βT, where α and β are greater than 0. These coefficients may be obtained through epidemiological studies that describe the association between integrated spinal loading parameters and lower back outcomes or *in-vitro* studies examining the influence of the magnitude of force and duration on injury mechanics from cumulative exposure.

Although not fully detailed by Jäger *et al.* (2000), one has attempted to potentially explain the physics foundation of their square algorithm. By definition, a dose is defined as:

$$D = \text{Force} \times \text{Time} = FT$$

where $F = \text{mass}\ (m) \times \text{acceleration}\ (a)$. Thus,

$$\begin{aligned} D &= m \times a \times T \\ &= m \times (\Delta v/T) \times T \\ &= m \times \Delta v = \text{change in momentum} \end{aligned}$$

where Δv is change in velocity. It should be noted that doubling the force or time will not change the dose as follows:

$$(2F)T = F(2T) = m\Delta v = \text{same dose}$$

Jäger *et al.* (2000) employed $\sqrt{F^2T}$ as a dose. From the above equation, this definition of dose is equal to:

$$F^2T = mF\Delta v = m \times \text{Power}$$

Therefore, a dose is proportional to the square root of power which discriminates between doubling the force versus doubling the time. This issue should be further investigated including the dose definition of the tetra weighting algorithm.

In addition to the algorithms proposed by Jäger *et al.* (2000), Callaghan *et al.* (2001) reported 27–69% errors for different techniques used for integrating spinal outcomes over time in comparison to rectangular integration at 30 Hz. In light of Callaghan's findings, two questions arise as they relate to the use of static analyses to estimate cumulative load estimates. First, how many samples of posture need to be analysed for each lift in order to accurately estimate cumulative load? Secondly, what is the optimal recommended rate for sampling posture in order to provide the most accurate cumulative load estimates? There are differences of opinion within the scientific community about these two issues, especially as they relate to various dynamic aspects of the loading activities, such as the speed of lift, mass of the object and the trajectory of motion. For example, Jäger *et al.* (2000) used sampling rates of 0.4–1.8 frames per second without discussing the implications of such rates to cumulative spinal loading calculations. Callaghan *et al.* (2001) showed that a reduced sampling rate of 5 Hz provided a good approximation to the cumulative load produced by the 60 Hz 'gold standard'. In that study, however, the 'gold standard' for cumulative load was not derived from a dynamic model, so the accuracy of the 'gold standard' was not known. In a later study, Andrews and Callaghan (2003) evaluated several different sampling rates to determine what the errors were for reduced sampling rates as compared to the 'gold standard' of 60 Hz. As before, however, the gold standard was not derived from a dynamic model. In a third study, Keown *et al.* (2001) evaluated a static and quasi-static approach and compared it to a dynamic approach. They reported that the static approach underestimated cumulative load by 14.0% compared to the dynamic approach and that the quasi-static approach under-estimated cumulative load by 2.3% compared to the dynamic approach. In this study, however, they did not examine how the number of samples or how different sampling rates would affect the cumulative load estimate compared to dynamic estimates. Therefore, additional research is needed to further address these issues so that cumulative load methods can be standardized and scientific studies can then be compared.

To date, no study has been conducted to compare the criterion validity of the different techniques reported by Jäger *et al.* (2000) and Callaghan *et al.* (2001) relative to lower back pain outcomes. Therefore, additional research is needed to determine which algorithms result in the highest measures of association with low back outcomes.

4.4. *Parameters to be measured*

The fourth issue of interest is whether cumulative compression, shear or moment would best predict risk of low back disorder. The integrals of cumulative compression loads and time are the most widely used, with cumulative shear and moment being used less frequently. Until new knowledge is generated about the relationship between the various spinal load metrics and their association with lower back outcomes, researchers should consider multiple parameters of integrated spinal loading. In addition, non-biomechanical factors such as perceived effort and work satisfaction or dissatisfaction should also be accounted for, since they have been implicated in the development and/or reporting of LBDs (Bigos *et al.* 1991, Kerr *et al.* 2001, Yeung *et al.* 2002).

With respect to integrated spinal loading measures, it appears that the coefficient of variation is higher for integrated shear and moment than that for integrated compression. The results by Norman *et al.* (1998) demonstrate that the average coefficient of variation for integrated compression was 23%, compared with values of 49% and 38% reported for integrated moment and shear, respectively. Similar observations are drawn from the data compiled by Kumar (1990), in which the average coefficient of variation for integrated shear was ~142% compared to 83% for integrated compression. This issue should be addressed in greater details in future research. As well, even when 3-D biomechanical models have been employed only 2-D low back joint kinetics have been reported. There has been little or no research evaluating the effect of cumulative loading outside the sagittal plane and the potential association of this exposure with the development of low back pain.

4.5. *Dose limit*

One last important issue to keep in mind is the metric and limit used to document the cumulative dose to which a worker is exposed. As pointed out by Callahgan (2004), Germany has led on this front with a recommended shift dose of 19.8 MN s. The validity of this dose limit and the corresponding metric is not known and additional research is needed to fully investigate what the dose limit should be. Also, research is needed to determine life-time exposure limits for cumulative spinal loading and how the body adapts to progressive loading. This approach would be similar to prior efforts made by work physiologists to develop a daily metabolic expenditure dose limit for heavy, dynamic work. For example, Grandjean (1991) proposed that an energy expenditure of 20 000 KJ per working day was reasonable for maximum heavy, dynamic work.

The National Institute for Occupational Safety and Health (NIOSH) has developed maximal disk compression limits for infrequent manual material handling activities (3400 N recommended maximal compression force limit and 6500 N upper limit in the development of the revised NIOSH lifting equation) (Waters *et al.* 1993, 1994). They have not, however, developed an overall cumulative spinal load limit. Genaidy *et al.* (1993) compiled an extensive list of biomechanical tolerance limits from various studies, developed regression equations for this purpose and recommended the concept of damage load, as proposed by Eie (1966), wherein the tolerance limit is given as a fraction of the lumbar compressive strength from the published literature (i.e. ~60%, on average, of the lumbar compressive strength). Similarly, Jäger and Luttmann (1996) documented an extensive list of lumbar compressive strength data.

Development of a load tolerance limit for repetitive loading will likely require detailed information about how the spinal tissues respond mechanically to repetitive loading, how they recover and how the load-tolerance limit changes as a result of these factors. A detailed discussion is provided of issues related to repetitive loading in a previous paper (Waters *et al.* 2005).

Based on a review of the literature, it is suggested that a cumulative spinal dose limit for repetitive loading would be most applicable if it incorporated factors that could mitigate cumulative exposure, such as the degree of repetitiveness of tasks, the magnitude of exposure and/or the duration of exposure, with a discounting factor for rest. For example, there might be one exposure limit for infrequent tasks (i.e. less than once every 5 min), another limit for low-to-moderately frequent tasks (i.e. between once every 5 min and less than or equal to 4 times per min) and yet another limit for frequent tasks (more than 4 times per min). In theory then, it would be possible to calculate a safe spinal dose for each level during a work shift and finally derive the shift dose.

5. Concluding remarks and directions for future research

This paper reviewed and critically appraised current methods for estimating cumulative spinal loading. There is a pressing need to develop an estimation method that is valid, reliable and practical. In the development of such a method, a number of factors should be considered, including: the method of obtaining postural data, the method for estimating biomechanical spinal loads, the method of integrating the loads over time and what parameter should be measured. In particular, additional research in the following areas is needed to develop and expand understanding of cumulative spinal loading as an exposure assessment tool:

(1) Development of new methods and improvement of existing methods for obtaining postural data, as well as investigation of the relationship between questionnaire and video-based methods.

(2) Evaluate spinal loading estimation methods for both individual and population based studies. With respect to biomechanical modelling, the potential application of the use of a nomogram to relate the integrated force time calculations while accounting for other variables such as speed of lift in individual-based studies should be explored. Development of new methods,

based on total mechanical work required during the work shift for population-based studies, should be examined.

(3) Different methods of integrating the loads over time should be developed and validated with respect to lower back outcomes.

(4) Determine which spinal parameters (e.g. compression, shear, moment, energy, etc.) best predict risk of lower back disorders. Studies are needed to determine why integrated moment and integrated shear have such high variability compared to that for integrated compression.

(5) Develop and validate an evidence-based dose limit for cumulative load, with respect to lower back outcomes that considers the degree of repetitiveness, magnitude and duration of exposure of the tasks during a work shift. Other factors that likely should be considered are the workplace psychosocial influences which have been associated with the reporting of LBP (Bigos *et al.* 1991, Kerr *et al.* 2001) and beneficial discounting factors such as rest or job rotation.

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