

Review article

A conceptual quantitative model for prevention of work-related carpal tunnel syndrome (CTS)

Shiro Tanaka and James D. McGlothlin

National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, OH 45226, USA

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Abstract

In this paper the authors present a pathogenic mechanism of carpal tunnel syndrome (CTS) and a heuristic conceptual model to assess the musculoskeletal stress of manual work for the purpose of establishing quantitative guidelines to prevent work-related CTS. The model is based on the concept that the frictional energy of manual work within the wrist initiates local tenosynovitis as the precursor of work-related CTS. It assumes that the frictional energy inside the carpal tunnel is a function of the product of three biomechanical factors of manual work: internal force, repetitiveness and wrist angles. To prevent work-related tenosynovitis and CTS, the value of the product should not exceed a limit derived from the population-based threshold. Reliable, validated techniques should be used for gathering data on the stress factors of manual work for the purpose of establishing quantitative guidelines to control and prevent work-related CTS.

Relevance to industry

The proposed model would be helpful to establish quantitative guidelines for prevention of work-related CTS. Such guidelines would assist industrial management, labor, and government agencies in quantifying the risk factors of work-related CTS, evaluating the effectiveness of various ergonomic interventions, and explaining why various intervention strategies might work.

Keywords

Carpal tunnel syndrome (CTS); cumulative trauma disorders (CTDs); ergonomic guidelines; manual work; wrist tenosynovitis.

Introduction and background

The wrist is one of the body parts most frequently affected by cumulative trauma disorders (CTDs), accounting for 48% of all claims for CTDs filed in a state workers' compensation program (Tanaka et al., 1988). Included in CTDs are such clinical entities as tendinitis, tenosynovitis (Welch, 1972) and carpal tunnel syndrome or CTS (Birkbeck and Beer, 1975). Industrial operations such as meat processing, assembly work, and plastics/rubber manufacturing have been reported to have a high incidence rate of these disorders (Jensen et al., 1983). In recent years, the incidence of CTDs, and CTS in particular,

has increased dramatically in many segments of American industry (Bureau of Labor Statistics, 1987).

CTS is the manifestation of median nerve dysfunction as it is compressed within the carpal tunnel of the wrist. Symptoms include pain, numbness, and tingling in the affected area of the hand and fingers resulting in difficulties performing daily manual activities (Phalen, 1951). These symptoms are often nocturnal. Conduction velocity of the median nerve across the wrist is slowed. In advanced cases of CTS, the thenar muscle may atrophy. Many underlying diseases (e.g., hypothyroidism) or conditions (e.g., pregnancy) are known to be associated with CTS (Spinner et al., 1989).

For work-related CTS, repetitive and forceful movements of the hand and deviated posture of the wrist joint while performing manual work have been postulated as risk factors (Armstrong et al., 1987).

At the same time, the work-relatedness of CTS has been challenged by those who maintain that the majority of work-related CTS or tendinitis cases are merely the manifestations of use-related

hand pains (Hadler, 1990). This disagreement seems to stem partly from the fact that CTS can be caused by various underlying conditions unrelated to the occupational hand use, and partly from the differences in the case definition of CTS among investigators. The diagnostic criteria for CTS may vary among physicians. A case definition for work-related CTS for surveillance purposes has been proposed only recently (MMWR,

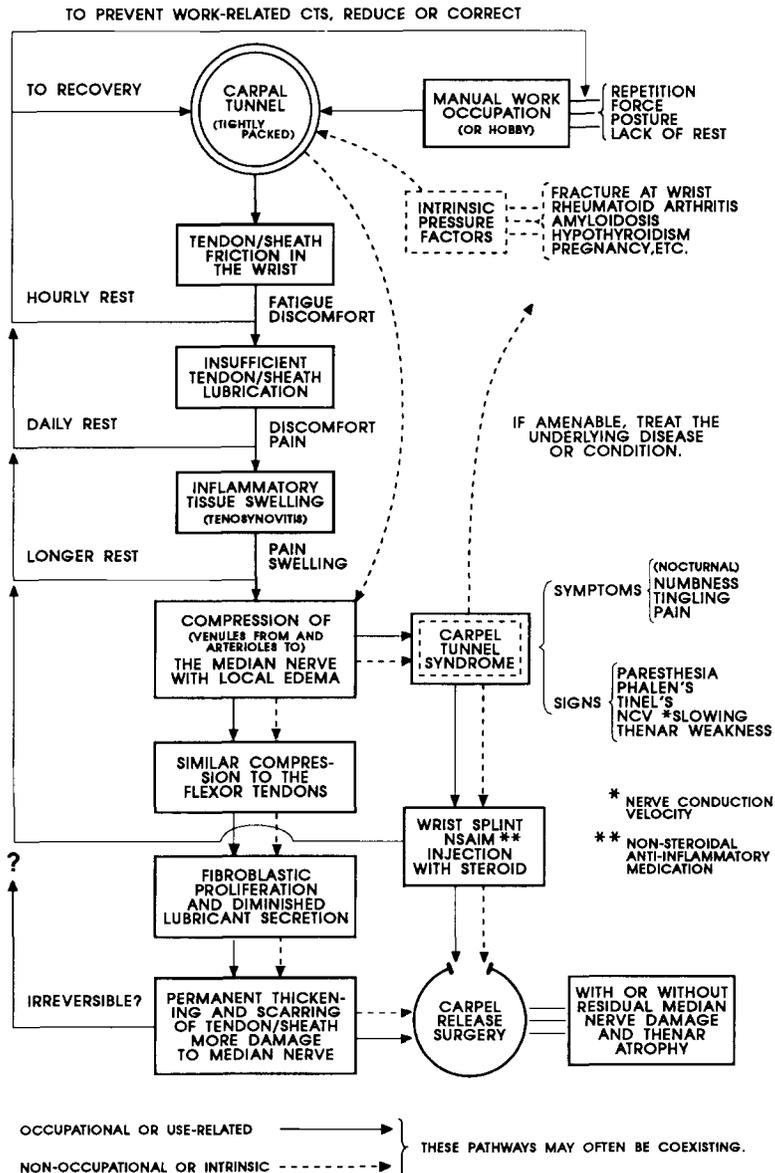


Fig. 1. A schematic presentation of the pathogenesis and progression of occupational and non-occupational carpal tunnel syndrome.

1989). It is often difficult to distinguish work-related (or use-related) CTS from non work-related (or intrinsic) CTS, since their clinical manifestations are similar. Manual work is an integral part of human activity regardless of the person's employment status. Empirically, however, it is recognized that "excessive" manual work causes disorders of the hand and wrist, such as pain, discomfort and swelling. The key question which must be addressed is: Just how much (stress) is too much? Qualitative guidelines for prevention of CTDs and CTS are available (Silverstein et al. 1986a; Putz-Anderson, 1988). A recent effort by the Occupational Safety and Health Administration (OSHA, 1990) to develop guidelines for safe work practices in the meat-packing industry is an example of steps to deal with the current epidemic of CTS in this segment of American industry. However, there are currently no quantitative guidelines for repetitive manual work. In contrast, quantitative work practice guidelines are available for manual lifting (NIOSH, 1981), suggesting a feasibility of preparing a similar equation which may be applicable to manual work.

In this paper, which is an expansion of its preliminary version (Tanaka and McGlothlin, 1989), we schematically present a pathogenic mechanism leading to CTS, and based on the

scheme, propose a heuristic conceptual model to assess the musculoskeletal stress of manual work for the purpose of establishing quantitative guidelines to prevent work-related CTS.

Rationale and assumptions

Although it may be often difficult to separate work-related CTS from intrinsic CTS, these two types can be schematically distinguished as shown in figure 1. The pathogenesis of work-related CTS is presented by solid lines, while the dotted lines indicate the pathogenesis of non work-related (intrinsic) CTS, although the two pathways may coexist in many cases. The basic assumptions and understanding of work-related CTS are as follows:

- (1) The carpal tunnel is a space tightly encircled by the carpal bones and the transverse carpal ligament (or flexor retinaculum), through which the finger flexor tendons, their sheaths and the median nerve pass (Robbins, 1963), as shown in figure 2. Therefore, an increase in the volume of the content inside the tunnel, or pressure from outside, will raise the intra-tunnel pressure.
- (2) If the pressure increase is sufficient, it causes

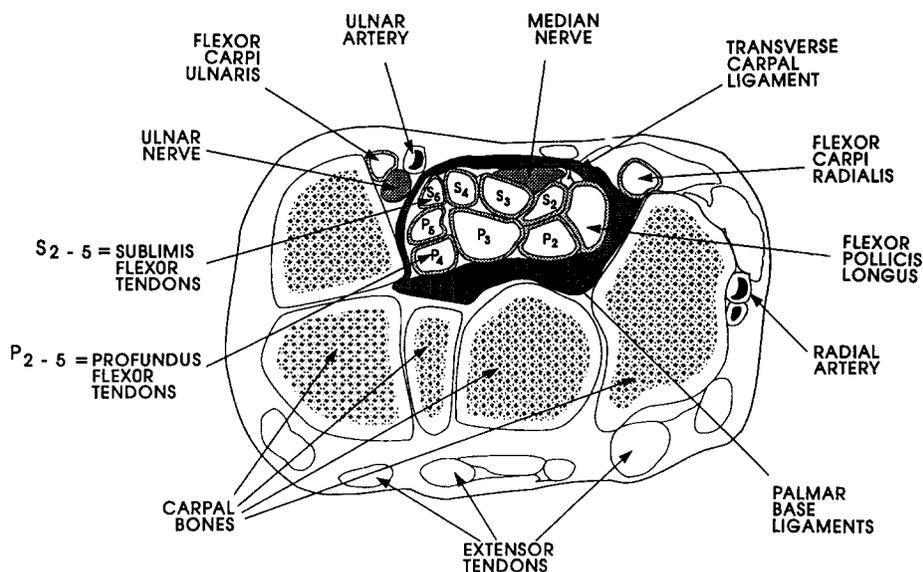


Fig. 2. Transverse section of right wrist looking distally (with the palm side up), showing relative positions of the median nerve, flexor tendons, transverse carpal ligament and carpal bones. Note that the shape of the median nerve is conforming to the space available to it inside the tunnel. (Based on a figure by H. Robbins, 1963; p. 957.)

local venous congestion within the vascular plexus of the nerve, as well as ischemia in arterioles nourishing the nerve, leading to endoneurial edema (Sunderland, 1976). Clinically, the patient feels numbness, tingling and pain in the hand corresponding to the distribution of the nerve. This is the initial stage of CTS. Various tests including the nerve conduction velocity across the wrist may reveal the abnormality (Lundborg et al., 1982).

- (3) The edema of the nerve segment increases the effect of the original compression, thus creating a vicious circle. If this condition persists for a prolonged period of time, fibroblasts proliferate within the nerve tissue leading to scarring (Eversmann, 1988). It can also be assumed that a similar congestive process may occur in the micro-circulation of the flexor tendons within the carpal tunnel, further complicating the local pathology.
- (4) Thus, any disease process, local or systemic, which increases the intra-tunnel pressure can cause CTS (Dawson et al., 1983), the severity of which would depend on the degree and duration of the compression.
- (5) When manual work is performed, under normal conditions, synovial lubrication of the tendon sheaths for smooth gliding of the tendons is adequate. This is a stage which was described as "... musculo-skeletal usage which in and of itself is reasonable, comfortable, and customary and which can be repeated without undue distress..." (Hadler, 1990). This statement implies that there seems to be a physiological limit for the synovial lubricating function, meaning that excessive use of the hand beyond this physiological limit will result in increased friction and inadequate lubrication within the carpal tunnel.
- (6) In actual industrial situations, some of the job requirements for manual work do not allow workers to stay within the "reasonable or comfort" range described by Hadler. When the movement of the hand/finger is too frequent, forceful, and/or angled (by work load and/or posture of the hand), the tendons become strained (Goldstein et al., 1987) and lubrication of the tendons would become inadequate.
- (7) It has also been shown that flexion at the wrist reduces the carpal tunnel size and, in particular, tension applied to the flexor tendons during wrist flexion markedly increases pressure in the carpal tunnel (Smith et al., 1977). This increase of intra-tunnel pressure is also observed in extension as well as in flexion (Gelberman et al., 1981), and can be expected to occur in radial or ulnar deviation of the wrist.
- (8) The inadequate lubrication will lead to increased friction, and this will produce histological changes referred to as a non-specific synovial reaction in the affected tendon-sheath unit (Sissons, 1979). At some point, the initial inflammation is perceived as local discomfort or pain, as a biological warning sign (Curwin and Stanish, 1984).
- (9) If the workload (internal force to do the work and/or repetitiveness of hand movement) and bending of the wrist are reduced at this time, and sufficient rest is given to the body part, the inflammation will subside and normal lubrication will be restored (Cailliet, 1982).
- (10) If the wrist has not rested enough before resumption of the task, or if the manual work is continued despite pain or discomfort, the initial inflammation may progress to swelling of the structures (Sissons, 1979). This can happen, since the tendon sheaths appear to need a much longer time to restore their normal lubrication than the time needed for the muscles to recover from their fatigued stage. Also, it takes time for an inflammatory process to subside.
- (11) This swelling causes a further increase in the carpal tunnel pressure, and the pathological process described above is further enhanced (Cailliet, 1982).
- (12) Initially, various methods of treatment to restore the local circulation will relieve the symptoms at least temporarily. Patients get some relief from the nocturnal attack of CTS by shaking their hand. Administration of non-steroidal anti-inflammatory medication (NSAIM) or a local injection of steroid may offer temporary relief. A wrist splint

worn at night will provide a local rest and prevent bending of the wrist (Cailliet, 1982).

- (13) However, continuation of the stressful manual work will lead to prolongation or repetition of the initial stage, which will eventually result in chronic tenosynovitis in the wrist and permanent damage to the median nerve. This condition is likely to be irreversible (Armstrong et al., 1984) as often seen in the advanced stage of CTS.
- (14) If the intra-tunnel pressure is not relieved by conservative treatment and there is a fear of permanent nerve damage, carpal release surgery may have to be performed to reduce the pressure (Duncan et al., 1987). When the median nerve is exposed, it is often described as taking the shape of an hour-glass showing the effect of mechanical compression. The effectiveness of the surgery would depend on the degree of damage to, and the recovery potential of, the median nerve.

In the case of work-related CTS, the authors postulate that; (1) the friction between the tendons and the tendon sheaths in the carpal tunnel is the factor most responsible for initiating and/or aggravating tenosynovitis, regardless of the types of the tasks performed by the hand and fingers (Armstrong and Chaffin, 1978); and (2) that the frictional energy is proportional to the product of internal force necessary to do the work, repetitiveness of movement, and wrist angles (extension/flexion, radial/ulnar deviation, or any combination of these).

Based on these postulates, the authors hypothesize that work-related CTS (in its pure form) is always preceded by, or concurrent with, frictional wrist tenosynovitis, and prevention of the initial tenosynovitis would prevent work-related CTS. (In contrast, theoretically, intrinsic CTS can occur without such a frictional effect; for example, a sudden onset of CTS after a fracture of a carpal bone is a typical case. In such an instance, any accompanying inflammatory process in the wrist is probably due to the secondary friction and to the pressure build-up within the carpal tunnel. However, these two pathogeneses may coexist in some cases.)

Further, on the assumption that compression of the median nerve is preceded by, or concurrent

with, hand/wrist pain, it can be theorized that preventing the onset of the hand pain or discomfort would also prevent occurrence of work-related tenosynovitis and CTS. (It is not clear what is the very first symptom of occupationally induced tenosynovitis before the onset of median nerve dysfunction. Some investigators (Feldman et al., 1987) place "nocturnal or at rest paresthesia in fingers/hand" before "pain in hand/fingers". The authors expect that there are certain variations among individuals, and would thus treat either pain or nocturnal paresthesia in the region interchangeably as the initial symptom.)

Therefore, a preventive principle dictates that a manual task must be such that it does not cause pain during, or after performing the repetitive work; or if such pain or other morbidity is reported by workers, the work methods have to be modified to reduce the frictional energy at the wrist. It can be accomplished by controlling the internal force to do the work, task repetitiveness, wrist angles, or any combination of these factors (assuming that other factors such as cold or vibration which will be discussed later are absent or negligible). It is also assumed that there is a population norm for pain threshold, which would follow a normal distribution pattern in relation to the amount of stimulus.

Construction of threshold lines

Clearly, there are physiological upper limits for the capacity of what the majority of the worker population can do safely (without experiencing pain or damage) with their hands in terms of the frequency of the movement and the forces they can exert. Similarly, the ranges of angular motions of the wrist are naturally limited. Furthermore, the manual tasks need to be performed *safely* (meaning without developing tenosynovitis or CTS) for many months and years of work. Upon these premises, it is proposed that the *product* of values of internal force, task repetitiveness and angles of hand/wrist motions must remain under certain limits to prevent inflammation. Mathematically, these three factors can be positioned in an inverse relationship for protection of workers against CTS. A partial supporting

evidence for this inverse relationship is found in recent epidemiologic and laboratory studies (Silverstein et al., 1986b; Snook et al., 1992a; Snook et al., 1992b). Thus, a mathematical model that is thought to contain appropriate risk factors is being proposed for epidemiological and experimental verification:

$$ELM = k \cdot \alpha F \cdot \beta R \cdot e^{\gamma A} \tag{1}$$

Where:

ELM = Exposure Limit for Manual Task (Ideally, ELM should be set toward the goal of the Occupational Safety and Health Act, which is to protect all workers.)

F = Internal musculoskeletal force exerted by the finger-hand-wrist-forearm complex needed to complete a typical task cycle. [At this stage of model development, we do not know what the most suitable expression for the force factor might be. It might be the average of the total internal force needed in a task cycle; or more dynamically, average angular velocity or acceleration at the wrist (Marras and Schoenmarklin, 1992; Schoenmarklin and Marras, 1992). Further research is needed to determine what measurement would best represent the force factor in relation to the risk of developing CTS.]

R = Repetition of the task cycle per unit time period; may be substituted by the number of similar products manufactured or processed per unit time.

A = Wrist angle: May be expressed as the sum of the proportions of measured wrist angles while performing the task in relation to the maximum angle possible in each direction of wrist bending. Thus: $A = \text{Flexion}/(\text{Maximum Flexion}) + \text{Extension}/(\text{Maximum Extension}) + (\text{Ulnar deviation})/(\text{Maximum Ulnar Deviation}) + (\text{Radial deviation})/(\text{Maximum Radial Deviation})$; $0 \leq A \leq 4$. Its exponential form is based on the equation described by Chaffin and Andersson (1984, pp. 218), in recognition of the fact that the finger-moving tendons are partly wrapped around the "anatomical pulley" in the wrist.

e = The base of natural logarithm (= 2.71...)

α, β, γ = Coefficients for each corresponding factor.

k = A constant to be determined for worker protection.

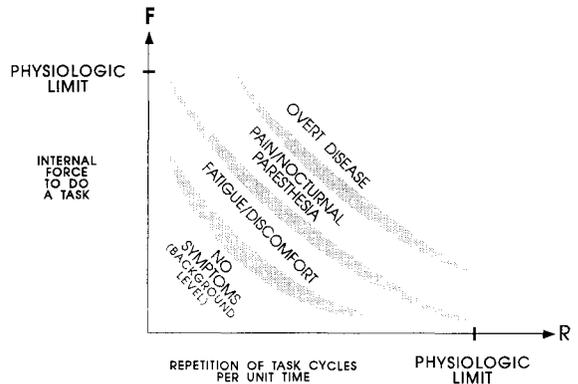


Fig. 3. Conceptual relationship between repetition frequency and internal force factors of manual work as related to hand/wrist disorders (wrist angle and other factors are ignored).

Graphically, equation (1) is presented two-dimensionally in figure 3 (if $A = 0$), and three-dimensionally in figure 4 (if $A > 0$), both of which have a concavity towards the top of the figure.

The practical upper limit of F will be determined by the largest internal force which can be exerted safely by a hand during a unit time. From equation (1), if F is at the maximum, the product of R and A must be reduced to the minimum to stay below ELM, meaning that the wrist should not be deviated and only a few repetitions will be allowed.

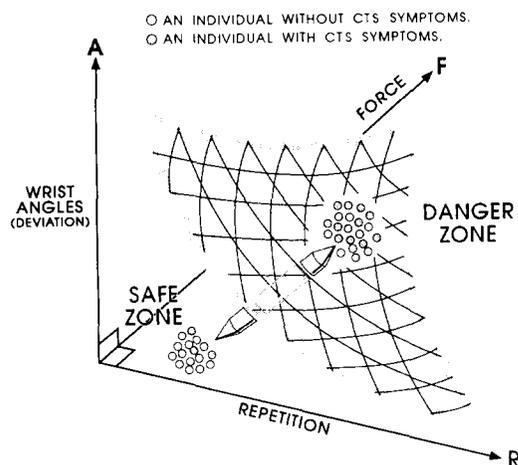


Fig. 4. A schematic presentation of equation (1) showing a theoretical threshold plane, across which different incidence rates of hand/wrist morbidity are shown among different groups of workers performing various repetitive manual work.

By the same token, there is also a maximum limit of repetitions per unit time a human hand can make safely to perform certain tasks in any manufacturing process. If R is very high, the product of F and A must be at the minimum, i.e. the force being the weight of only the fingers and hand, and the wrist being kept in neutral position. This is at the right end of the triangle in figure 4. An example may be the keyboard operation in office settings, in which the frequency of finger taps may be extremely high. [In case of fast-paced and continuous VDT operations, other stress factors such as visual and mental fatigue, static loading on the neck-shoulder-arm, and psychosocial factors must be considered as well as the number of keystrokes for health protection of VDT operators (Kiesler and Finholt, 1988).] Very low R values would represent static job/task, to which this model may not apply.

If A is at the maximum, the product of F and R needs to be minimal to be safe. This is at the upper left angle of the triangle in figure 4. One special instance of this situation is Phalen's test for diagnosis of CTS, in which the wrist is maximally flexed and kept in this position for 60 seconds. Even healthy individuals may feel numbness and tingling in the area of the median nerve distribution if held for a longer time period.

These extreme situations are uncommon but helpful in determining the borders of the curved plane. In accordance with equation (1), if the internal force must be increased as required by the task, the repetition rate and/or wrist angles of such movement must be reduced to prevent the development of hand pain. Similarly, if the wrist angle must be increased, either or both of force and repetition have to be reduced, since angulation of tendons in the carpal canal greatly increases the frictional energy (Smith et al., 1977). If the task frequency per unit time is increased, the force and/or angle factor must be reduced to stay below the ELM.

In real life, however, this curved line (or plane) should be a fuzzy band with some thickness to accommodate a variety of individuals in the working population. (In the 3-dimensional figure, it is presented as a triangular kite-like plane with a certain thickness.) Below the fuzzy band would be jobs which could be performed by almost all workers without development of symptoms, and

above it would be jobs which would produce symptoms in a large proportion of workers. Within the band, some workers may have symptoms of pain or nocturnal paresthesia, while others are not affected. Thus, the model could also be expressed in probabilistic terms for each of the axes, defining the criteria of risk (degree of exposure) that are acceptable and can be mathematically adjusted for protection of workers' health, regardless of personal attributes such as gender or wrist size.

Methodology for data collection

Data can be collected from controlled human experiments (Moore and Wells, 1989; Snook et al., 1992a,b) and field surveys in which workers in various industrial settings are studied for ergonomic risk factors and disease outcome (Armstrong et al., 1982; Marras and Schoenmarklin, 1991). Due to the difficulty of quantitatively assessing the musculoskeletal risk factors, the data presented by the majority of field studies in the past contain only the morbidity rates and qualitative description of stress factors (Feldman et al., 1987; Habes and Putz-Anderson, 1985; Masear et al., 1986). While the quantification of tasks has been limited to the frequency of task cycles, development of methodology to measure more precisely the wrist angles (Schoenmarklin and Marras, 1989) and internal force (Moore and Wells, 1989), and angular velocity and acceleration at the wrist (Marras and Schoenmarklin, 1991) have been reported.

In a semi-quantitative scheme, Silverstein et al. (1986b) used a dichotomy of high/low force and high/low frequency, in which "high force jobs were those with estimated average hand force requirements of more than 4 kg and low force jobs were those with...below 1 kg; and high repetitive jobs were those with a cycle time of less than 30 seconds or more than 50% of the cycle time involved performing the same type of fundamental cycles". Wrist deviations were not measured. As shown in figure 5, if these criteria are transposed onto figure 3, it will divide the plane into five sections by combination of force (F) and repetition (R); *LoF-LoR*, *LoF-HiR*, *HiF-LoR*, and *HiF-HiR* (and the area of intermediate force

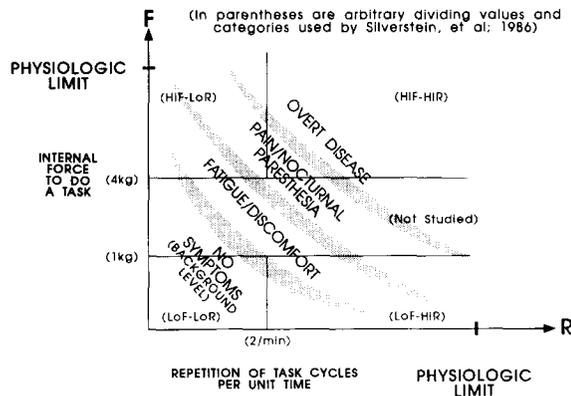


Fig. 5. The epidemiologic criteria for the frequency and force of manual works used by Silverstein et al. (1986) are superimposed on figure 3, suggesting that their results and equation (1) are compatible in two-dimensional presentation (assuming that the wrist angles were not measured or involved).

which was not studied). These authors reported that the *HiF-HiR* group had odds ratios of 5 to 30 for hand/wrist CTDs compared to the *LoF-LoR* group; the *HiF-LoR* and *LoF-HiR* groups had lower but still elevated odds ratios. As seen in figure 5, these data appear to support the notion that the product of force times repetition may remain rather constant and must be below a certain limit to prevent CTS, and that the threshold line would probably be concave. If studies similar to those by Silverstein and her colleagues were conducted among other various manually repetitive jobs and their data plotted on the common chart, eventually a threshold plane would emerge, which might serve as guidelines for prevention of work-related CTS.

In actual industrial jobs, even the same task may be performed somewhat differently by each individual worker. This individual difference may be visualized as a cluster of small spheres as shown in figure 4. Each sphere represents the data from a single worker's average force, frequency and wrist angles in the task. As a group, their mean force, frequency and wrist angles can be calculated with standard deviations. Then, the group data can be presented as statistical means and standard deviations, and plotted on the chart with notations about the group's incidence rate of CTS symptoms. As shown in figure 4, if individuals having pain or other CTS symptoms are represented by dotted spheres (positive) and those

without symptoms by blank spheres (negative), it is very likely that there will be more dotted spheres in the concave side of the threshold plane (toward increasing repetition, force, or wrist angles), and more blank spheres in the opposite side. After conducting many such surveys using standardized methods, a threshold plane would emerge among these data points. Combined with the data from laboratory experiments, it might also become possible to determine the coefficients of various factors (α , β and γ) for equation (1). More dynamically, measurement of angular velocity and acceleration in flexion/extension at the wrist was reported to be the best predictor of CTD risk (Marras and Schoenmarklin, 1992).

Industrial ergonomic surveys may include both cross-sectional comparisons of groups of workers performing different tasks, and a longitudinal comparison of the same worker group for "before and after" any change in production methods or ergonomic intervention. Frequently, workers start having symptoms of the hand/wrist after the workload is increased; for example, speeding up the production line. In such a case, ergonomic stress factors prior to the change can be assessed in simulation, which will show that the data points have shifted toward the more stressful direction; namely, higher above the concave side of the threshold plane. At the same time, hand/wrist morbidity which can be assessed by a questionnaire survey, physical examinations, or a review of medical and worker's compensation records, will document a higher incidence rate of regional morbidity in the group with a higher degree of musculoskeletal stress.

Similarly, when an intervention program is implemented, it will provide an opportunity to conduct an ergonomic survey on the same group of workers several months after such implementation. The data points are likely to move toward the direction of less stress and the incidence rate of workers with hand/wrist morbidity is likely to have decreased. The effectiveness of ergonomic intervention programs has been reported (Tichauer and Gage, 1977; McKenzie et al., 1985; McGlothlin, 1988). With the availability of the high-performance microcomputers, quantitative assessment of the stress factors and ergonomic improvements in manual jobs have become feasible (Marras and Schoenmarklin, 1992).

It must be cautioned that once the median nerve has been damaged permanently and/or the tendo-synovial pathology has progressed to a chronic stage, a complete recovery may not be achieved. This, however, should not be considered as a failure of intervention. Rather, it would further emphasize the importance of preventing the pathological process from progressing to the chronic and irreversible stage. A longitudinal follow-up study of newly assigned workers may show that they would present much less morbidity under improved working conditions.

Even if there are no comparison groups available, or no intervention measures implemented, the ergonomic and morbidity survey data, if collected using a standard method, still need to be reported and plotted on the common chart, since they are representing various working conditions involving the hand/wrist. Likewise, negative survey results with low exposure indices and low symptom rates should also be reported, since they would be helpful in defining the lower border of the threshold plane.

Additional factors

In the foregoing discussions we have limited our attention to the three primary stress factors of hand/wrist work; internal force, repetition and wrist angles. Such restriction was justified not only for the sake of simplicity but also due to the fact that they are universally present in any work situations involving the hand/wrist. However, other variables have been suggested or shown to be influential in the development of hand/wrist CTDs. Let us examine whether or not, and how, equation (1) can address these other factors.

(i) *Worker variables (gender, body size, etc.)*. The available data for the effect of gender on CTDs are conflicting. Women are reported to be at a higher risk of developing hand/wrist CTDs than men (Armstrong, 1982). This may be attributed to the anatomical difference of the carpal tunnel size (Bleeker et al. 1985) or the diameter of the "anatomical pulley" (Chaffin and Andersson, 1984), or endocrine factors which are likely to cause fluid retention (Cannon et al., 1981). Also, there is a social factor that more women may be employed in jobs requiring repetitive

manual tasks. Silverstein et al. (1987) presented epidemiologic data showing that there are no significant differences in the rate of CTDs between male and female workers performing similar tasks. Since the work force is made up of workers of both genders and varying size, the guidelines should be set to protect the workers regardless of their age, sex or body size.

(ii) *Task variables*. In addition to the three key variables (force, repetition and wrist angles) which are always present in any manual task, there are incidental risk factors imposed by the nature of work or working environment. These include use of vibrating tools, use of gloves, cold exposure, and pinch grip (with the finger tips).

Use of vibratory tools has been shown to be associated with the development of CTS (Cannon et al., 1981). However, Chatterjee et al. (1982) reported that among the CTS cases exposed to vibration, the nerve conduction velocity (NCV) of the median nerve was slowed across the affected wrist, while NCV of the ulnar nerve was not. This difference can be explained by the fact that the median nerve was entrapped within the carpal tunnel, while the ulnar nerve which does not run inside the carpal tunnel was not affected. If the vibration was directly harmful to the local nerves, then NCV of the ulnar as well as the median nerve would have been slowed.

Rather, it could be explained that, in doing a similar task, a greater flexor muscular force must be exerted to do the task using a vibrating hand tool than using a non-vibrating tool of the same size and weight (Armstrong et al., 1987). This notion has been confirmed by electromyographic measurements taken while using vibrating tools (Baumgartner and Krueger, 1984; Norlander and Wos, 1990). Therefore, although the use of vibrating hand tool is an important contributing risk factor for CTS and the control of vibration is very important for prevention of CTS, it can be deduced that vibration *by itself* would not likely cause CTS. Thus, inclusion of the vibration factor into the force factor, rather than adding a separate factor in equation (1), would help to keep the quantitative model simple.

A similar logic could be applied to other task-specific CTS risk factors such as exposure to cold temperature, use of gloves or pinch grip (Silverstein et al., 1986a). Assuming all other task fac-

tors (including repetition rate and wrist angles) are equal in equation (1), it could be hypothesized that addition of vibration, cold, or use of gloves or pinch grip would necessitate workers to exert more force on the hand and fingers to do the same task. Thus, it can be stated that equation (1) will be able to absorb these incidental risk factors into the force factor without additional terms. Again, well-controlled measurements of the force factor with and without gloves (or cold, pinch grip, etc.) would be useful in determining the role of these variables.

(iii) *Time factor.* Time factor in performing repetitive tasks is very complex and is not currently included in equation (1). This issue relates to the question of cumulative dose-over-time effect of repetitive stress injury to the tendon-sheath complex and its recovery process. Equation (1) would be established fairly easily, if all of the repetitive works were spread evenly over an 8-hour work shift. However, work schedule may vary considerably from place to place. For example, which work schedule of the following would be most hazardous to the hand; a repetitive task performed 6,000 times evenly spread over 8 hours; performed 6,000 times over 2 hours but no stress in the remaining 6 hours, or performed 2,000 times in each of three 2-hour periods with 1 hour rest inserted in between?

Konz (1990) addresses the time factor in several ways: (1) the rest/work ratio which can be calculated over a 24-hour period or over an 8-hour working period; (2) a provision for various allowances either as a percent of the worktime or as a percent of the shift time; and (3) applying penalty multipliers against continuous work.

Arndt (1987) demonstrated electromyographically that, when the same task was performed at a faster pace (as in the case of machine pacing or incentive pay), the required internal force to do the task increased simultaneously. In other words, according to Newton's second law, it is unavoidable that a worker performing a manual task faster is unintentionally exerting more internal force in the hand(s) than a worker performing at a slower pace. This observation suggests that increase in repetition per unit time would not only move the data points to the right in figure 3, but also to the higher force area, subjecting workers to a disproportionately higher risk of developing

CTDs. Similarly, Schoenmarklin and Marras (1991) reported that there is a three-dimensional relationship among wrist extension angle, angular acceleration and the reaction force against a flexor tendon (from the adjacent tissue).

In the NIOSH Work Practices Guide for Manual Lifting (1981), this question is addressed by providing a table for "maximum frequency of lifting which can be sustained for 1 hour and 8 hour periods". Whether or not a similar scheme would be applicable to hand/wrist repetitive work remains to be determined by further investigations.

(iv) *Psychosocial factors.* These would include management style, labor relations, job satisfaction, and so forth, and are suggested to be part of the overall CTD problem (Kiesler and Finholt, 1988). Are workers who are tense for some reason at higher risk of developing CTS? Given two similar situations of manual work in terms of force, repetition and wrist angles, if one group of workers had a higher hand/wrist morbidity than another, an evaluation of psychosocial factors may reveal some differences between these two groups. Therefore, equation (1) might be used to tease out intricate risk factors of CTS.

The interaction of the above and perhaps other factors related to the etiology of hand/wrist CTDs appears very complex. The proposed model is not intended to present the exact mechanism of how the hand, wrist and their tenosynovium behave under biomechanical stress. Much more research is needed to elucidate the biodynamics of such a process. However, to protect workers and to stem the ever-increasing tide of work-related CTS, it is justifiable to start a process of guideline development with reasonable assumptions and hypothesis generation. This heuristic model is presented with an intent to stimulate additional research for generation of quantitative guidelines to prevent work-related CTS.

Applications

"Effectiveness of ergonomic intervention is being accepted, in large part, on faith" (Silverstein, 1987). This is probably the result of, at least partly, the fact that there are currently no quantitative guidelines for repetitive manual work.

When Silverstein et al. published a series of epidemiologic-ergonomic studies (1986–87) using such criteria as “cycle time of 30 seconds or less” and “muscular force of 4 kg or more”, some people quickly accepted these as a “safety standard” (which was not intended by these investigators). Indeed, workers performing tasks with stress levels below these values experienced CTDs of the upper extremity much less frequently than those who were performing above these values. However, it is clear from the foregoing and figure 5 that the “twice a minute and 4 kg” criterion is only one specific situation in equation (1), and there can be many other combinations and the wrist angle factor needs to be considered.

Once validated, the quantitative model would be a convenient tool when one tries to explain or evaluate the effectiveness of intervention strategies; i.e., reduction of force, repetition and/or wrist angles. Comparison of measurements on these risk factors taken before and after intervention might be able to show the improvements quantitatively. Similarly, when a hand/wrist problem is reported among workers, the three risk factors of the on-going manual tasks should be assessed. It is likely that the product of these 3 factors is above the threshold plane, pointing to the need for improvement by reducing one or more of the factors.

In the future, it may be even possible to prepare a table of internal forces required to do various manual tasks (analogous to the table of caloric requirements in doing various activities). Such an approximation might allow us to do away with on-site industrial EMG measurements.

Conclusions

A conceptual mathematical model is presented as a method toward establishing quantitative guidelines for prevention of work-related wrist tenosynovitis and carpal tunnel syndrome (CTS). It is based on the concept that the product of three basic stress factors of manual work (internal force, repetition and wrist angles) must be below a certain value for prevention of these disorders.

Researchers in biomechanics and ergonomics are urged to conduct laboratory and field mea-

surements using standardized methodologies, so that the data may be pooled in a common chart for the purposes of finding the population-based threshold and establishing quantitative guidelines for prevention of work-related CTS.

The authors emphasize that the proposed model is not being advanced as a panacea to solve all the complex problems of CTS. Rather, the conceptual model is proposed as a heuristic model to be tested, validated, or modified. Nonetheless, the authors believe and hope that the model would serve as a useful guidepost for the advancement of etiologic research and prevention strategies of work-related CTS.

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