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Rapid Communication

Wrist motions in industry

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Cumulative trauma disorders (CTDs) are disorders of the body's tendons and nerves due to repeated exertions and excessive movements. Workers in industrial tasks who have to move their hands and wrists repeatedly and/or forcefully are susceptible to CTDs. One of the major research voids in the study of occupational wrist CTDs is the lack of quantification of the relationship between the known kinematic risk factors, such as wrist angle and repetition, and CTD risk. A quantitative surveillance study was performed in industry in which workers' three-dimensional wrist motions were monitored on the factory floor. A total of 40 subjects from eight industrial plants participated in this study (20 workers in each of two risk groups, low and high). The wrist motion parameters that were monitored for each subject were position, angular velocity, and angular acceleration measures in each plane of movement (radial/ulnar, flexion/extension, and pronation/supination). Descriptive analyses of these measures indicated that generally the mean of the high-risk subjects was larger in magnitude than that of their low-risk counterparts. However, only the velocity and acceleration parameters resulted in significant differences between low- and high-risk groups. These results demonstrate the importance of dynamic components in assessing CTD risk.

1. Introduction

Cumulative trauma disorders (CTDs) are disorders of the soft tissues (most frequently the tendons and nerves) due to repeated exertions and excessive movements of the body (Armstrong 1986). In this document, the term CTDs will refer to only CTDs of the wrist. It has been shown that workers in industrial tasks who move their hands and wrists repeated and/or forcefully are susceptible to CTDs (Silverstein *et al.* 1986, 1987). Some specific CTDs of the hand and wrist are carpal tunnel syndrome (CTDs), tenosynovitis, tendinitis, and De Quervain's disease.

Repetitive movements of the hand and wrist in industrial tasks are known to be an important risk factor associated with CTDs (Armstrong 1986, Silverstein *et al.* 1986). Although wrist posture and repetition have been cited often as a risk factor for CTDs overall, few researchers have quantitatively investigated the issue of 'how much' and 'what type' of wrist deviation and motion increases the risk of CTDs (Armstrong *et al.* 1982, Silverstein *et al.* 1986, Silverstein *et al.* 1987). A major research impediment to further knowledge development in the study of occupational wrist CTDs is that we have been unable to quantify wrist motions and thus have been unable to explore the relationship between kinematic risk factors, such as wrist angle and repetition, and CTD risk. Therefore, the objective of this research was to *quantify* what type and how much wrist motion can be expected in industrial jobs overall and jobs of high and low CTD risk.

2. Methods

2.1. *Approach*

The approach in this study was to collect wrist motion data from industrial workers on the factory floor. Industrial plants in the Midwest that required highly repetitious, hand-intensive work were selected as sites for data collection. Dichotomous CTD risk levels (low and high) of repetitive jobs in the participating plants were determined by US Occupational Safety and Health Administration (OSHA) 200 logs. Wrist motions of workers in these high- and low-risk jobs were monitored on the factory floor while they were performing their tasks in a normal manner. Wrist motion data were analysed as a function of CTD risk level in order to establish quantitative guidelines or 'benchmarks' for industry to utilize.

2.2. *Subjects*

A total of 40 industrial workers volunteered to participate in this study (range 25–62 years). The gender distribution of subjects within each risk group was identical in that there were 11 men and nine women in each of the low- and high-risk groups. All the workers in the high-risk group were right-handed, and 19 of the 20 subjects in the low-risk group were right-handed. Although a few of the subjects did have previous CTD injuries, all of the subjects were healthy and free of injury at the time their wrist motion was monitored.

The subjects in the low-risk group were significantly older than their counterparts in the high-risk group (46·9 vs 36·6 years). The low-risk employees also worked about twice as many years for their respective companies than the workers in the high-risk group (20·0 vs 10·9 years). The older age and longer tenure of the low-risk workers is probably partially due to the seniority systems at the plants. In most of the eight participating companies, the management and union worked out a structured job selection system in which workers could select their jobs based on seniority. Workers with more seniority had the opportunity to bid for less strenuous jobs.

2.3. *Experimental design*

The independent variable was exposure to CTDs. Exposure had two nominal levels, jobs that had low and high-risk of CTDs. Risk of CTDs was determined from evaluation of OSHA 200 logs and medical records in participating companes. In high-risk jobs, the median incidence rate and average lost days count were 18·4 reported claims and 111·5 days per 200 000 worker-hours of exposure, respectively. By definition, all the low-risk jobs had an incidence rate and lost days count of zero. Two industrial workers from each of 10 jobs were monitored in each risk group.

The dependent variables were the following wrist motion variables in the radial/ulnar (R/U), flexion/extension (F/E), and pronation/supination (P/S) planes:

1. mean, minimum, maximum, and range* of wrist angle;
2. mean, minimum, maximum, and maximum difference** of angular velocity;
3. mean, minimum, maximum, and maximum difference** of angular acceleration.

* range = maximum—minimum

** maximum difference = maximum—minimum

2.4. *Apparatus*

Goniometric instrumentation was used to collect wrist motion data in the R/U, F/E, and P/S planes. A wrist monitor was developed in the Biodynamics Laboratory at Ohio State University to collect on-line data on wrist angle in R/U and F/E planes simultaneously, and further analysis of wrist angle data yielded velocity and acceleration in both planes of motion. The design of the wrist monitor is proprietary, so its description is brief. The wrist monitor was composed of two segments of thin metal that were joined by a rotary potentiometer. The potentiometer measured the angle between the two metal segments. The potentiometers were taped to the centre of the wrist in the R/U and F/E planes. This wrist monitor was small, light (approximately 0·05 kg), recorded R/U and F/E angles independently, and did not have to be calibrated extensively for each subject.

The P/S device recorded the P/S angle of the forearm. The P/S device consisted of a rod that remained parallel to the forearm during rotation. The rod was attached to a bracket affixed to the proximal end of the forearm with a Velcro cuff. The rod did not rotate with respect to the proximal cuff. On the distal end of the forearm, the rod was connected to a potentiometer that was attached to a bracket. As the forearm rotated, the potentiometer rotated with respect to the fixed rod, and voltages from the potentiometer recorded the angular displacement of the forearm. The R/U, F/E, and P/S voltages were monitored at 300 Hz.

2.5. *Integrated data collection system*

The goniometers were combined with customized data collection software into a portable, self-contained system. Figure 1 shows a schematic of the flow of data. Six channels of wrist motion were monitored directly on the factory floor, and these voltages were transmitted to a 12 bit analogue-to-digital (A/D) converter board. The six channels comprised R/U, F/E, and P/S motion of both upper extremities.

The data from all eight channels were stored on a portable 386 microcomputer and analysed later in the laboratory. In the laboratory, the wrist motion voltages were converted into R/U, F/E, and P/S angles by regression equations, and the position, velocity, and acceleration were calculated using a Laplace transform (Marras and Schoenmarklin 1991).

The summary statistics (mean, maximum, minimum, and range/maximum difference) of the position, velocity, and acceleration were computed for each interval within all the data trials. These summary statistics were transmitted to a mainframe computer and were analysed by statistical software. In order to remove handedness from the dataset, only the kinematic data from the affected hand were analysed. The affected hand in high-risk jobs was the hand of injury, and the affected hand in low-risk jobs was the hand of dominant motion.

2.6. *Selection of participating companies and jobs*

Eight manufacturers in the Midwest volunteered to participate in this study. All of these companies' manufacturing operations required repetitive, hand-intensive work, and most of these companies manufactured products for the transportation industry. The monitored jobs required handling of lightweight parts and required minimal use of handtools. The average weight of handled parts was 1·38 and 0·87 kg for the high-risk and low-risk jobs, respectively (no significant difference). The type

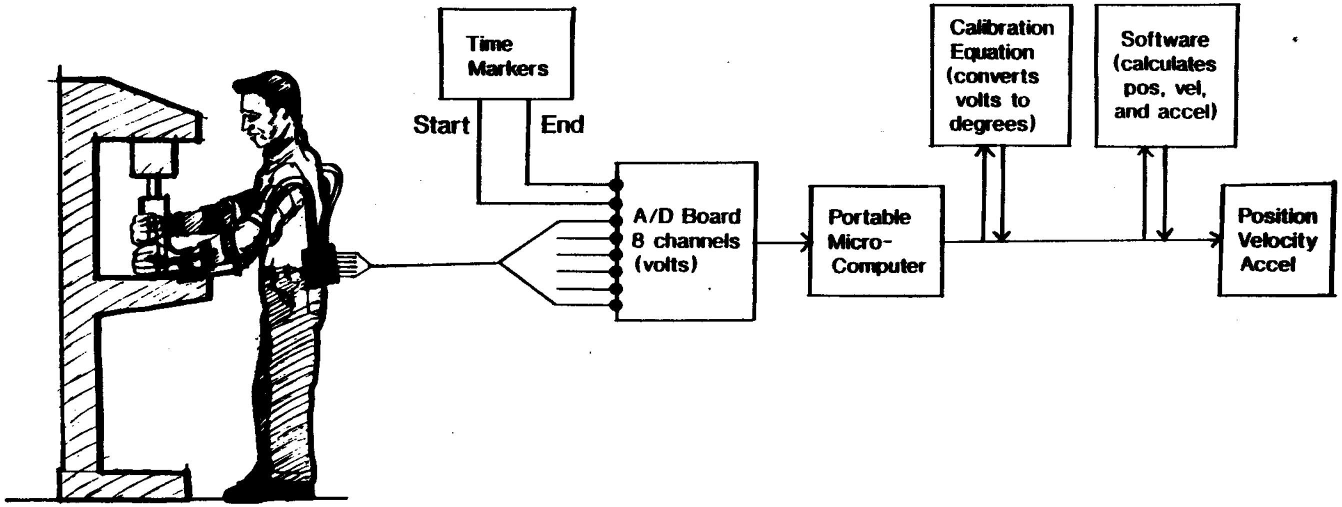


Figure 1. Integrated data collection system consisting of hardware and software that monitor wrist motion on the factory floor and process the data in the laboratory.

of manufacturing operation and the number of jobs and subjects who were monitored at the plants are listed in table 1.

Table 1. Type of manufacturing operation and number of jobs and subjects whose wrist motion was monitored.

Type of mfg operation in participating companies	High risk		Low risk	
	Jobs	Subj	Jobs	Subj
Automotive suspension parts and assembly	2	3	3	6
Automotive engine parts and assembly	2	4	2	4
Automotive brake parts and assembly	1	2	1	2
Automobile final assembly	2	4	0	0
Truck parts assembly	0	0	2	4
Plastic injection molding	1	2	1	2
Commercial building products	1	3	1	2
Vehicle seating and upholstery assembly	1	2	0	0
	10	20	10	20

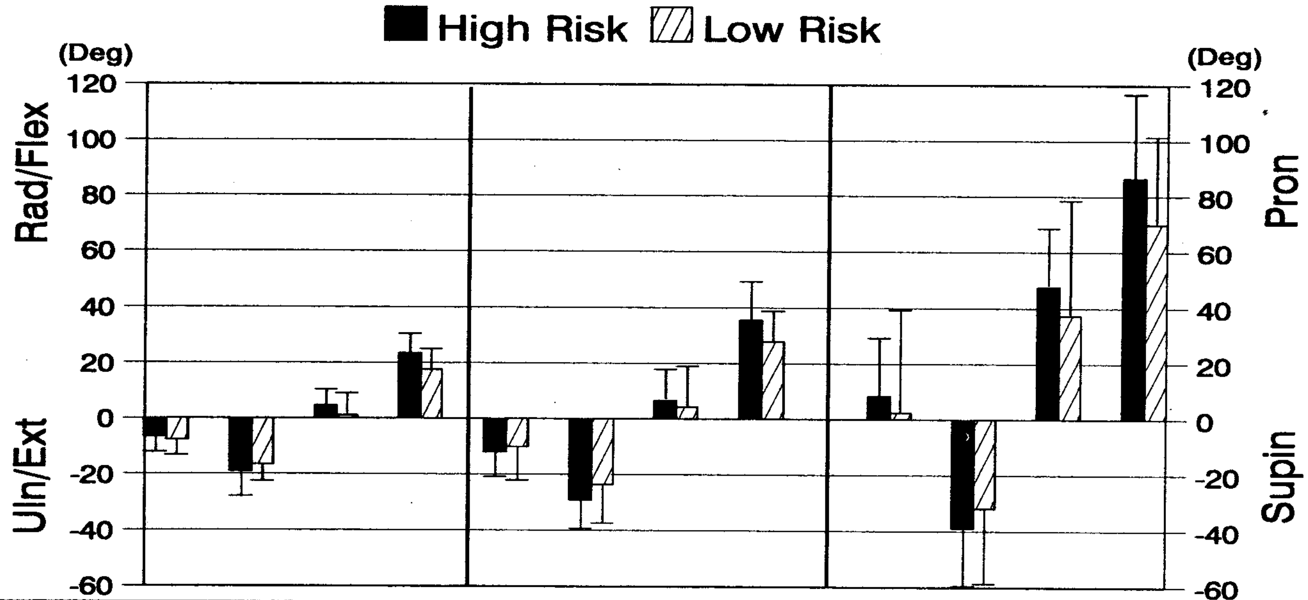
The jobs within the eight plants were selected based on number of wrist movements and risk of CTDs. The minimum acceptable number of wrist movements was 13 000 fundamental wrist movements (Barnes 1981) during an 8 h shift, which represents one fundamental wrist movement approximately every 2 s. There was no significant difference between the number of fundamental wrist movements in the low- and high-risk jobs. The average (and standard deviation) number of wrist movements was 24 738 (10 432) and 26 132 (15 259) for high- and low-risk jobs, respectively. In all the monitored jobs, the workers were paid a straight hourly salary and were not on an incentive pay system.

2.7. *Experimental protocol*

Once the goniometers were positioned and calibrated, a brief task analysis of the subject's job was performed to identify the work cycles. The subject was asked to perform his job while wrist motion data were collected. A minimum of ten trials were collected from each subject. Schmitt triggers identified the work cycle during data collection. The number and distribution of work intervals were time-weighted in order to represent the percentage of time that each subject spent in each phase of his job. During data collection, the subject performed his job as he normally would (the job was not simulated). Every attempt was made to minimize any possible interference with the job.

3. Results

The overall summary statistics of wrist motion as a function of CTD risk groups are shown in figures 2 through 4. Within each bar chart, the mean, minimum, maximum, and maximum difference were plotted as a function of risk level. The maximum difference was the maximum minus the minimum.



	mean	min	max	range@	mean	min	max	range	mean	min	max	range
High Risk Mean	-6.73	-18.96	4.69	23.65	-12.02	-29.08	6.56	35.63	8.3	-38.93	47.7	86.63
High Risk S.D.	4.66	5.78	4.76	6.71	7.16	7.32	11.11	11.53	20.5	23.4	19.48	25.47
Low Risk Mean	-7.62	-16.51	1.12	17.64	-10.09	-23.58	4.35	27.95	2.47	-31.84	37.36	69.91
Low Risk S.D.	4.42	5.57	6.17	7.53	11.88	13.12	12.36	9.92	38.63	38.76	38.69	29.55
	Radial/Ulnar				Flex/Ext				Pron/Supin			

@ = sig. at 0.05 level

Figure 2. Mean and standard deviation values of wrist *position* in the radial/ulnar, flexion/extension, and pronation/supination planes as a function of CTD risk level. Each bar's height represents the mean of twenty subjects' data.

The pictorial trend across all the position, velocity, and acceleration values in figures 2 through 4 is that the mean high-risk values were generally greater in absolute magnitude than the mean low-risk values. Moreover, the velocity and acceleration measures appeared to separate CTD risk levels more distinctly than position measures. The percentage increase of the high-risk position values were about 20% to 30% greater than low-risk values with a mean of 28·1%. As groups, the velocity and acceleration variables showed increases in high-risk levels of 46·2% and 67·1%, respectively, over the low-risk values.

Individual analyses of variance (ANOVAs) were performed on the effect of CTD risk on each dependent variable. The statistical results of the ANOVAs are shown in table 2. For each significant *t*-test, the high-risk value was greater than the low-risk value. The overall pattern of table 2 shows that the mean, minimum, maximum, and difference values of velocity and acceleration significantly discriminated between low- and high-risk groups, whereas only one position variable significantly discriminated between risk levels.

4. Discussion

The kinematic investigation in this study is a follow-up to the work of Silverstein *et al.* (1986, 1987), who provided epidemiological evidence for repetition as a risk factor for CTS and CTDs. These researchers did not investigate the dynamic components that comprise repetition—angular velocity and acceleration. The study summarized in this article was essentially a micro-motion investigation that addressed the follow-up questions to Silverstein *et al.*'s (1986, 1987) studies: 'what type' and 'how much' wrist motion in highly repetitious jobs increased the risk of CTDs?

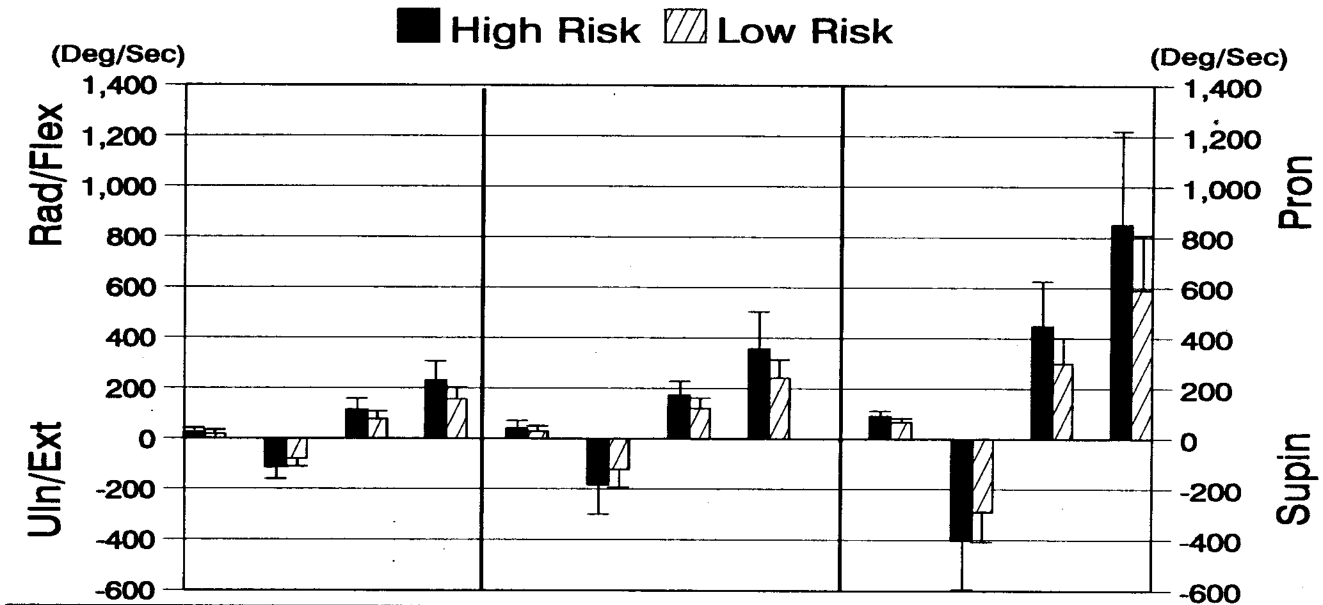
Based on results from this study, the velocity and acceleration variables significantly differentiated CTD risk levels, whereas wrist position variables as a group did not (refer to table 2). These results demonstrate the importance of dynamic components in assessing CTD risk.

Table 2. Probability of type I error from analysis of variance of motion variables. The effect tested was risk of CTDs (degree of freedom = 1).

	AVG	MIN	MAX	DIFF
R/U Pos	0·5995	0·2781	0·0920	0·0429*
F/E Pos	0·5644	0·1821	0·5560	0·0666
P/S Pos	0·6279	0·5761	0·3658	0·1267
R/U Vel	0·0016*	0·0148*	0·0074*	0·0081*
F/E Vel	0·0014*	0·0099*	0·0104*	0·0085*
P/S Vel	0·0079*	0·0223*	0·0357*	0·0210*
R/U Accel	0·0005*	0·0040*	0·0018*	0·0024*
F/E Accel	0·0008*	0·0006*	0·0003*	0·0004*
P/S Accel	0·0018*	0·0073*	0·0112*	0·0080*

* = significant at the 0·05 level
R/U = radial/ulnar; F/E = flexion/extension; P/S = pronation/supination
AVG = mean; MIN = minimum; MAX = maximum;
DIFF = maximum difference = MAX–MIN.

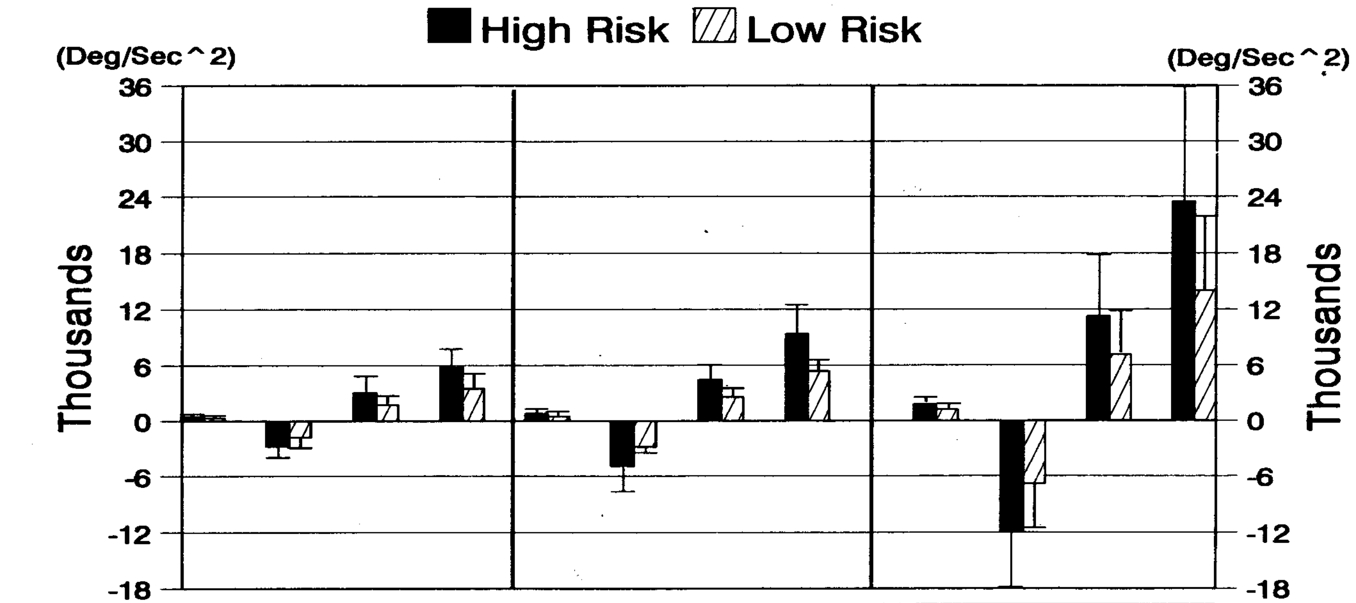
The dynamic aspects of wrist movement are important in the etiology of CTDs



	Radial/Ulnar Mean@*	Radial/Ulnar Min@	Radial/Ulnar Max@	Radial/Ulnar Diff@	Flex/Ext Mean@*	Flex/Ext Min@	Flex/Ext Max@	Flex/Ext Diff@	Pron/Supin Mean@*	Pron/Supin Min@	Pron/Supin Max@	Pron/Supin Diff@
High Risk Mean	25.9	-115.1	115.7	230.8	42.2	-183.7	174.2	358	91.3	-403.2	449.2	852
High Risk S.D.	6.7	36.5	39.5	71.9	11.7	76.8	58.4	128.5	23.3	149.1	256.2	394.6
Low Risk Mean	17	-79.3	77.3	156.6	28.7	-121.2	120.3	241.5	67.7	-289.9	300.2	590.5
Low Risk S.D.	6.7	34.9	31.1	63.4	7.6	42.8	38.1	78.2	19.5	112	129	211.2

@ = sig. at 0.05 level * = Mean ABS(Vel)

Figure 3. Mean and standard deviation values of wrist *velocity* in the radial/ulnar, flexion/extension, and pronation/supination planes as a functon of CTD risk level. Each bar's height represents the mean of twenty subjects' data.



	Radial/Ulnar Mean@*	Min@	Max@	Diff@	Flex/Ext Mean@*	Min@	Max@	Diff@	Pron/Supin Mean@*	Min@	Max@	Diff@
High Risk Mean	494	-2,776	3,077	5,853	824	-4,927	4,471	9,398	1,824	-11,987	11,291	23,490
High Risk S.D.	142	913	1,313	2,176	268	1,913	1,527	3,388	533	6,330	4,954	11,483
Low Risk Mean	301	-1,755	1,759	3,518	494	-2,788	2,588	5,377	1,222	-6,811	7,169	14,000
Low Risk S.D.	125	818	834	1,641	156	862	802	1,630	384	2,571	2,980	5,545

@ = sig. at 0.05 level * = Mean ABS(Accel)

Figure 4. Mean and standard deviation values of wrist *acceleration* in the radial/ulnar, flexion/extension, and pronation/supination planes as a function of CTD risk level. Each bar's height represents the mean of 20 subjects' data.

because tendon force, which is a risk factor of CTDs, is affected by wrist acceleration. The association between acceleration and CTD risk can be explained biomechanically by Newton's second law, force = mass × acceleration, and friction. In order to accelerate the wrist, the extrinsic muscles in the forearm have to exert force which is transmitted to the tendons. Some of the force transmitted through the tendon is lost to friction against the ligaments and bones that form the carpal tunnel. This frictional force could irritate the tendons' synovial membranes and cause 'synovitis', the thickening of the synovial membrane (Armstrong 1983). Irritation could precipitate tendon inflammation, which could result in tenosynovitis and/or CTS through compression of the median nerve. In a histological investigation of tendon sheaths, Armstrong *et al.* (1984) found sizeable increases in synovial hyperplasia and synovium density in the carpal tunnel area, which they attributed to repeated F/E exertions.

Tanaka and McGlothlin (1989) hypothesized that the friction between tendons and adjacent structures is a major cause of CTDs, and Moore *et al.* (1991) showed that the frictional work generated in the carpal tunnel supported Silverstein *et al.*'s (1986, 1987) dose–response relationship between repetition and CTD risk.

The literature on biomechanical modelling of the wrist also supports the association between wrist dynamics and CTD risk. In a biomechanical model of the wrist joint, Schoenmarklin and Marras (1990) demonstrated that wrist acceleration dramatically increases the resultant reaction force on the tendons passing through the carpal tunnel. The resultant reaction force on the tendons from acceleration could degenerate and inflame the tendons, thereby causing tenosynovitis, or compress the median nerve between the carpal ligament and tendons, which could cause CTS.

5. Conclusions

The methodology and technique described in this article provided the wherewithal for an industrial surveillance study that addressed one of the major research voids in occupational wrist CTDs. This research void is the lack of quantification of the relationship between the risk factors of wrist angle and repetition and CTD incidence rate. The objective of this industrial surveillance study was to determine *quantitatively* the association between specific wrist motion parameters and the incidence of CTDs as a group. In this study, wrist motion of workers who performed highly repetitive, hand-intensive jobs was monitored by goniometers on the factory floor.

The dynamic measures of wrist motion, angular velocity and acceleration, significantly differentiated CTD risk levels in all three planes, whereas wrist position measures did not. The findings in this study emphasize the importance of dynamic measures in the ergonomic assessment of jobs.

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References

ARMSTRONG, T. J. 1983, An ergonomics guide to carpal tunnel syndrome, *Ergonomics Guides* (American Industrial Hygiene Association).

Armstrong, T. J. 1986, Ergonomics and cumulative trauma disorders, *Hand Clinics*, **2**, 553–565.

Armstrong, T. J., Foulke, J. A., Joseph, B. S. and Goldstein, S. A. 1982, Investigation of cumulative trauma disorders in a poultry processing plant, *American Industrial Hygiene Association Journal*, **43**, 103–116.

Armstrong, T.J., Castelli, W.A., Evans, F.G. and Diaz-Perez, R. D. 1984, Some histological changes in carpal tunnel contents and their biomechanical implications, *Journal of Occupational Medicine*, **26**, 197–201.

Barnes, R. M. 1981, *Motion and Time Study* (John Wiley, New York).

Marras, W. S. and Schoenmarklin, R. W. 1991, Quantification of wrist motion in highly repetitive, hand-intensive industrial jobs. Final Report. Grant nos. 1 R01 OH02621-01 and 02 funded by the US National Institute for Occupational Safety and Health (NIOSH).

Moore, A., Wells, R. and Ranney, D. 1991, Quantifying exposure in occupational manual tasks with cumulative trauma disorder potential, *Ergonomics*, **34**, 1433–1453.

Schoenmarklin, R. W. and Marras, W. S. 1990, A dynamic biomechanical model of the wrist joint, in *Proceedings of the 34th meeting of the Human Factors Society*, Orlando, FL, 805–809.

Silverstein, B. A., Fine, L. J. and Armstrong, T. J. 1986, Hand-wrist cumulative trauma disorders in industry, *British Journal of Industrial Medicine*, **43**, 779–784.

Silverstein, B. A., Fine, L. J. and Armstrong, T. J. 1987, Occupational factors and carpal tunnel syndrome, *American Journal of Industrial Medicine*, **11**, 343–358.

Tanaka, S. and McGlothlin, J. D. 1989, A conceptual model to assess musculoskeletal stress of manual work for establishment of quantitative guidelines to prevent hand and wrist cumulative trauma disorders (CTDs), in A Mital (ed.) *Advances in Industrial Ergonomics and Safety I* (Taylor & Francis, London), 419–425.

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