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Quantification of Wrist Motion in Highly Repetitive, Hand-Intensive Industrial Jobs

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16. Abstract (Limit: 200 words) A study was conducted to investigate the effects of wrist motion components on risk of hand/wrist cumulative trauma disorders (CTDs) in an industrial environment. A quantitative surveillance study was performed in industry in which workers' wrist motion was monitored on the factory floor. A total of 40 subjects from eight industrial sites participated in the study. The wrist motion parameters that were monitored on each subject were static (position), and dynamic (velocity and acceleration measures in each plane of movement radial/ulnar, flexion/extension, and pronation/supination). The major findings of the study were that wrist position parameters were limited in predicting CTD risk; that there were significant differences between CTD risk levels for all angular velocity and acceleration parameters in all three planes of wrist movement; that the best predictor of CTD risk was flexion/extension average acceleration; that the second best predictor of CTD risk was flexion/extension average velocity; and that there is a need for further research on the dynamic components of wrist motion in order to effectively use quantitative measures of wrist motion to prevent CTDs in industry.

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II

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES (continued) PAGE

LIST OF TABLES

TABLES (continued) PAGE

SIGNIFICANT FINDINGS

The purpose of this study was to investigate the effects of wrist motion components on risk of hand/wrist cumulative trauma disorders (CTDs) in an industrial environment. The major conclusions of this study are:

1. Wrist position parameters were limited in predicting CTD risk.

2. There were significant differences between CTD risk levels for all angular velocity and acceleration parameters in all three planes of wrist movement.

3. The best predictor of CTD risk was flexion/extension average acceleration.

4. The second best predictor of CTD risk was flexion/extension average velocity.

5. There is a need for further research in dynamic components of wrist motion in order to effectively use quantitative measures of wrist motion to prevent CTDs in industry.

QUANTIFICATION OF WRIST MOTION IN HIGHLY REPETITIVE, HAND-INTENSIVE INDUSTRIAL JOBS

by

William S. Marras, Ph.D.
Richard W. Schoenmarklin, M.S.

ABSTRACT

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' wrist motion was monitored on the factory floor. A total of forty subjects from eight industrial plants participated in this study (twenty workers in each of two risk groups, low and high). The wrist motion parameters that were monitored on each subject were static (position) and dynamic (velocity and acceleration) measures in each plane of movement (radial/ulnar, flexion/extension, and pronation/supination).

Of all the kinematic parameters measured, statistical analysis of the motion data revealed that acceleration in the flexion/extension (F/E) plane discriminated the best between low and high risk groups. The epidemiological association between F/E acceleration and CTD risk is compatible with results from empirical studies and theoretical models in the physiologic and biomechanical literature.

The mean acceleration values of high and low CTD risk groups can serve as preliminary, albeit crude, benchmarks to establish injurious and safe levels of wrist motion in industry. Industrial practitioners can use this methodology and these data to enhance ergonomic assessments of jobs and their efforts to prevent CTDs in the workplace.

Chapter I

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, 1986a). In this document, the term CTDs will refer to only the CTDs of the wrist. Workers in industrial tasks who have to move their hands and wrists repeatedly and/or forcefully are susceptible to CTDs. Some specific CTDs of the hand and wrist are carpal tunnel syndrome (CTS), tenosynovitis, tendinitis, and De Quervain's disease.

The incidence of occupational CTDs is growing precipitously. According to the Bureau of Labor Statistics (1990), almost 50% of all reported occupational illnesses in the U.S. that were reported to the Bureau were due to repeated trauma (refer to figure 1). The number of cases reported nationally in 1988 was 115,000. Furthermore, the actual cost of each CTD case ranges from $15,000 to $25,000 (Pinkham, 1988). A very conservative estimate of the total direct and indirect costs of CTDs in the U.S. is at least two billion dollars per year.

Deviated wrist postures and high repetitions of the hand in industrial tasks are known to be important risk factors associated with CTDs (Armstrong, 1986a). One of the

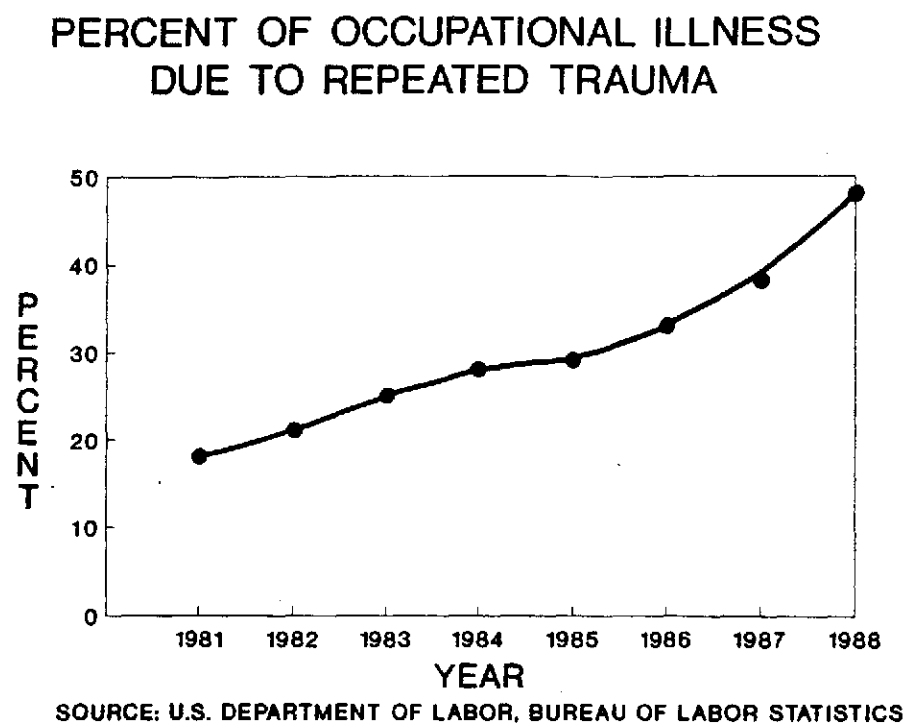


Figure 1. Percentage of occupational illness due to repeated trauma in U.S. as reported to U.S. Department of Labor from 1981 to 1988 (Bureau of Labor Statistics, 1990).

major research voids in the study of occupational wrist CTDs is the lack of quantification of the link between the known kinematic risk factors, such as wrist angle and repetition, and CTD risk.

The objective of this research was to estimate quantitatively the extent to which specific wrist motion parameters were associated with incidence of CTDs as a group. Quantification of the relationship between wrist motion parameters and CTDs can be used to construct preliminary motion benchmarks that can provide insight into injurious and safe levels of wrist motion. In addition, ergonomic practitioners could use these benchmarks to evaluate existing workplaces (tasks and tools) and test the ergonomic impact of alternate work designs. Overall, knowledge of specific wrist motion parameters that are associated with incidence of CTDs would substantially aid practitioners in quantitatively assessing the risk of CTDs in the workplaces and would enhance their efforts in the prevention of CTDs.

Chapter II

LITERATURE REVIEW

Magnitude of CTDs

CTDs can be generally defined by investigating the meaning of each word in the term CTD (Putz-Anderson, 1988). Unlike instantaneous trauma, "cumulative" means that the injury developed gradually over a period of time as a result of repeated stress. "Trauma" means bodily injury from mechanical stress, and "disorder" indicates physical ailments or abnormal conditions.

CTDs appear to be work-related in that they occur more often in working people than the general population (Putz-Anderson, 1988). The overall incidence of CTDs in the industrialized world is unknown, but epidemiological data reveal that CTDs are a growing problem. According to the Bureau of Labor Statistics (1990), industrial injuries due to repeated trauma increased from approximately 20% of all recorded injuries in 1981 to almost 50%, or 115,000 cases, in 1988 (refer to figure 1). Overall, CTDs are the second most frequently reported category of occupational illness after skin disease (Tanaka et al., 1988). Because of the frequency and impact of CTDs on worker health, the National Institute of Occupational Safety and Health (NIOSH) has designated musculoskeletal injuries (including CTDs) as one of the ten leading work-related diseases and injuries (Tanaka et al., 1988).

During the five year period from 1980 through 1984, data from the Ohio Industrial Commission showed that the wrist was affected in almost half of all CTD claims, and 75% of the wrist CTDs cases were "tenosynovitis due to continuous motion" (Tanaka et al., 1988). During the same period, the number of overall CTD cases increased dramatically. This increase was partially due to growing awareness of CTDs among workers, employers, and health professionals (Tanaka et al, 1988).

The incidence rate of CTDs varies according to individual work sites, but reports from some sites suggest that the incidence rate "approaches epidemic proportions and are a major cause of lost work in some settings" (Armstrong, 1986a, p. 553). From three years of data collected in an electronics firm, Hymovich and Lindolm (1966) reported an incidence rate of 6.6 cases per 200,000 work hours. In a poultry processing plant, Armstrong et al. (1982) found an incidence rate of 12.8 cases per 200,000 work hours. In a study of 574 active workers from six different industrial plants, Silverstein et al. (1986) found CTD prevalence rates of 4.2% and 13.6% in male and female workers, respectively. (If 100 employees worked 50 weeks * 40-hour weeks = 200,000 hours, then the incidence rate per 200,000 work hours would equal the prevalence.)

Based on available data from reported cases, CTDs appear to be a major health problem in some industries (Armstrong, 1986a). However, the incidence rates of CTDs are generally underreported, so the total costs to these industries would be even greater. CTDs are underreported for several reasons (Armstrong, 1986a). First, CTDs develop gradually and are difficult to trace to a specific event. Some of the symptoms of CTDs, such as pain, stiffness, and numbness, occur at night and are difficult to trace to occupational causes. Workers may be treated by personal physicians rather than by company physicians. Also, CTDs may be miscategorized and may be omitted from CTD data banks.

Carpal Tunnel Syndrome

A specific CTD that has been receiving much attention in the research community and the general population is carpal tunnel syndrome (CTS). CTS is a disorder that affects the median nerve as it passes through the carpal tunnel at the wrist joint. As illustrated in figure 2, the carpal tunnel is a tunnel formed by the wrist bones on the dorsal side of the wrist and the flexor retinaculum, a strong transverse ligament, on the palmar side. Ten tendons

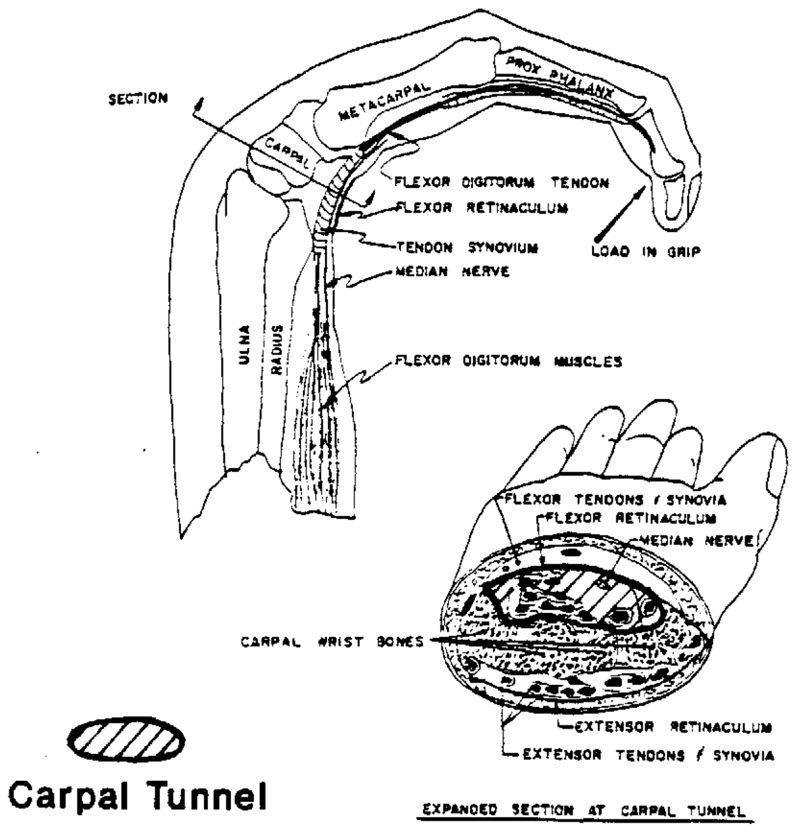


Figure 2. Cross-section of the wrist illustrating the carpal tunnel. The carpal tunnel is formed by the carpal bones on the dorsal side and the flexor retinaculum on the palmar side. Ten tendons (eight flexor digitorum superficialis and profundus, flexor pollicus longus, and flexor carpi radialis) and the median nerve pass through the carpal tunnel. Adapted from Chaffin and Andersson (1984).

transmitting mechanical forces from the extrinsic muscles in the forearm to the hand and digits pass through the carpal tunnel. As the hand and digits are repeatedly moved, the tendons rub against the carpal tunnel structures and each other. Excessive repetition and force could cause excessive lubrication between tendons and their sheaths, which could increase the pressure on the median nerve. Excessive repetition and force could also decrease the natural lubrication and cause tendinous inflammation (Kroemer, 1989). The inflamed tendons will occupy more volume in the carpal tunnel and will impinge upon the median nerve. The inflamed tendons and compressed median nerve could cause motor and sensory decrements, including (Armstrong, 1983):

1) reduced muscle control in the thumb and ultimately thenar muscle atrophy.
2) diminished grip strength and hand clumsiness.
3) numbness, tingling, and pain, particularly during the night.
4) loss of sensory feedback (e.g. many CTS patients cannot distinguish hot from cold).
5) loss of sweat function in areas of hand innervated by median nerve, resulting in reduced ability to grasp and manipulate objects with the hand.

Literature Review of CTD Risk Factors

The epidemiological and biomechanical literature is replete with references to wrist posture, repetition, and force as risk factors for CTS and CTDs overall. Before these risk factors are discussed, the kinematic movement in the wrist and forearm will be briefly described (refer to figure 3). There are two degrees of freedom in the wrist joint, radial-ulnar deviation (R/U) and flexion-extension (F/E). The third degree of freedom, pronation-supination (P/S), is generated in the forearm by the radial bone crossing over the ulna bone.

Wrist Posture. Wrist posture has been cited often as a risk factor for CTS and CTDs overall (Alexander and Pulat, 1985; Armstrong, 1983, 1986a, 1986b; Armstrong and Chaffin, 1979a, 1979b; Armstrong et al., 1982; Armstrong et al., 1986; Browne et al., 1984; Charash, 1989; Eastman Kodak Co., 1986; Fraser, 1989; Greenberg and Chaffin, 1975; Konz, 1983; McCormick and Sanders, 1982; Phalen, 1966; Tichauer, 1966, 1978). Wrist flexion and extension are associated with CTS and tenosynovitis of the flexor tendons (Phalen, 1966), and wrist radial and ulnar deviation are associated with tenosynovitis and De Quervain's disease (Armstrong, 1983).

Even though wrist posture has been cited often as a risk factor for CTDs overall, few researchers have mentioned the issue of "how much" wrist deviation exposes a worker to CTDs. The suggested association between wrist posture and CTDs has been explained biomechanically. When the wrist is maintained in a neutral position, the tendons of the flexor and extensor finger muscles that pass through the wrist, are "well separated, run straight, and can operate efficiently"

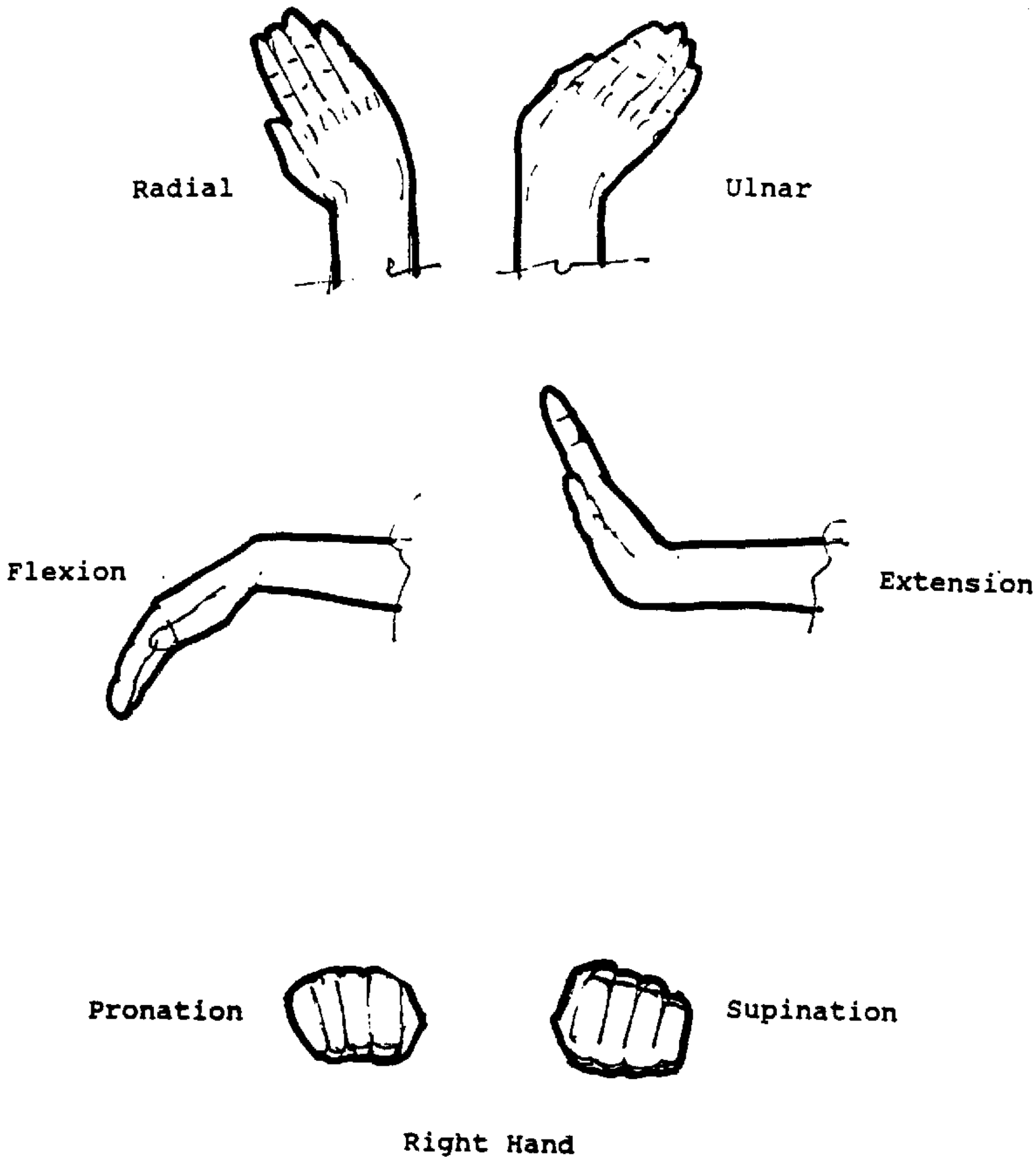


Figure 3. Three planes of movement of the hand. Radial/ulnar deviation and flexion/extension occur in the wrist joint, and pronation/supination is a function of the radius rotating around the ulna in the forearm.

(Tichauer, 1978, p. 67). When the wrist is in extreme deviated postures, the high shear forces and friction exerted by the carpal bones and flexor retinaculum on the tendon sheaths can irritate and inflame the tendon sheaths, causing a common CTD, tenosynovitis (Tichauer, 1978). The inflamed flexor tendon sheaths also occupy more space in the carpal tunnel, thus compressing the median nerve and contributing to CTS (Cunningham and Johnston, 1985).

Armstrong and Chaffin (1979a) developed a static biomechanical model of the wrist that demonstrated theoretically why deviated wrist angles could expose workers to CTS and CTDs overall. In their model, as wrist angle deviates from the neutral position, the resultant reaction forces on the median nerve and flexor tendons increase (refer to figure 4). High reaction forces could directly compress the median nerve, thereby contributing to CTS, and/or irritate and inflame flexor tendons passing through the carpal tunnel, thereby causing tenosynovitis. Furthermore, inflamed tendons occupy more volume in the carpal tunnel and could indirectly contribute to CTS by compressing the median nerve.

Repetition. Silverstein et al. (1985, 1986, 1987) conducted two epidemiological studies that provided evidence for a crude dose-response relationship between jobs that require highly repetitive wrist movements and incidence of

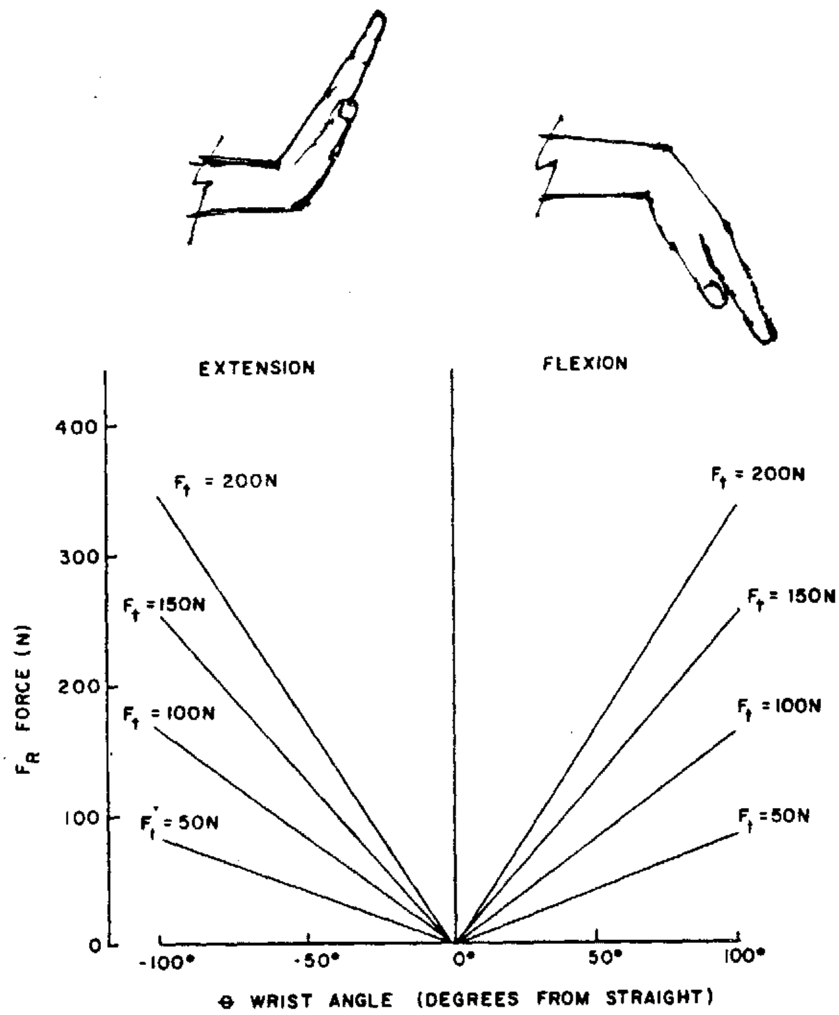


Figure 4. The resultant reaction force (Fr), as modeled by Armstrong and Chaffin (1979), that is exerted against the flexor tendons as a function of wrist angle and tendon force. Adapted from Chaffin and Andersson (1984).

CTS and CTDs overall. After controlling for potential confounders, Silverstein et al. (1987) reported that the odds ratios for in high force-high repetition industrial jobs compared to low force-low repetition jobs were more than 14 and 30 for CTS and CTDs, respectively. High repetition-low force jobs had odds ratio of 1.9 and 3.6 for CTS and CTDs, respectively, compared to low repetition-low force jobs.

Unlike static wrist posture, repetition involves the dynamic components of angular velocity and acceleration, which could contribute to CTS and CTDs risk. Technically, repetition can be defined in biomechanical terms as cyclic angular acceleration, peak velocity, and deceleration about the wrist joint. In order to accelerate the hand or digits, the extrinsic muscles in the forearm have to generate force based on Newton's second law of motion, $F = M*A$. Based on this law, the force that these extrinsic muscles in the forearm have to exert is proportional to the acceleration of the hand. Schoenmarklin and Marras (1991a) developed a dynamic biomechanical model of the wrist joint that explained how angular acceleration of the wrist theoretically increases the resultant reaction force on the median nerve and flexor tendons and median nerve, thereby increasing the risk of CTS and CTDs overall. Figure 5

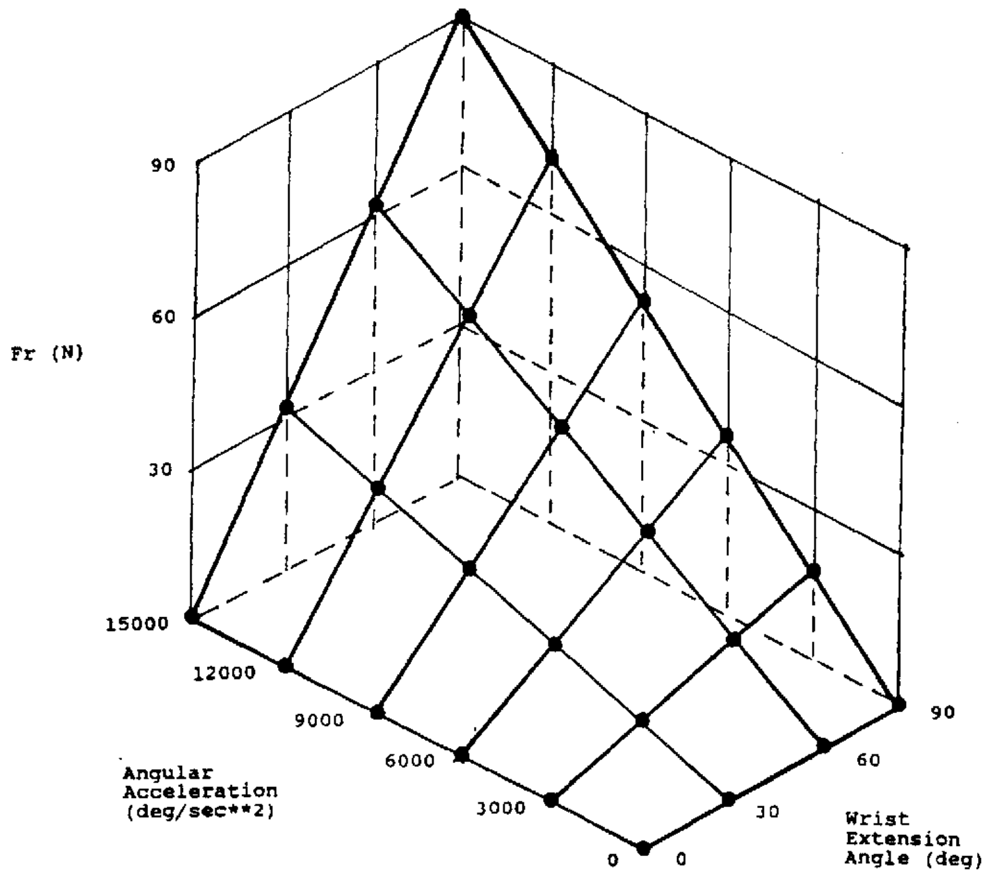


Figure 5. The resultant reaction force (Fr) exerted by the carpal bones or flexor retinaculum against a flexor tendon as a function of wrist angle and acceleration. (Schoenmarklin and Marras, 1991a)

illustrates the effect of acceleration on the resultant reaction force on the median nerve and tendons.

Due to the friction between the tendons and their adjacent surfaces, part of the tendon force generated by the extrinsic muscles will be lost to friction. As the tendon is moved over the adjacent surfaces, frictional energy is generated. This frictional energy, which is absorbed by the tendons and/or their surrounding tissues, could deteriorate and inflame the tendons, thereby contributing to CTS and CTDs. Tanaka and McGlothlin (1989), Moore and Wells (1989), and Moore (1988) hypothesized frictional work as a major cause of CTDs.

Another biomechanical way in which repetition could cause CTS and CTDs overall is based on the force-velocity relationship of muscle. As the velocity of shortening of a muscle increases, the maximal force that the muscle can generate decreases (Winter, 1979). Compared to a static posture, the extrinsic muscles in the forearm have to expend more energy to exert the same external force in a dynamic movement. The greater expenditure of energy will lead to earlier muscle fatigue. Premature muscle fatigue could bring about substitution patterns in muscle activation, and muscles which are not normally recruited may be activated in fatigued states. This abnormal usage may change the nature of forces within the wrist and put these seldom recruited muscles' tendons at risk of inflammation in the carpal tunnel, which could lead to CTS.

Tendon Force. Similar to repetition, Silverstein et al. (1986, 1987) found a crude dose-response relationship between a job's force requirements and the incidence rate of CTS and CTDs overall. The odds ratios for CTS and CTDs overall for jobs with high force-low repetition requirements and low force-low repetition jobs were 1.8 and 4.9, respectively.

With respect to resultant reaction forces, the association between tendon force and incidence of CTDs can be explained by Armstrong's and Chaffin's (1979a) static model of the wrist. As illustrated in figure 4, the resultant reaction force on tendons increases linearly as tendon force increases. The resultant reaction force contributes theoretically to the deterioration and inflammation of the tendons.

With respect to friction between tendons and their adjacent structures, an increase in total tendon force also increases the frictional force component within the tendon (except when the wrist is in a neutral posture). The friction between the tendons and the bones and ligaments has been hypothesized as a major contributor to CTDs (Tanaka and McGlothlin, 1989; Moore and Wells, 1989; Moore, 1988).

The above discussion of occupational risk factors of CTDs -- wrist posture, repetition, and tendon force -- points out the dearth of practical quantitative data on the relationship between each risk factor and incidence of CTDs. In order for industry to effectively prevent CTDs, industry needs the quantitative association between micro-components of each risk factor and incidence of CTDs. The focus of this research was intended to partially fill the present research voids by determining quantitatively the association between wrist motion and incidence of CTDs. Wrist motion contains the essential elements of the wrist posture and repetition risk factors. The static (wrist angle) and dynamic (angular velocity and acceleration) components of wrist motion were monitored by devices developed in the Biodynamics Laboratory. The following section is a literature review of motion monitoring devices.

Literature Review of Measurement of Wrist Motion

Cinematographic Methods. Heretofore, the state of the art in quantifying wrist movement in the workplace was cinematography. Cinematography produced gross angular results and required much effort to analyze. Armstrong et al. (1979) described a method for documenting hand position by filming a task with a super 8 mm motion picture camera and, subsequently, recording manually the type of hand position for each frame on a sheet of paper. This method required much time and effort because each individual frame had to be analyzed manually, and this method was also subject to human errors in angle measurement. In addition, two cameras were required to record the wrist angles in the radial/ulnar and flexion/extension planes, and synchronization of the wrist angles from these two cameras was difficult.

The cinematographic method was used in an investigation of hand and arm movement in a poultry processing plant (Armstrong et al., 1982) and in a task where a typewriter housing's flashings were filed (Burnett and Bhattacharya, 1986). In the poultry plant case, wrist positions were catalogued into a few discrete angles in increments of 25 to 45 degrees. The gross documentation of wrist angles in the poultry plant case is a product of the insensitivity of the cinematographic method. Fine adjustments in wrist angle, velocity, and acceleration and quick wrist movements, such as jerking the wrist, would be difficult to measure and calculate using the cinematographic method because the sampling rate (60 Hz) is too low. Much higher sampling rates are required to record dynamic movements of the upper limb.

Knowlton and Gilbert (1983) used high speed photography to record the ulnar deviation of a carpenter striking nails.

Like Armstrong's et al. (1979) method, Knowlton's and Gilbert's method appeared to require excessive time to measure the ulnar angle on each frame, as evinced by the fact that they measured the ulnar deviation of only one subject instead of all their subjects. Cinematography is an impractical technique to assess the biomechanical impact of highly repetitive wrist motion found in industry.

Electromechanical Devices. A few electromechanical devices have been developed to measure wrist angle, but their use appears to have been limited to measuring wrist motion in ordinary tasks of daily living. Brumfield and Champoux (1984) developed a uniaxial electrogoniometer that measured wrist flexion and extension. An et al. (1986) and Palmer et al. (1985) developed electrogoniometers that measured wrist motion in both planes of movement, and they recorded empirical data on the range and nature of wrist movement in daily tasks ranging from turning a steering wheel to combing hair. Tobey et al. (1985) developed a photogoniometer that measured wrist motion data from two lines that were attached to the back of the hand and are connected to two sliding wires. As the sliding wires were linearly displaced by the two lines, an optical encoder mechanism converted the linear displacement into analog voltages. The wrist angle data were synchronized with two video camera images for evaluation.

Schoenmarklin and Marras (1987) developed an electromechanical device that accurately measured wrist motion in two planes, and this device was used to measure wrist motion in simulated industrial tasks. This device was called a wrist monitor, and is shown in figure 6. The wrist monitor was a small plastic box that was strapped to the wrist and collected voltages from two potentiometers. Two lines were connected to the index and ring fingers, and as the hand moved, the two lines pulled at different distances from the box. As the wrist was ulnarly or radially deviated, one line increased its distance from the monitor while the other shortened its distance. This resulted in one voltage increasing and one voltage decreasing. As the wrist was flexed or extended, the voltages increased or decreased in tandem. The wrist monitor produced accurate and repeatable results, even during a hammering task in which the arm and hand were vigorously shaken and the wrist was repeatedly snapped (Schoenmarklin, 1988a and 1988b). The disadvantages of this wrist monitor were that radial/ulnar and flexion/extension angles were not measured independently and extensive calibration was required for each subject.

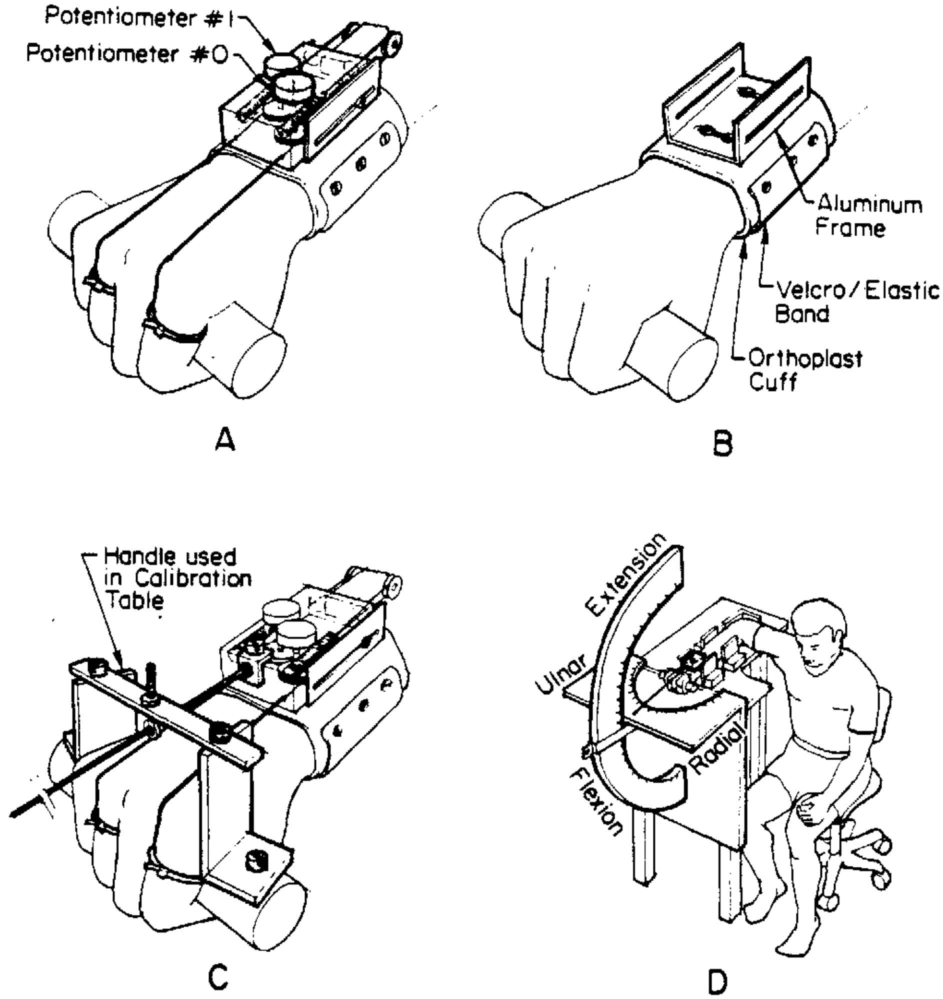


Figure 6. Wrist monitor and calibration equipment described in Schoenmarklin and Marras (1987) and used in Schoenmarklin (1988a). A) shows the wrist monitor strapped to a subject's wrist. B) shows the the Orthoplast cuff that is custom-molded to a subject's wrist. C) illustrates handle and pointer used to calibrate the monitor. D) shows a subject sitting nest to the calibration table with his hand aligned on top of the table. The two semi-circular arcs have tic marks to record the angles in the radial/ulnar and flexion/extension planes.

Review of Research Voids and Objective

The relationship between the three most cited occupational factors, wrist posture, repetition, and force, and specific wrist CTDs has been cited often in the literature. Except for a few notable studies (Armstrong et al., 1982; Silverstein et al., 1986, 1987), the context of this relationship has been qualitative and inconclusive by epidemiological data. With respect to wrist posture, the discussion has not even considered the full range of anatomical issues. Much of the discussion in the literature on wrist posture has centered on flexion/extension and radial/ulnar deviation, neglecting the third degree of movement, pronation/supination.

In Silverstein's et al. (1986, 1987) studies, a gross dose-response relationship was established between dichotomous levels of repetition and incidence of CTS and CTDs overall. These investigators found that the odds ratios for risk of CTS and CTDs were 1.9 and 3.6, respectively, in high repetition jobs compared to jobs that required a low number of repetitions. Silverstein et al. (1986, 1987) demonstrated that workers in jobs that required highly repetitious, hand-intensive work were at a significantly greater risk of developing CTS and CTDs than their counterparts in low repetition jobs. These researchers did not investigate the dynamic components that comprise repetitious wrist motions -- angular velocity and acceleration. The dynamic aspects of wrist motion must be explored because tendon force, which is a risk factor of CTDs, is affected by acceleration. Based on Newton's second law, the tendon force is proportional to wrist acceleration (F = M*A).

The work of Silverstein et al. (1986, 1987) provided the basis for the followup question: "What type" and "how much" wrist motion in highly repetitious jobs exposed a worker to CTDs? Heretofore, there was a lack of data on the kinematic aspects of wrist motion in industrial jobs, and no one had been able to quantify precisely wrist angle, velocity, and acceleration in high risk repetitive industrial tasks. Thus, we were not able to understand which specific wrist motion parameters were associated with wrist CTDs as a group.

In order to effectively prevent CTD injuries in the workplace, industry needs quantitative guidelines on the specific wrist motion parameters that expose workers to CTDs. Qualitative guidelines, such as "Keep your wrist in a neutral position", are impractical for industry to use as a preventive tool. Quantitative guidelines are needed to evaluate the CTD risk level of jobs and test alternative workplace layouts.

The objective of this research project was to determine quantitatively what kind (R/U, F/E, P/S) and how much wrist motion in the kinematic parameters (angle, velocity, and acceleration) were associated with high risk of CTDs. The association between wrist motion parameters and CTD risk is important to know since most jobs require some wrist motion, yet heretofore the quantity of wrist motion that was injurious to workers was not known. The jobs in this study were limited to only highly repetitive, hand-intensive tasks.

Since most of the symptoms of CTDs in industry are recorded generically on OSHA 200 logs as wrist strains, sprains, or tendinitis and also since the symptoms of many CTDs overlap, then a study associating wrist motion with a specific CTD, such as CTS, is impractical. Practically speaking, in order to determine the association between wrist motion and CTDs, CTDs was considered as a group. The intent of this research study was to determine the association between wrist motion parameters and wrist CTDs as a group.

Chapter III

METHODS

Approach

The incidence of CTDs is growing in the workplace, yet heretofore we did not have any quantitative guidelines on two often cited occupational risk factors, wrist posture and repetition, for industry to utilize. One of the major research voids in the study of occupational CTDs has been the lack of quantification of the link between static (wrist angle) and dynamic (velocity and acceleration) kinematic parameters of wrist motion and incidence of CTDs. The objective of this study was to determine quantitatively the association between specific wrist motions and incidence of CTDs as a group. Industry can use these quantitative guidelines to evaluate CTD risk levels of jobs and establish effective ergonomic programs to prevent CTDs.

The approach in this study was to collect wrist motion data from industrial workers at the factory floor level. 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 OSHA logs and medical records, and wrist motion of workers in high and low risk jobs was monitored on the factory floor while they were performing their tasks in a normal manner. Wrist motion data were analyzed as a function of CTD risk level in order to establish quantitative guidelines or "benchmarks" for industry to utilize.

Subjects

A total of 40 subjects volunteered to participate in this study. 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. Although several of the subjects had previous CTD injuries (six low risk subjects, five high risk subjects), all of the subjects were healthy and free of injury at the time their wrist motion was monitored.

Experimental Design

In epidemiological terms, the experimental design was a cross-sectional cohort study in which the only independent variable was exposure to CTDs in selected jobs at participating companies. Exposure had two nomimal levels, jobs that had low and high risk of CTDs. Risk of CTDs was determined from evaluation of Occupational Safety and Health Administration (OSHA) 200 logs and medical records in participating companies.

The experimental design was a fully nested design, as illustrated in figure 7. Subjects, which were nested under jobs, and jobs, which were nested under risk levels, were random variables. Risk was a fixed variable. Within each risk level, ten repetitive, hand-intensive jobs were randomly selected from the set of participating companies. Within each job, two subjects were randomly selected.

The dependent variables comprised three categories: subject characteristics, job characteristics, and wrist motion metrics. The subject characteristics were age, gender, handedness, work experience, job satisfaction, and anthropometric dimensions, whereas the job characteristics included number of wrist motions per eight hour shift, weight of loads, handgrip types and forces, work heights, and motion descriptions. The wrist motion measures consisted of the following statistics in the R/U, F/E, and 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

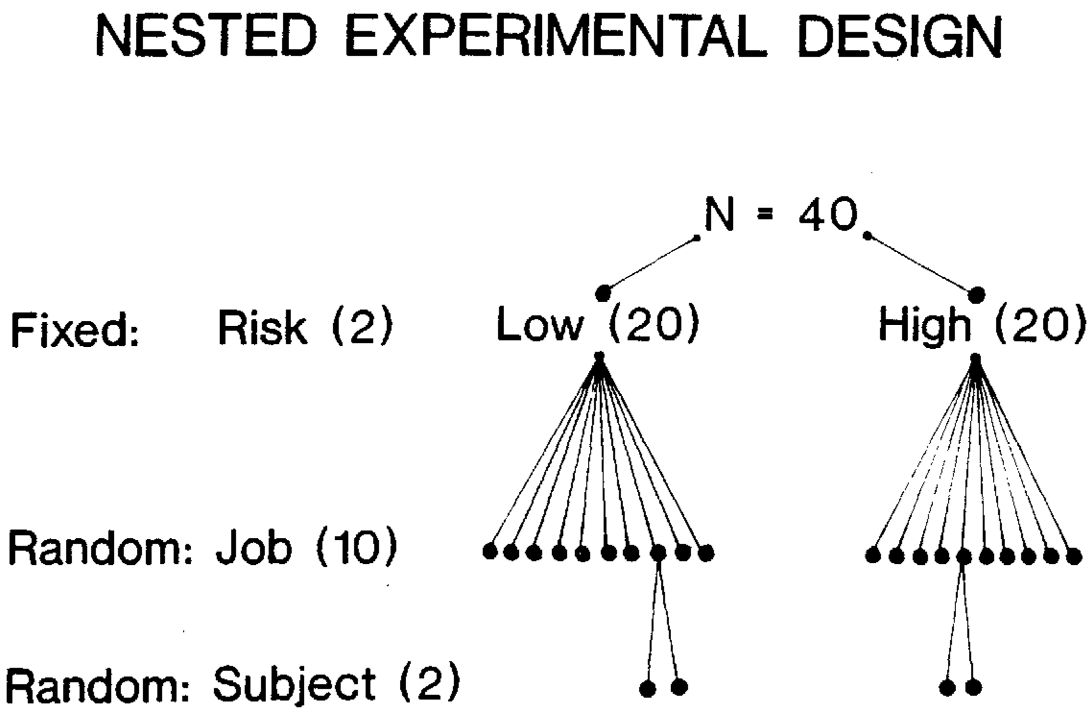


Figure 7. Experimental design of the industrial quantification phase. The experimental design was a fully nested design in which CTD risk level was fixed at two levels. Jobs were nested under risk level, and subjects were nested under jobs. Jobs and subjects were randomly selected.

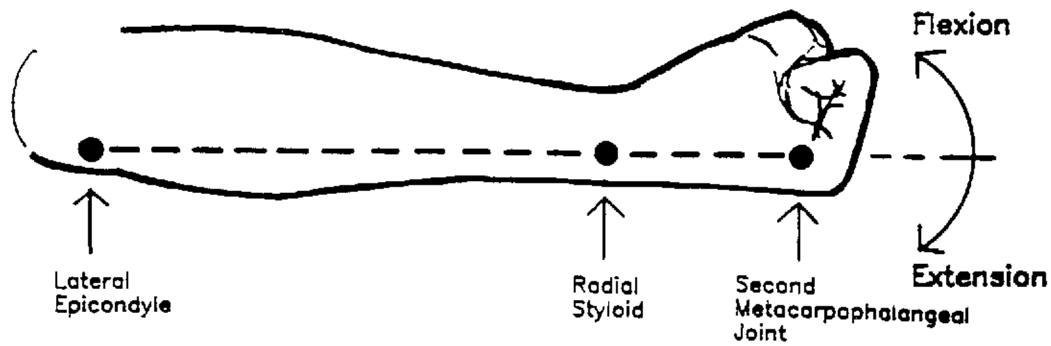
Apparatus

Goniometric instrumentation was used to collect wrist motion data in the R/U, F/E, and P/S planes. These devices are described in the following sections.

Wrist Monitor. A wrist monitor was developed in the Biodynamics Laboratory 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 still proprietary, so the description will be limited. This 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 segments of thin metal. The potentiometers were placed on the center 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 monitor was calibrated to each subject by recording the voltages of the R/U and F/E potentiometers while the subject's wrist was in neutral position on a calibration table. The bony landmarks shown in figure 8 were used as reference points to align the wrist in the R/U and F/E planes. In both the R/U and F/E planes, the wrist is in a neutral position when the longitudinal axis of the radius is

A)



B)

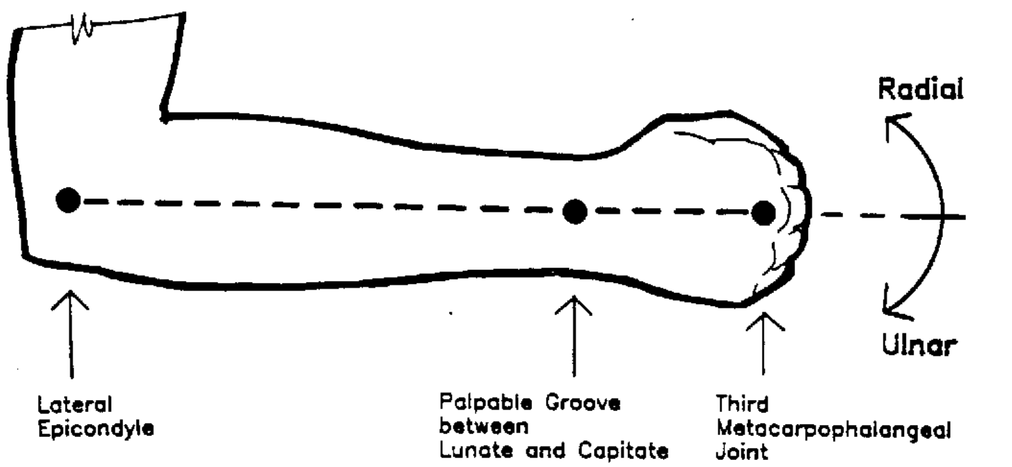


Figure 8. Bony landmarks on the elbow, wrist, and hand that were used to align the wrist in a neutral position in the radial/ulnar and flexion/extension planes. (Schoenmarklin and Marras, 1989b)

parallel to the third metacarpal bone (Taleisnik, 1985; Palmer et al., 1985). Neutral position in the R/U plane was accomplished by aligning marks placed on the third metacarpophalangeal joint (middle finger knuckle), the center of the wrist, and lateral epicondyle of the elbow (Taylor and Blaschke, 1951; Knowlton and Gilbert, 1983). The center of the wrist on the dorsal side is the "palpable groove between the lunate and capitate bones, on a line with the third metacarpal bone" (Webb Associates, 1978, p. IV-61). The wrist was aligned in a neutral position in the F/E plane when the center of the second metacarpal head, radial styloid, and lateral epicondyle were collinear (Brumfield and Champoux, 1984).

The angular deviation of the wrist in the R/U and F/E planes was calculated according to equation **(1)**.

$$\theta = (Vij - Vnj) * (65 \text{ deg/volt}) \quad (1)$$

where:

- **θ** = angular deviation in deg. from neutral angle in plane **j** (plane **j** corresponds to potentiometer **j**)
- **Vij** = voltage recorded at time **i** from potentiometer **j**
- **Vnj** = voltage recorded at neutral angle from pot. **j**
- **65** = ratio between angular deviation (deg) and change in voltage

The constant ratio of 65 degrees per volt obviated the need for exhaustive calibration of each subject. Only the neutral voltages in the R/U and F/E planes were needed to provide reference voltages in each plane. Once the reference voltages were known, then all wrist angles during the trials were calculated according to equation (6).

The sign convention for angles in the R/U and F/E planes was as follows:

R/U:	Pos = radial deviation	Neg = ulnar deviation
F/E:	Pos = flexion	Neg = extension

Pronation/Supination Device. The P/S device recorded the P/S angle of the forearm. The P/S device consists 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 record the angular displacement of the forearm.

The ratio between angular excursion and change in voltages was not constant for subjects in the P/S plane, so this ratio had to be calculated for each subject. The P/S device was calibrated by the use of a P/S dial. While a subject held his elbow at 90 degrees next to his side and his forearm parallel to the ground, the experimenter adjusted the height of the calibration dial. The subject grasped the handle on the dial. When the handle was aligned vertically, this position was defined as the neutral P/S angle. Voltages were collected from the P/S potentiometers in both arms when the forearms were aligned in a neutral position. Then, the subject was asked to maximally pronate his forearms within comfortable limits. Voltages were recorded while his forearms were maximally pronated. Maximal supination was recorded in a manner similar to pronation.

Based on the three pairs of angular and voltage data, a best-fitting regression line was calculated for each subject's forearm. The relationship between P/S and voltage was highly linear, as evinced by r-squared values that averaged about 0.98.

The P/S angle was calculated according to regression equation **(2)**.

$$\Theta = Bo + B1*(Vi) \tag{2}$$

where:

Θ = pronation/supination angle at time i
Bo = regression intercept
B1 = regression slope
Vi = voltage at time i

The sign convention for angles in the P/S plane was as follows:

P/S: Pos = pronation Neg = supination

Sampling Frequency. The R/U, F/E, and P/S voltages were monitored at 300 Hz. This frequency was selected based on computations of the minimum frequency needed to capture a reasonable amount of information in maximal extension/flexion (E/F) movements. Based on empirical data, a person can move from a maximal extension angle to flexion angle within approximately 0.1 seconds. Figure 9 represents the angular displacement of a maximal E/F movement. The angular displacement of a maximal E/F movement as a function of time was modeled as an exponential decay function. The exponential model that is illustrated in figure 9 is defined in equations **(3)** and **(4)**.

$$x(t1) = (e\hat{}(b*(t1 - t0)))*(x(t0)) \quad (3)$$
$$x(t1)/x(t0) = e\hat{}(b*(t1 - t0)) \quad (4)$$

where:
t0 = start of maximal extension to flexion movement
t1 = end of " " " " " " "
x(t0) = wrist angle at time **t0**
x(t1) = wrist angle at time **t1**
b = coefficient of exponential model
t1-t0 = time interval of maximal movement, approximately 0.1 seconds

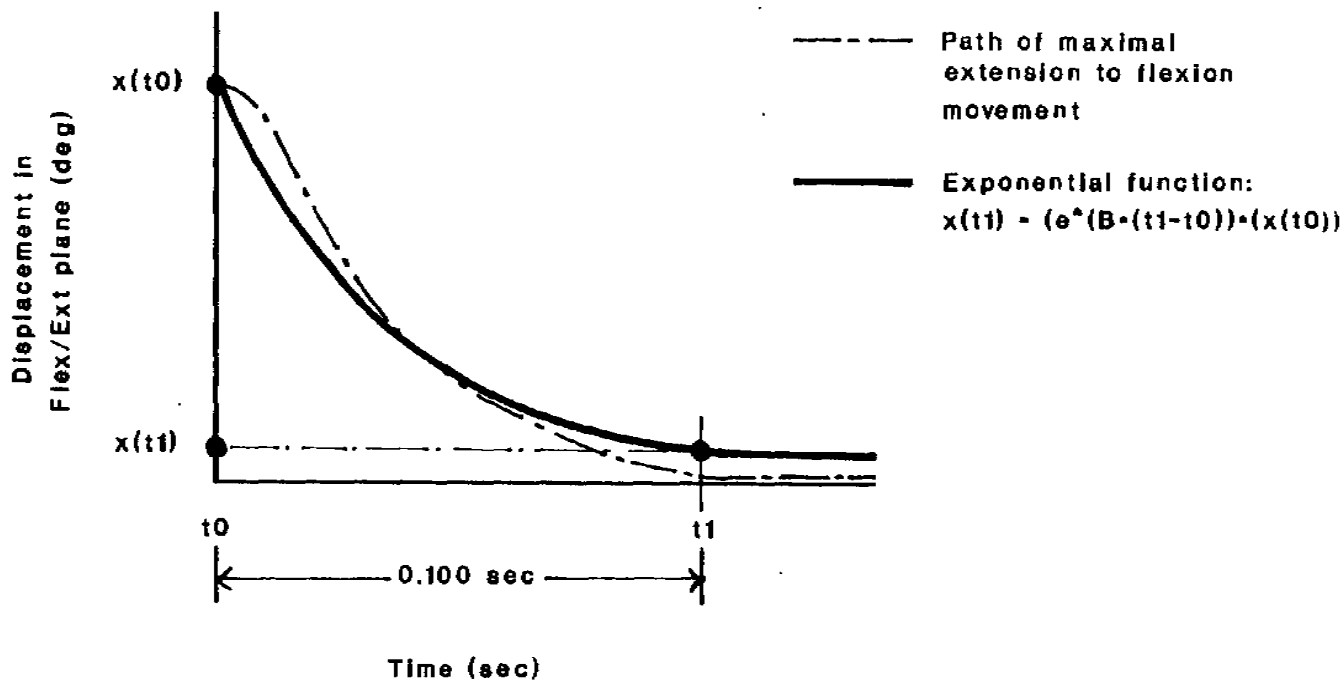


Figure 9. Displacement of a maximal wrist movement from full extension to flexion. Normal subjects can accomplish this task in approximately 0.1 seconds. The path of wrist movement is modeled as a negative exponential function.

Solving for **b** in equation **(4)** with natural logarithms results in equation **(5)**. For **(t1 - t0)** = 0.1 seconds and an maximum allowable value of **x(t1)/x(t0)** = 0.05 or 5%, **b** = -30.

$$b = \ln(x(t1)/x(t0)) / (t1 - t0) \qquad (5)$$

The estimation of **b** is sensitive to the time interval **(t1 - t0)**, but more importantly, the exponential model is only a crude estimate because the displacement curve in figure 9 is clearly not a pure exponential function. However, this model does provide a rough estimate of the angular displacement path of the wrist.

The change in angle between two consecutive sampling points should be less than 10%, which can also be expressed as a 90% ratio of angles between two consecutive sampling points. Δ is the maximum time interval between consecutive sampling points. The two consecutive sampling points are at times **((n+1)Δ)** and **(nΔ)**. Equation **(6)** is a transformation of equation **(4)** using sampling rate variables.

$$x((n+1)\Delta)/x(n\Delta) = e\hat{}(b*\Delta) \qquad (6)$$

where:

Δ	= maximum time interval
x((n+1)Δ)	= wrist angle at data point **n+1**
x(nΔ)	= wrist angle at data point **n**
b	= coefficient of exponential model

Solving for Δ in equation (6) results in equation (7).

$$\Delta = \ln(x((n+1)\Delta)/x(n\Delta)) / b \qquad (7)$$

For $b = -30$ (from equation (10)) and $x((n+1)\Delta)/x(n\Delta) = 0.90$, $\Delta = 0.003512$ seconds. The inverse of Δ is 285 Hz, which is the minimum sampling rate. A sampling frequency of 300 Hz was selected to ensure an upper limit of 10% change in displacement between consecutive data points during maximal wrist movements.

Advantages of Wrist Monitor and P/S Device. The wrist monitor and P/S device were used as a means to quantify wrist motion in high and low risk industrial jobs. These monitors provided data that addressed the research void of lack of association between specific wrist motions and CTD risk. Strapped to workers' wrists and forearms in industry, the monitors collected three-dimensional wrist motion and repetition data at high frequencies (300 Hz) for long sampling periods.

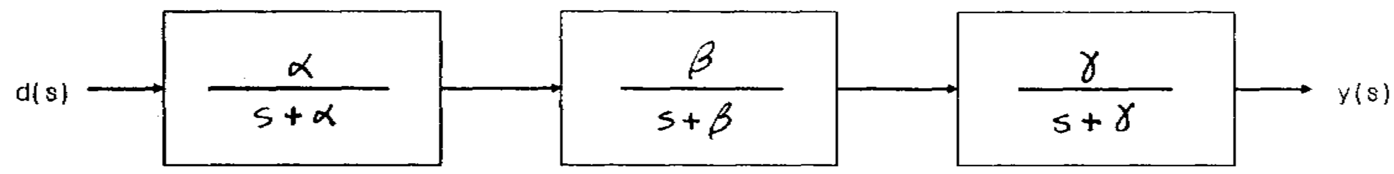
Data Conditioning

Filter. The filter utilized in this project is structurally different from the conventional finite difference method used to compute velocity and acceleration.

With the finite difference method, the position of each point in time is computed, and then the velocity is calculated as the derivative of position. Subsequently, acceleration is computed as the derivative of velocity. However, the filter in this study calculated position, velocity, and acceleration simultaneously. In addition to the computation of three kinematic measures, the filter conditioned the data by sifting out a certain amount of noise.

Concept of Filter. The filter is a sequence of three simple first order low pass filters cascaded together. The parameters, α, β, and γ, determine the cutoff frequency in radians/sec. Figure 10 illustrates the three cascaded filters in which the Laplace transforms of raw data, **d(s)**, and filtered data, **y(s)**, are the inputs and outputs of the model, respectively. The three cascaded filters in figure 10 can also be represented as the flow chart in figure 11. By expansion, the flow chart in figure 12 is identical to figure 11.

The form in figure 11 communicates the intuitive nature of how the low-pass filter works. For steady state operations with sinusoidal inputs, **s = j*w**, where **j = (-1)^(.5)** and **w** is a frequency. Therefore, each block of the form, **r/(j*w + r)**, is a complex number. For **w < k**, where **k** is the cutoff frequency, the magnitude of the



d(s) = Laplace transform of raw data
y(s) = Laplace transform of filtered data

Figure 10. Three first order low pass filters cascaded together. The Laplace transforms of the raw data and filtered data (**d(s)** and **y(s)**) are the input and output.

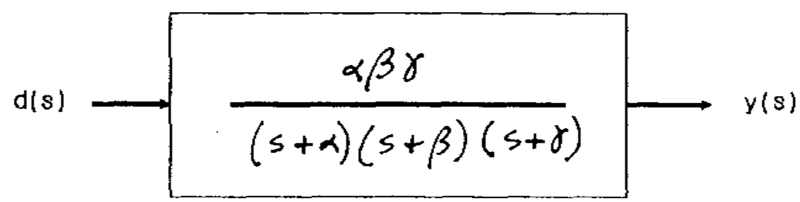
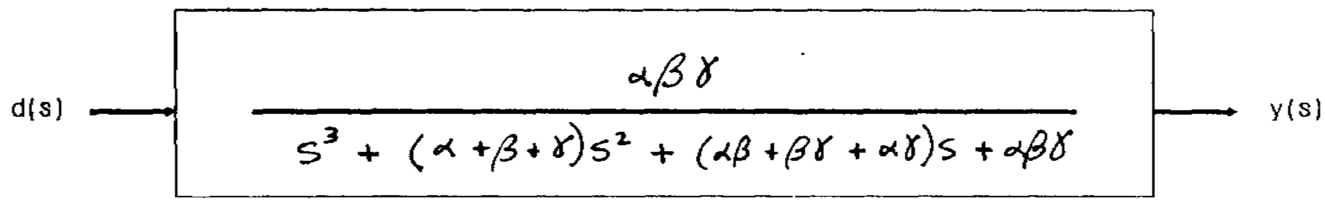


Figure 11. Product of the three low pass filters shown in figure 10. This filter is identical to the one in figure 10.



d(s) = Laplace transform of raw data
y(s) = Laplace transform of filtered data

Figure 12. Expansion of the filter shown in figure 11. This filter is identical to the one in figure 11.

complex number approaches 1. For **w** > **k**, the magnitude approaches 0. The filter passes frequencies below **k** unattenuated and greatly attenuates higher frequency signals.

The form of the filter in figure 12 is equivalent to the first form (figure 11), but it is better suited for the task of estimating velocity and acceleration. The transfer function in figure 12 provides the basic structure and mathematical properties of the filter, but it does not specify its implementation. By writing the differential equation of the filter and inverting the transform, the filter becomes equation (8).

$$(\alpha\beta\gamma)d(t) = \dddot{y}(t) + (\alpha+\beta+\gamma)\ddot{y}(t) + (\alpha\beta+\beta\gamma+\alpha\gamma)\dot{y}(t) + (\alpha\beta\gamma)y(t) \qquad (8)$$

where:
$d(t)$ = continuous data signal (not available due to sampling)
$y(t)$ = filtered position signal
$\dot{y}(t)$ = filtered velocity signal
$\ddot{y}(t)$ = filtered acceleration signal
$\dddot{y}(t)$ = filtered derivative of acceleration

<u>Implementation of Filter</u>. The filter must be expressed in a form suitable for use with sampled data. The following is one way to achieve that end. Define:

$$\begin{aligned} X1(t) &= y(t) \\ X2(t) &= \dot{y}(t) \\ X3(t) &= \ddot{y}(t) \end{aligned} \qquad (9)$$

The x variables on the left of equation (9) are state variables corresponding to data of interest, namely, position, velocity, and acceleration.

$$
\begin{aligned}
\dot{x}1(t) &= x2(t) \\
\dot{x}2(t) &= x3(t) \\
\dot{x}3(t) &= -(\alpha\beta\gamma)x1(t) - (\alpha\beta + \beta\gamma + \alpha\gamma)x2(t) \\
&\quad -(\alpha+\beta+\gamma)x3(t) + (\alpha\beta\gamma)d(t)
\end{aligned} \tag{10}
$$

The first two equations in (10) are definitions of the variables, and the third equation is derived from equation (8). The equations in (10) can be expressed in matrix form, as indicated in figure 13. Based on linear systems theory, the matrix equation in figure 13 was modified for computation and transformed into a software program. Values of 105, 107, and 109, were selected for α , β , and γ , respectively. These values correspond to cutoff frequencies of approximately 17 Hz.

In order to filter out noise, the data were passed through the filtering system twice. In the first pass, the raw position data entered the filter and the position, velocity, and acceleration were calculated. In the second pass, the estimated position data from the first pass entered the filter and the position, velocity, and acceleration were calculated in a similar manner. The effect of the two passes on the kinematic measures was a

$$\begin{bmatrix} \dot{x}1(t) \\ \dot{x}2(t) \\ \dot{x}3(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\alpha\beta\gamma & -(\alpha\beta + \beta\gamma + \alpha\gamma) & -(\alpha+\beta+\gamma) \end{bmatrix} \begin{bmatrix} x1(t) \\ x2(t) \\ x3(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \alpha\beta\gamma \end{bmatrix} d(t)$$

$$\underline{\dot{x}}(t) = A \; \underline{x}(t) + \underline{B} \; d(t)$$

$$\underline{\dot{x}}(t) = A^{*}\underline{x}(t) + \underline{B}^{*}d(t)$$

Figure 13. Matrix form of the filter shown in figure 12. Refer to text for definitions of variables.

time delay of approximately 0.06 sec (18 data points sampled at 300 Hz) between the raw and calculated position data, as illustrated in figures 14 and 15.

Validation of Filter. When compared to a video-based Motion Analysis system, the position data from the wrist monitor and pronation/supination device were within 4% of the Motion Analysis angular data. Since Motion Analysis collects data at a slow rate of 60 Hz, data from the wrist monitor and P/S device, which are collected at 300 Hz, are probably more believable, particularly in dynamic movements.

The filter was validated by comparing the traces of the raw and calculated position data. Figures 14 and 15 show the traces of the position data from maximal ballistic R/U and slow F/E movements, respectively. The calculated position followed the path of the raw position quite well in both plots.

The filter was further validated by integrating the calculated acceleration twice, which resulted in position estimates, during maximal ballistic movements in the R/U, F/E, and P/S planes. The range of motion (ROM) of estimated position data from integration was compared to the raw ROM. In the R/U and F/E planes, the estimated ROMs were within 3%, while the estimated ROMs were within 7.5% in the P/S plane.

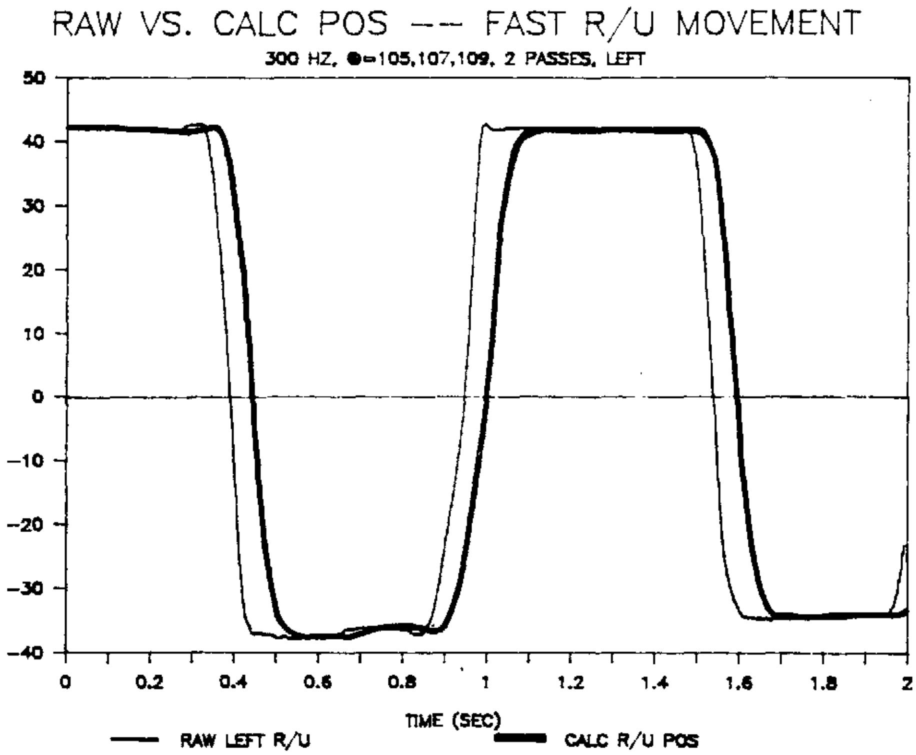


Figure 14. Displacement of the raw and filtered position of a fast radial/ulnar movement.

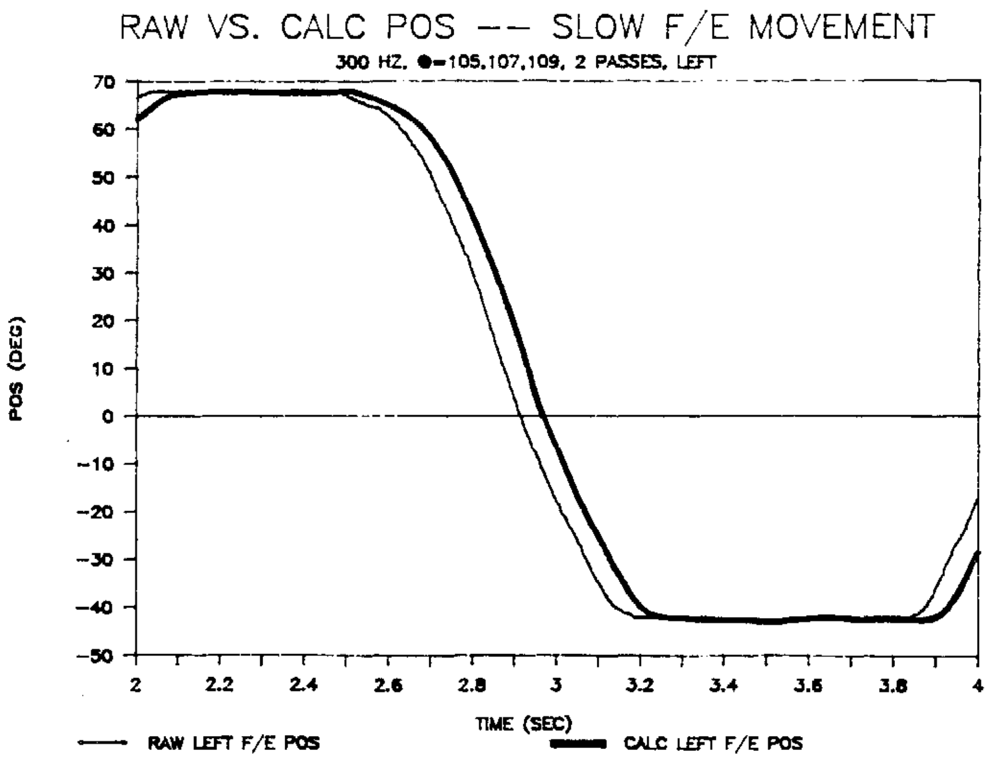


Figure 15. Displacement of the raw and filtered position of a slow flexion/extension movement.

The integration method confirms the extremely large peak accelerations and velocities that were measured in maximal ballistic motions. Based on empirical data, peak accelerations in the R/U, F/E, and P/S planes were approximately 15,000, 30,000, and 90,000 deg/sec^2, respectively. Peak velocities in the three planes were within upper limits of 1000, 2000, and 3000 deg/sec. The high compatibility between the raw ROM and ROM from integration confirms the extremely high accelerations and velocities that were calculated during ballistic trials. In order to physically move from one extreme angle to another within a brief time interval (approximately 0.1 seconds), the wrist has to accelerate at an immense rate.

Integrated Data Collection System

The goniometers were combined with customized data collection software into a portable, self-contained system. Figure 16 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 analog-to-digital (A/D) converter board (Labmaster). The six channels comprised R/U, F/E, and P/S motion of both upper extremities.

In addition to the six channels of wrist motion, two time marker channels were transmitted to the A/D board.

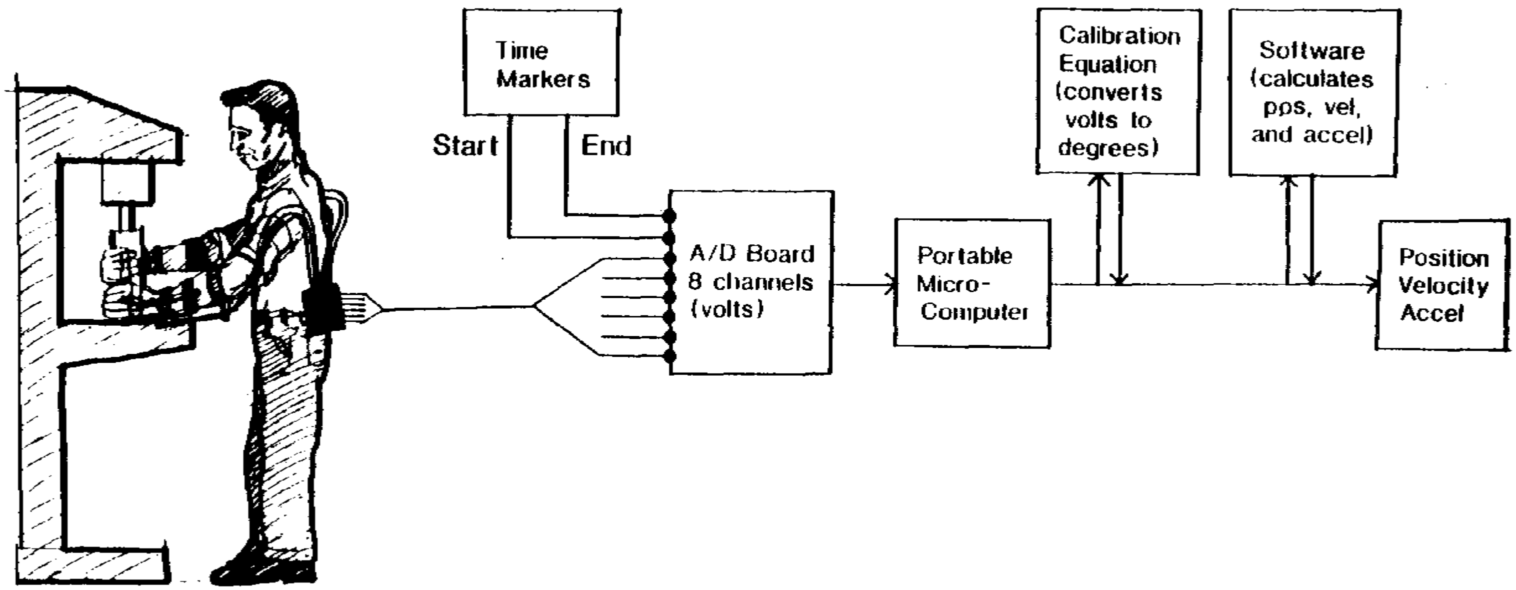


Figure 16. Integrated data collection system consisting of hardware and software that monitor wrist motion on the factory floor and process the data in the laboratory.

These time markers signaled the start and end of selected intervals of interest, as illustrated in figure 17. Each interval represented a motion component during the repetitive cycle; the idle time between motion components during a cycle was not of interest. Each interval was recorded by the experimenter pressing hand-held switches at the start and end of each interval. The switches generated electronic pulses that were transmitted to the A/D board.

The data from all eight channels were stored on a portable 386 micro-computer and analyzed later in the laboratory. In the laboratory, the wrist motion voltages were converted into R/U, F/E, and P/S angles by equations (1) and (2), and the position, velocity, and acceleration were calculated according to the filter described earlier. 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 an IBM mainframe computer and were analyzed by SAS Institute, Inc., software.

Selection of Participating Companies and Jobs

Eight manufacturers in the Midwest volunteered to participate in this study. All of these companies' manufacturing operations required highly repetitive, hand-

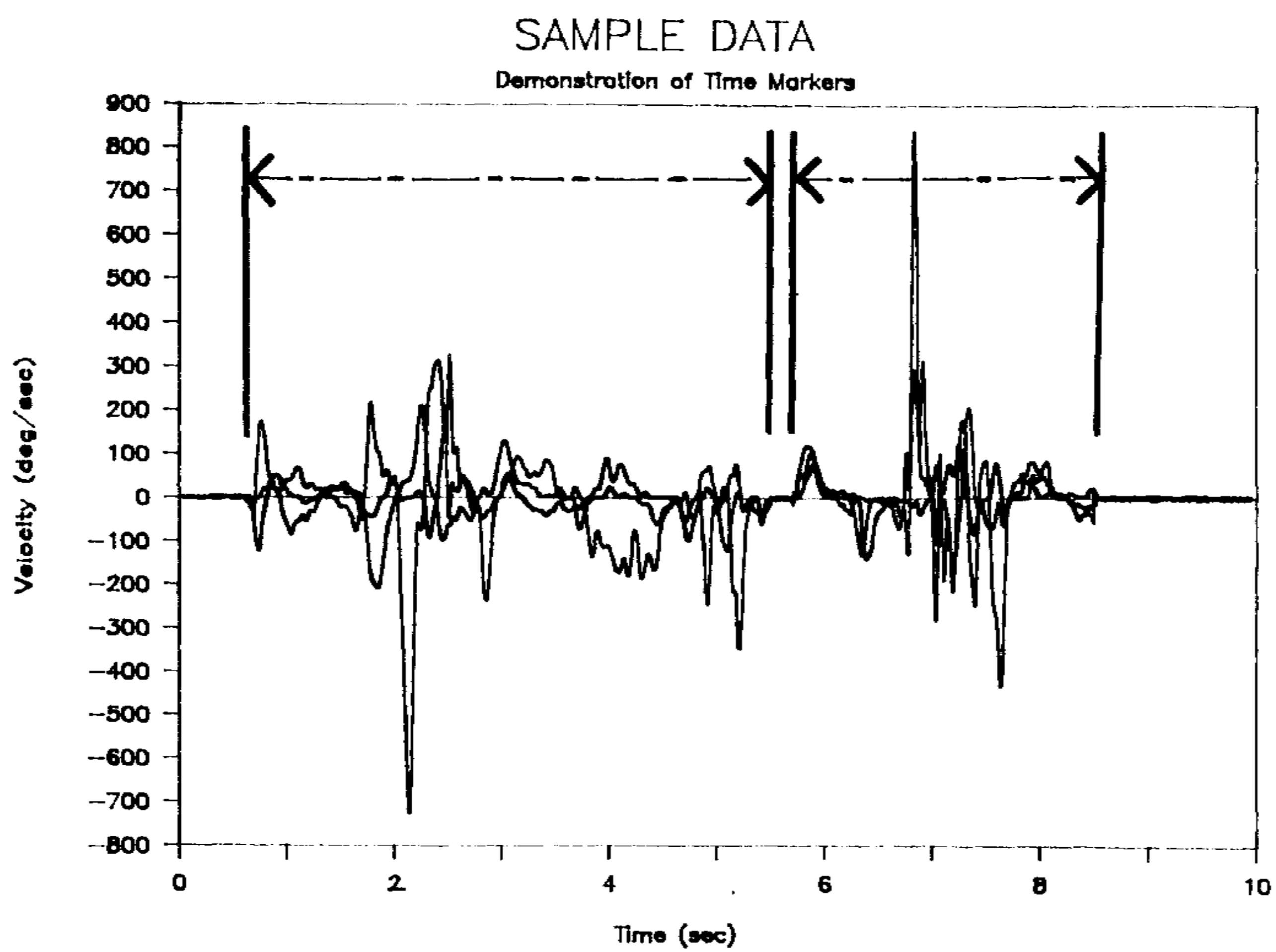


Figure 17. Trace of wrist velocity data during a ten second trial. Within the ten second period, there were two time intervals of interest. Each interval represented a motion component.

intensive work, and most of these companies manufactured products for the transportation industry. As part of the agreement between Ohio State University and the participating companies, the identity and location of these manufacturing plants must remain confidential. The type of manufacturing operation and the number of jobs and subjects who were monitored at the plants are listed in table 1. All of the jobs except two (one low risk and one high risk) required gloves, and all of the jobs comprised primarily handling of parts with minimal use of tools.

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

Type of mfg operation in participating companies	# of Jobs	# of Subj
Automotive suspension parts and assembly*	5	9
Automotive engine parts and assembly	4	8
Automotive brake parts and assembly	2	4
Automobile final assembly	2	4
Truck parts assembly	2	4
Plastic injection molding	2	4
Commerical building products**	2	5
Vehicle seating and upholstery assembly	1	2
Total: 8 plants	20 jobs	40 subjects

* only one subject was monitored in one job
** three subjects were monitored in one job

Table 2. Number of fundamental wrist movements in each monitored job.

High Risk Jobs	# of wrist movements
Vehicle strut assembly	20,250
Shock absorber rod loader	25,200
Brake liner loader	30,926
Steering column assembly	16,400
Oil filter string tie	51,428
Oil filter welder	25,920
Rubber hose molder	17,590
Pipe insulation jacketer	22,793
Vehicle weatherstrip assembly	16,400
Vehicle seat assembly	19,200
	mean = 24,738 s.d.= 10,432

Low Risk Jobs	# of wrist movements
Shock absorber bracket installer	19,000
Shock absorber cap installer	37,500
Shock absorber rod installer	37,500
Brake liner cutter	13,130
Oil filter bracket inspector	20,160
Large oil filter assembly	63,000
Rubber parts inspector	24,000
Pipe insulation socker	17,500
Air hose terminator	14,000
Air hose assembly	15,530
	mean = 26,132 s.d.= 15,259

The jobs within the eight plants were selected based on number of wrist movements, personnel policies, and risk of CTDs. The minimum acceptable number of wrist movements was 13,000 fundamental wrist movements (Barnes, 1981) during an eight hour shift, which represents one wrist movement approximately every two seconds. Table 2 shows the number of wrist movements for each monitored job. In addition, potential jobs were scrutinized according to whether there was job rotation among workers. The presence of job rotation could confound the incidence rate of CTDs. Only jobs that met the minimum number of wrist movements and did not involve rotation among workers were candidates for inclusion in this study.

The risk of CTDs was computed according to equation **(11)** from 1988 or 1989 OSHA 200 log data. Based on a survey of over ten companies, reports of CTDs were not generally recorded on OSHA logs until 1988 or 1989.

$$\text{incid rate} = \left((\#inc) / ((workers) * (hrs/wk) * (wks/yr)) \right) * (200{,}000 \text{ worker-hrs}) \qquad (11)$$

where:

incid rate	= number of incidents recorded on OSHA 200 logs per 200,000 worker-hours of exposure for a particular job
#inc	= number of incidents recorded on OSHA 200 logs during a one year period for a particular job
workers	= number of workers in a particular job
hrs/wk	= average number of hours each worker on a particular job worked during the week
wks/yr	= average number of weeks that each worker in a particular job worked during the year
200,000 worker-hours	= the aggregate number of worker-hrs of 100 full-time workers who work 50 40-hour weeks a year

A low risk job was defined as having a zero incidence rate, whereas a high risk job was defined as having an incidence rate of eight or more.

Experimental Protocol

Subjects who met the prerequisites in the Subjects section filled out a consent form and a background survey form. The background survey form included age, health status, history of CTDs, work experience, number of years worked on current job, job satisfaction, etc. In addition, anthropometric recordings of each subject's gross and upper extremity dimensions were measured. The wrist monitor and pronation/supination device were strapped on the subject's right and left forearms and hands, and neutral calibration voltages were recorded, as described in this Chapter. With his arms at his sides and elbows bent at 90 degrees, the subject moved his hands from one extreme angle to another as quickly as he could in the R/U, F/E, and P/S planes. The data from these dynamic trials were later analyzed in the laboratory to compute the maximum range of motion, velocity, and acceleration in each plane.

After the setup, calibration, and dynamic trials were completed, a brief task analysis of the subject's job was performed. In consultation with the subject, specific phases of the subject's job were selected to monitor. Wrist motion during the idle time between cycles or within a cycle was not monitored. Next, the subject was asked to perform his job while we collected wrist motion data during ten second sampling periods. A minimum of ten trials was collected from each subject. As described earlier, time markers were used to mark the time that intervals of interest started and ended throughout the ten second trials. Through the use of time markers, the wrist motion of motion components and specific phases of each subject's job was monitored. The number and distribution of intervals and ten second trials 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. Video documentation was used to document finger position, hand configuration, and work ambience. After data collection, the wrist monitor was taken off the subject, and anthropometric dimensions of the full body and upper extremities were measured. The subject was asked to simulate the amount of force that he exerts on the job with a Smedley grip strength dynamometer. The distance between the Smedley's gripping surfaces were adjusted to reflect the grip span of the worker's hand configuration on the job.

The subject was then thanked for his time and efforts and was given a Biodynamics Lab T-shirt in return for his participation.

Chapter IV

RESULTS

Subject Characteristics

Age and Work Experience. As indicated in table 3, the subjects in the low risk group were significantly older than their counterparts in the high risk group (46.9 vs. 36.6 years old). 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 fact that the workers in the low risk group were older and had a longer tenure with the company is probably partially due to the seniority system. 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. Since most of the low risk workers had more seniority than their high risk counterparts, they had the opportunity to bid for the less strenuous jobs.

Handedness. All the workers in the high risk group were right-handed, and nineteen of the twenty subjects in the low risk group were right-handed.

Table 3. Mean values, standard deviations, and probability of type I error of subject characteristics and anthropometric dimensions. The effect tested was risk of CTDs (DF = 1), and the error term was job nested within risk level (DF = 18).

Dependent Var.	High Risk Mean	High Risk St.Dev.	Low Risk Mean	Low Risk St.Dev.	Type I Error
SUBJECT CHARACTERISTICS					
Age (years)	36.6	(10.2)	46.9	(8.12)	0.0025*
Years on job	3.90	(3.40)	7.00	(6.13)	0.1751
Years with company	10.9	(8.10)	20.0	(5.45)	0.0024*
Job satisfaction**	6.45	(2.11)	7.40	(1.93)	0.1527
ANTHROPOMETRIC DIMENSIONS					
Gross Dimensions (kg and cm)					
Weight	77.5	(15.7)	84.6	(15.2)	0.2084
Stature	173.4	(9.68)	171.3	(10.8)	0.5999
Shoulder height	143.3	(9.17)	142.8	(9.20)	0.8677
Arm length	76.2	(4.80)	75.9	(5.97)	0.8728
Trunk depth	23.7	(4.42)	28.0	(5.72)	0.0202*
Shoulder-elbow length	36.5	(2.44)	36.6	(3.03)	0.9210
Elbow-wrist length	28.4	(2.07)	28.7	(2.36)	0.7094
Elbow-hand length	46.3	(2.49)	46.7	(3.68)	0.7769
Dominant Hand Dimensions (cm)					
Hand length	18.3	(1.06)	18.4	(1.46)	0.7034
Thumb length	5.84	(0.40)	5.85	(0.83)	0.9759
Middle finger length	7.75	(0.43)	7.96	(1.05)	0.5085
Hand breadth	8.03	(1.35)	8.33	(0.76)	0.4967
Hand thickness	3.08	(1.16)	2.92	(0.33)	0.5728
Wrist breadth	5.79	(0.87)	6.04	(0.64)	0.3928
Wrist thickness	4.03	(0.49)	4.13	(0.46)	0.5222
Wrist circum.	16.6	(1.62)	17.6	(1.74)	0.1082
Forearm circum.	26.70	(3.11)	26.73	(4.79)	0.9852
Maximum grip strength (kgf)	39.4	(14.9)	36.8	(15.1)	0.6539

* statistically significant at the 0.05 level

** job satisfaction data were analyzed by the Kruskal-Wallis one-way nonparametric test, which employs a chi-square.

Job Satisfaction. The mean subjective ratings of job satisfaction between the low and high risk groups were not significantly different, as indicated in table 3. Since the subjective rating scales were not continuous but ordinal in nature, a nonparametric Kruskal-Wallis one-way procedure was used to test for significant differences in ratings.

Anthropometric Dimensions. Except for trunk depth, the gross and upper extremity dimensions were not significantly different between subjects in both risk groups (see table 3). The greater trunk depth of the low risk subjects is probably attributable to the positive correlation between weight and age (Webb Associates, 1978). The anthropometric data in table 3 were measured according to established guidelines in NASA 1024 (Webb Associates, 1978) and Garrett (1970) for gross and upper extremity dimensions, respectively.

Maximal Wrist Movement Performance. The summary statistics of the maximal dynamic movements in the R/U, F/E, and P/S planes generally did not reveal any pattern of significant differences between subjects from both risk groups. These summary statistics can be found in Schoenmarklin and Marras (1991b).

Job Characteristics

Number of Wrist Movements. The mean number of fundamental wrist motions in both risk levels did not significantly differ, as shown in table 4. The mean number of wrist motions per eight hour shift was approximately 25,000.

Incidence Rate. As indicated in table 4, the median incidence rate of the high risk jobs was 18.4 reported claims per 200,000 hours of exposure. By definition, all the low risk jobs had an incidence rate of zero.

Lost and Restricted Days. The median number of lost and restricted days in high risk jobs were 111.5 and 42.9, respectively. These values were normalized to 100 full-time workers per year (200,000 hours of exposure), which is the statistical convention that the Bureau of Labor Statistics (1990) employs. The median value of 111.5 lost days from the high risk jobs in this study is approximately the same as the 107.4 lost work days that the Bureau of Labor Statistics (1990) reported for the national manufacturing industry as a whole (based on 1988 data).

By definition, there were no lost or restricted days in the low risk jobs in this study.

Table 4. Mean values, standard deviations, and probability of type I error of job characteristics. The effect tested was risk of CTDs (DF = 1), and the error term was job nested within risk level (DF = 18).

Dependent Var.	High Risk Mean	St.Dev.	Low Risk Mean	St.Dev.	Type I Error
JOB CHARACTERISTICS					
Number of wrist movement**	24738	10432	26132	15259	0.8178
Number of workers	16.9	(15.6)	6.50	(2.56)	0.0581
Number of incidents	3.90	(3.14)	0	-	-
Incidence rate***	18.4@	(56.0)	0	-	-
Lost days****	111.5@	(419)	0	-	
Restricted days****	42.9@	(131)	0	-	-
Turnover rate (%)	33.0@	(85.7)	0.50@	(6.06)	0.0569
Wt. of object (kg)	1.38	(1.51)	0.87	(1.31)	0.4320
Work height (m)	0.87	(0.15)	1.01	(0.13)	0.0328*
Moment arm (m)	0.70	(0.25)	0.60	(0.13)	0.2609
Left hand grip force (kgf)	12.8	(8.65)	4.80	(3.73)	0.0198*
Right hand grip force (kgf)	12.0	(8.26)	4.58	(3.96)	0.0194*

@ median value
* statistically significant at the 0.05 level
** per eight hour shift
*** normalized to 200,000 hours of exposure
**** normalized to 100 full-time workers per year

Turnover rate. The turnover rate of workers in each job was calculated according to equation **(12)**. (Note: the turnover rate can be greater than 100%.)

$$\textbf{turnover rate} = (\textbf{wleft} / \textbf{positions}) * 100 \qquad (12)$$

where:

wleft = number of workers who left job during time period that OSHA logs were monitored

#positions = number of positions (workers) within job

The median turnover rate in the high risk jobs was approximately 66 times as great as in low risk jobs (33% vs. 0.5%).

Physical Attributes of Workplace. Except for the work height, the weights of parts and moment arm from the work area to the lower spine were not significantly different (see table 4). The work height in the low risk jobs was higher than in high risk jobs.

Handgrip Types and Forces. The type of hand configurations that workers utilized to perform their tasks were classified into two general groups, power and pinch grips. The power and pinch grasps were split about evenly among the subjects within each risk group.

As estimated by the Smedley grip strength dynamometer, the grip forces required in the high risk jobs were about three times as great as the low risk grip forces (left hand: 12.8 kgf vs. 4.8; right hand: 12.0 vs. 4.58) (see table 4). These values are similar to the grip forces that Silverstein et al. (1986, 1987) measured in jobs that were classified as high and low force jobs. In Silverstein's et al. (1986) epidemiological study investigating CTDs, the mean adjusted grip forces in the high and low force jobs were 12.7 and 3.0 kgf, respectively. In Silverstein's et al. (1986, 1987) studies, the mean adjusted grip force was defined according to equation **(13)**.

$$\textbf{Mean adjusted force (kgf)} = \textbf{(var/mean)} + \textbf{mean} \qquad \textbf{(13)}$$

where:

var = variance of grip force within a subject during a task

mean = mean grip force within a subject during a task

Structure of Statistical Analysis

The statistical analyses of wrist motion data were structured according to figures 18 and 19. In figure 18, there were three sets of data, with each of the latter two sets encompassing the collapsed means of the previous set. For example, the first data set, D1, contained all the data from all intervals within trials. D1 had 1528 lines of data (each line was considered an observation). The summary

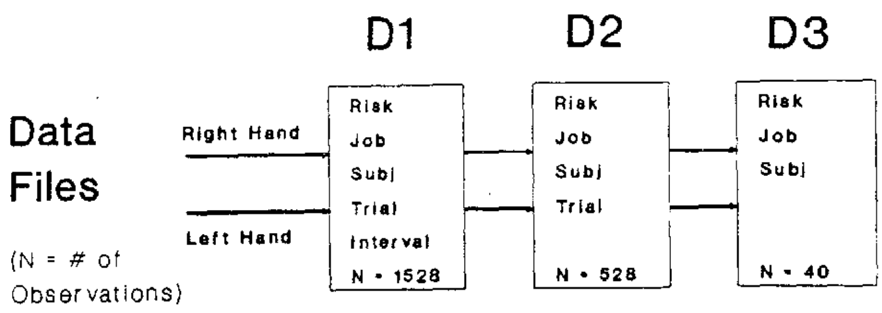


Figure 18. Conditioning of data collapsed over intervals and trials.

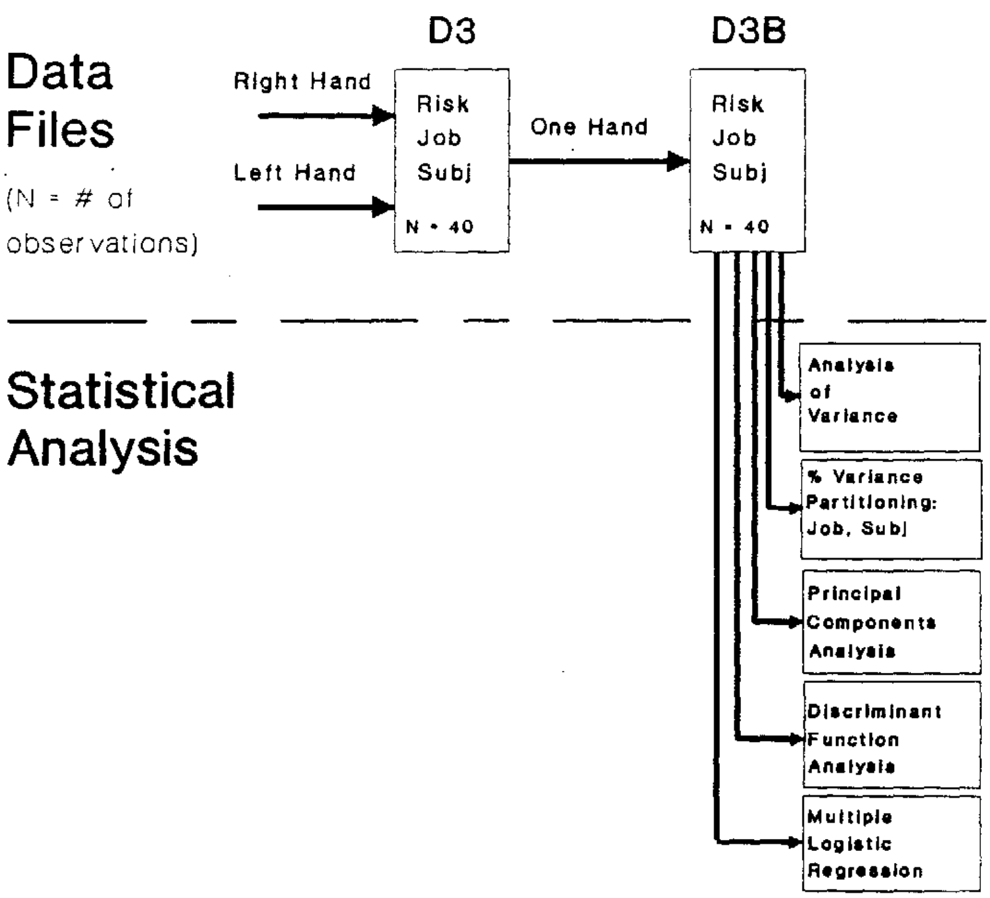


Figure 19. Statistical analysis of data collapsed over hands.

MOTION DEP. VARIABLES

			RAD/ULN												FLEX/EXT	PRON/SUP
			POS				VEL				ACCEL					
			Avg	Min	Max	Rge	Avg	Min	Max	Dif	Avg	Min	Max	Dif	" "	" "
HIGH RISK	Job 1	Subj 1														
		Subj 2														
	Job 2	Subj 3														
		Subj 4														
	" "	" "														
	Job 10	Subj 19														
		Subj 20														
LOW RISK	Job 11	Subj 21														
		Subj 22														
	Job 12	Subj 23														
		Subj 24														
	" "	" "														
	Job 20	Subj 39														
		Subj 40														

Figure 20. Structure of independent variable (CTD risk) and kinematic dependent variables. Each horizontal line represents one subject's data, and each vertical line represents mean values of the respective parameter for each subject.

statistics of the intervals were then averaged and collapsed over all trials to obtain set D2, which contained 528 lines. Likewise, all the summary statistics from the trials were averaged and collapsed over all subjects to produce the 40 observations in set D3. Each observation in D3 referred to a subject.

In order to remove handedness from the dataset, the kinematic data from both hands were then collapsed into one hand, as indicated in figure 19. This was accomplished by considering the wrist motion from only the injured hand in high risk jobs, which was determined from OSHA logs and medical records, and only the hand of dominant motion in low risk jobs. Figure 20 represents the structure of data from set D3B.

Descriptive Analysis of Wrist Motion

Scatter Plots. With respect to each kinematic variable, the means were plotted against the standard deviation of each subject. Figure 21 illustrates the scatter plot for F/E acceleration, which was typical for most kinematic variables. Figure 21 clearly shows the separation between the low and high risk values. The high standard deviation of the point in the upper right hand corner of figure 21 was due to the variance between subtasks for that particular subject.

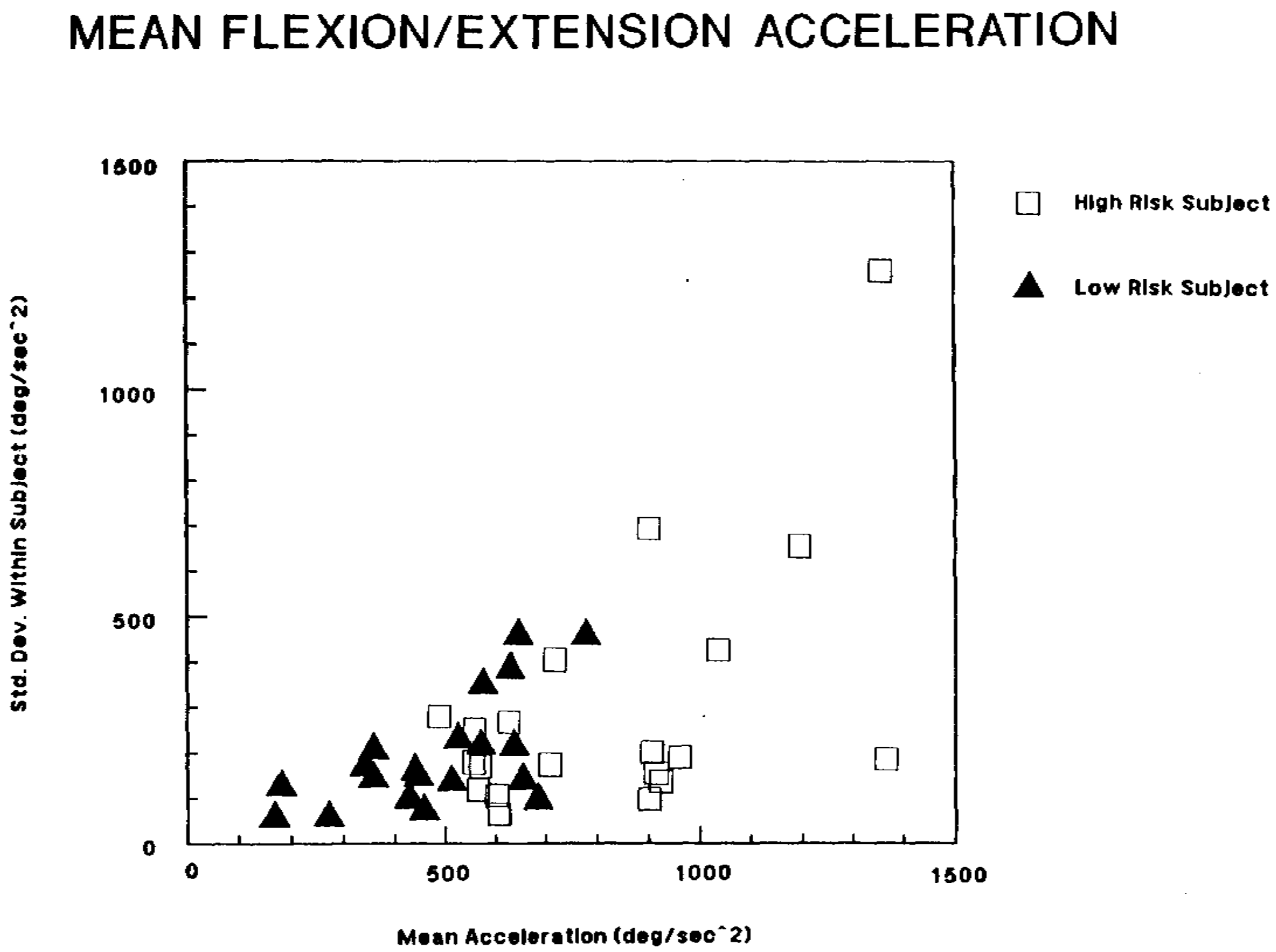


Figure 21. Scatter plot of flexion/extension mean acceleration as a function of CTD risk level. Each symbol represents one subject's respective data.

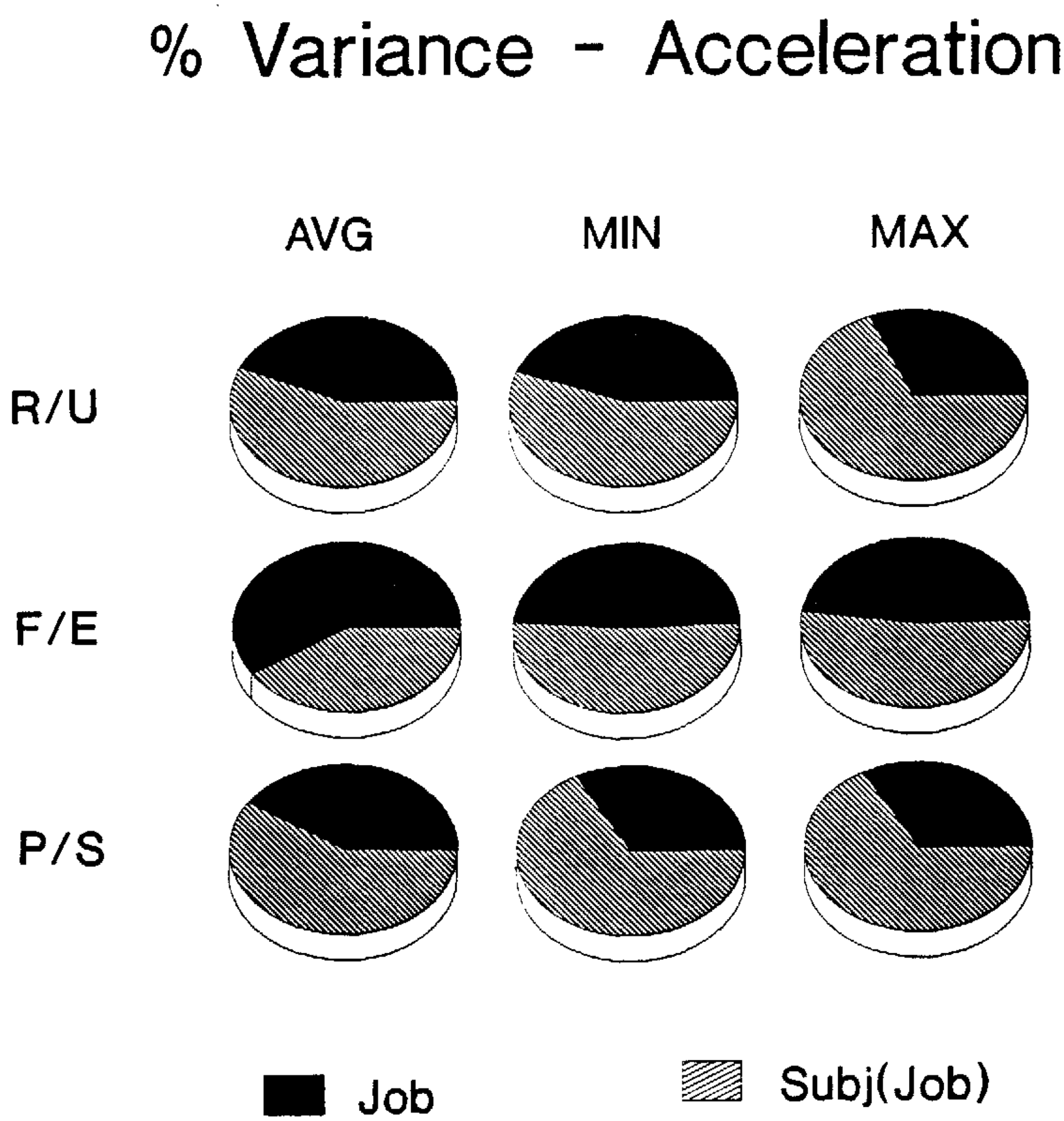


Figure 22. Partitioning of mean acceleration variance into two components, job and subject nested under job.

Partitioning of Variance -- Job and Subject. Since the experimental design in this study was a fully nested design (refer to figure 7), the percentage of variance attributable to individual sources was partitioned from data in set D3B (refer to figure 19). Figure 22 illustrates the percentage of variance of acceleration variables attributable to two components, jobs and subjects nested within jobs. The pattern in figure 22 was similar to the overall patterns for position and velocity in that the variance between subjects within jobs accounted for a substantial, and often majority, amount of variance.

Wrist Motion -- Means of High vs. Low Risk Values. The average values of the wrist motion summary statistics are listed in table 5 and illustrated in bar chart form in figures 23 through 28. These values are the collapsed results from both hands of data (set D3B, figure 19). Figures 23 through 25 show the R/U and F/E mean values while figures 26 through 28 reveal the P/S results. Within each bar chart, the mean, minimum, maximum, and maximum difference were plotted as a function of risk level. The maximum difference was calculated according to equation (14).

$$\textbf{Maximum Difference} = \textbf{Max} - \textbf{Min} \quad (14)$$

where:

Max Diff. = maximum value minus minumum value within an interval, trial, subject, or risk level

Max = maximum value within an interval, trial, subject, or risk level

Min = minimum value within an interval, trial, subject, or risk level

The pictorial trend across all the position, velocity, and acceleration values in figures 23 through 28 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. According to table 6, the percent increase of the high risk position values were about 20% to 30% greater than low risk 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.

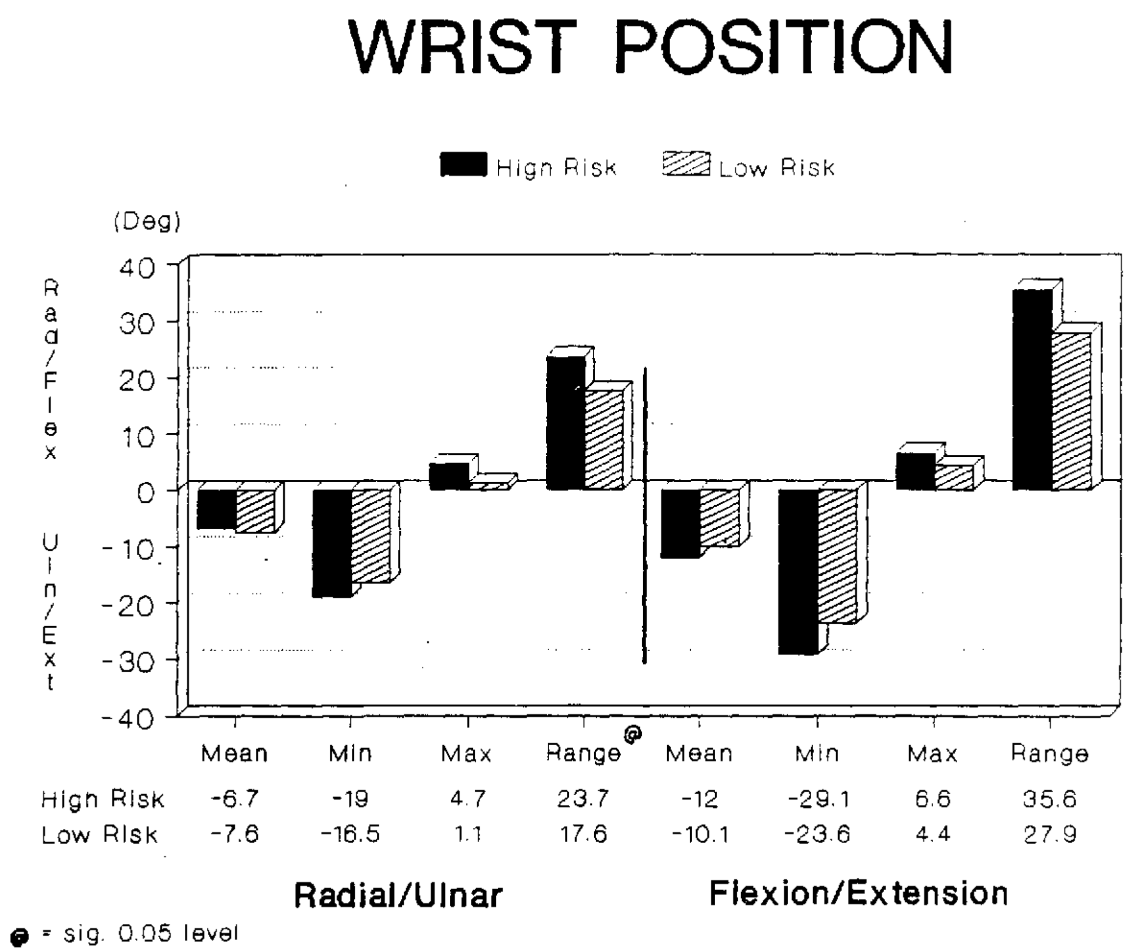


Figure 23. Mean values of wrist position in the radial/ulnar and flexion/extension planes as a function of CTD risk level. Each bar's height represents the mean of twenty subjects' data.

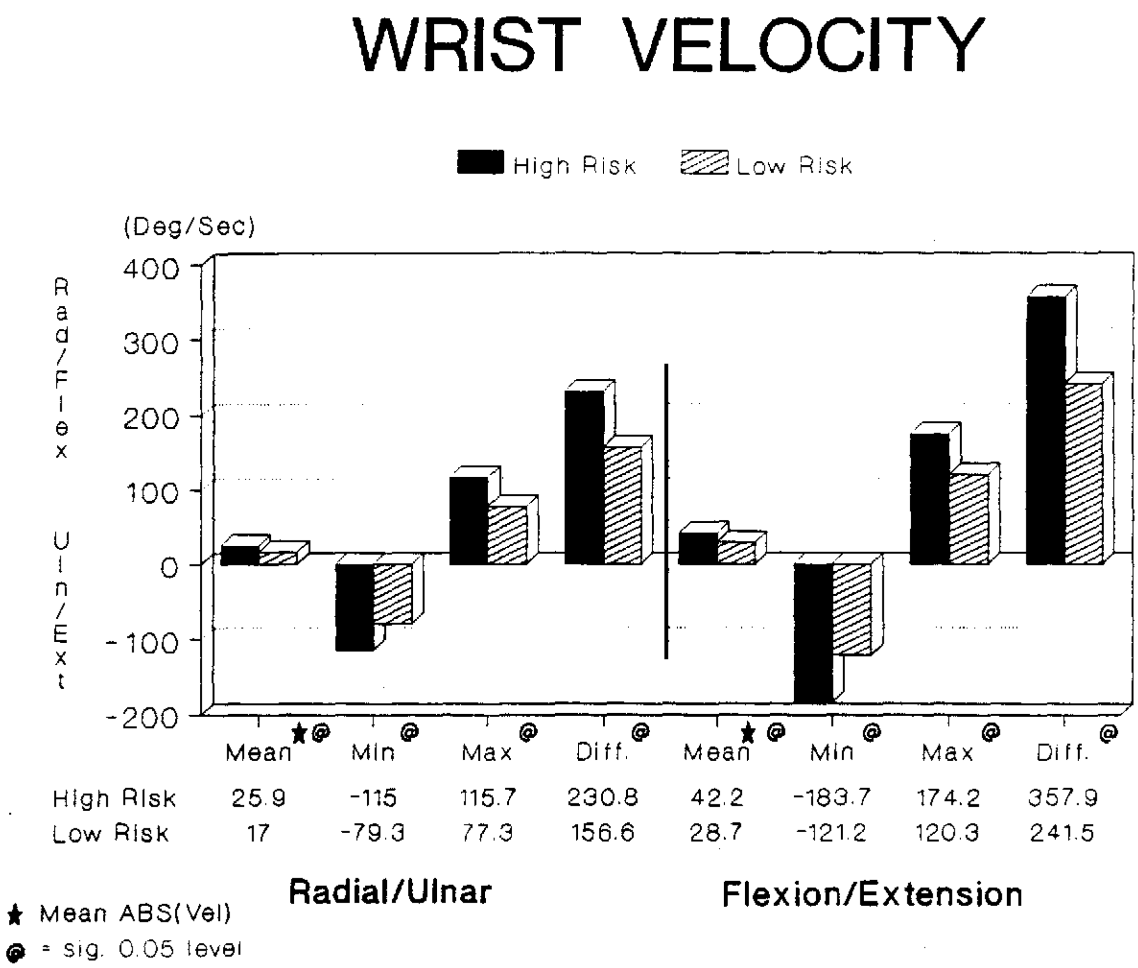


Figure 24. Mean values of wrist velocity in the radial/ulnar and flexion/extension planes as a function of CTD risk level.

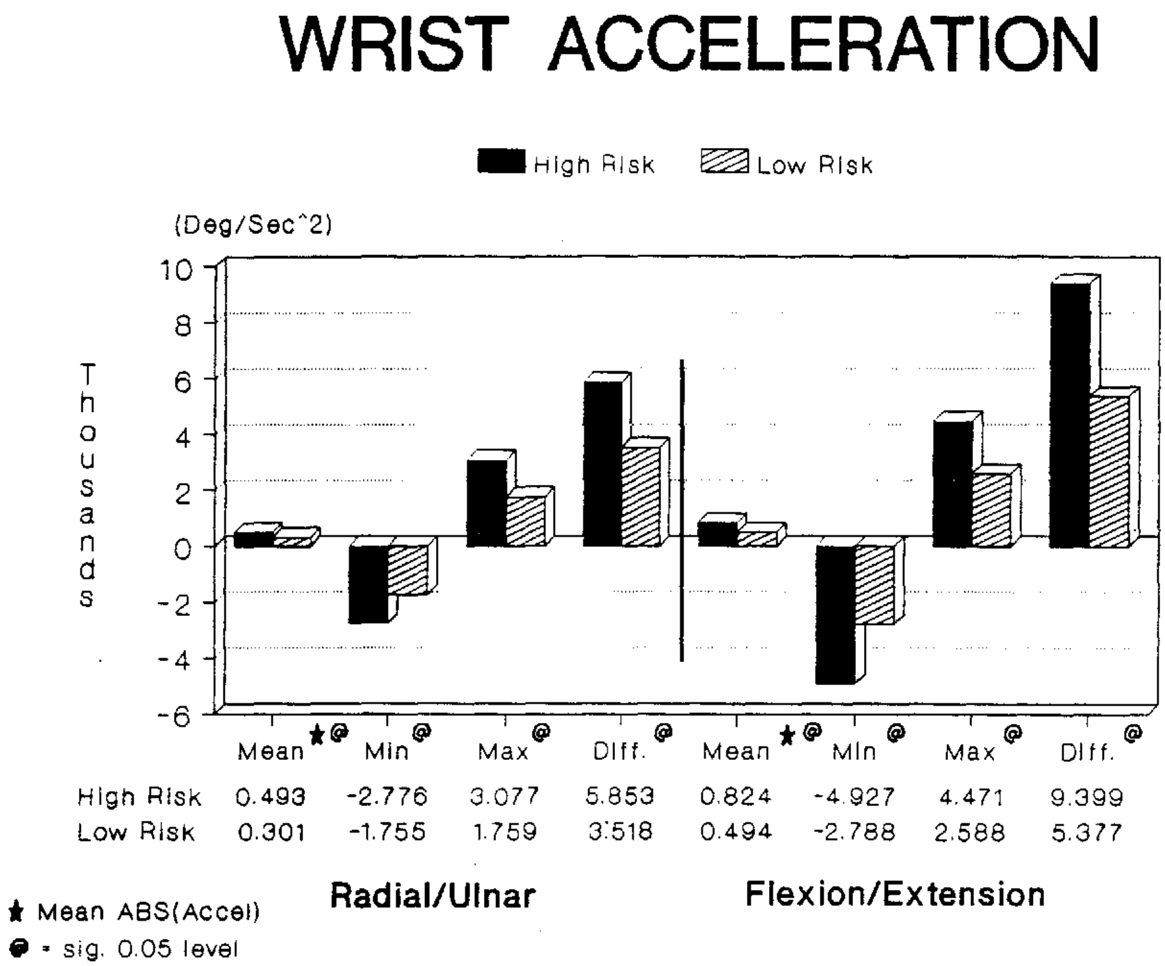


Figure 25. Mean values of wrist acceleration in the radial/ulnar and flexion/extension planes as a function of CTD risk level.

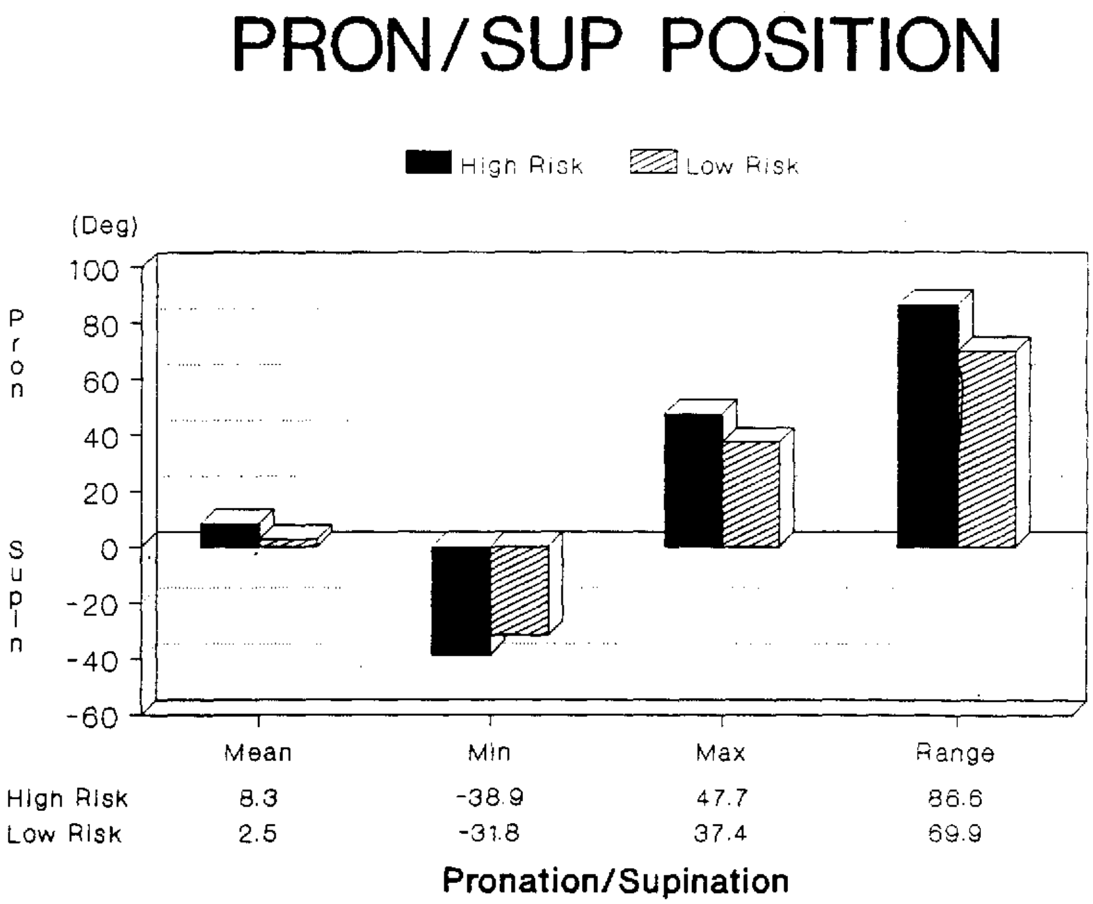


Figure 26. Mean values of wrist position in the pronation/supination plane as a function of CTD risk level.

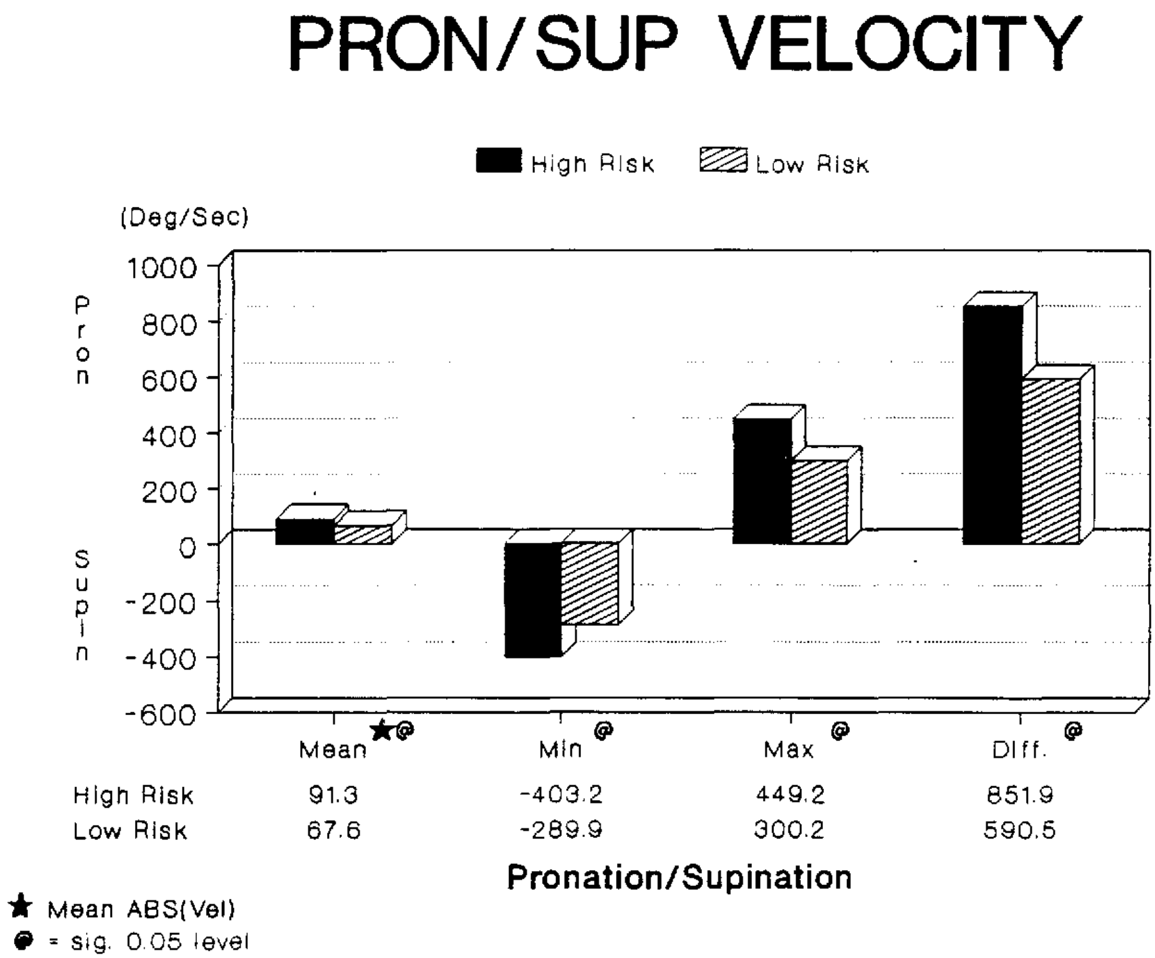


Figure 27. Mean values of wrist velocity in the pronation/supination plane as a function of CTD risk level.

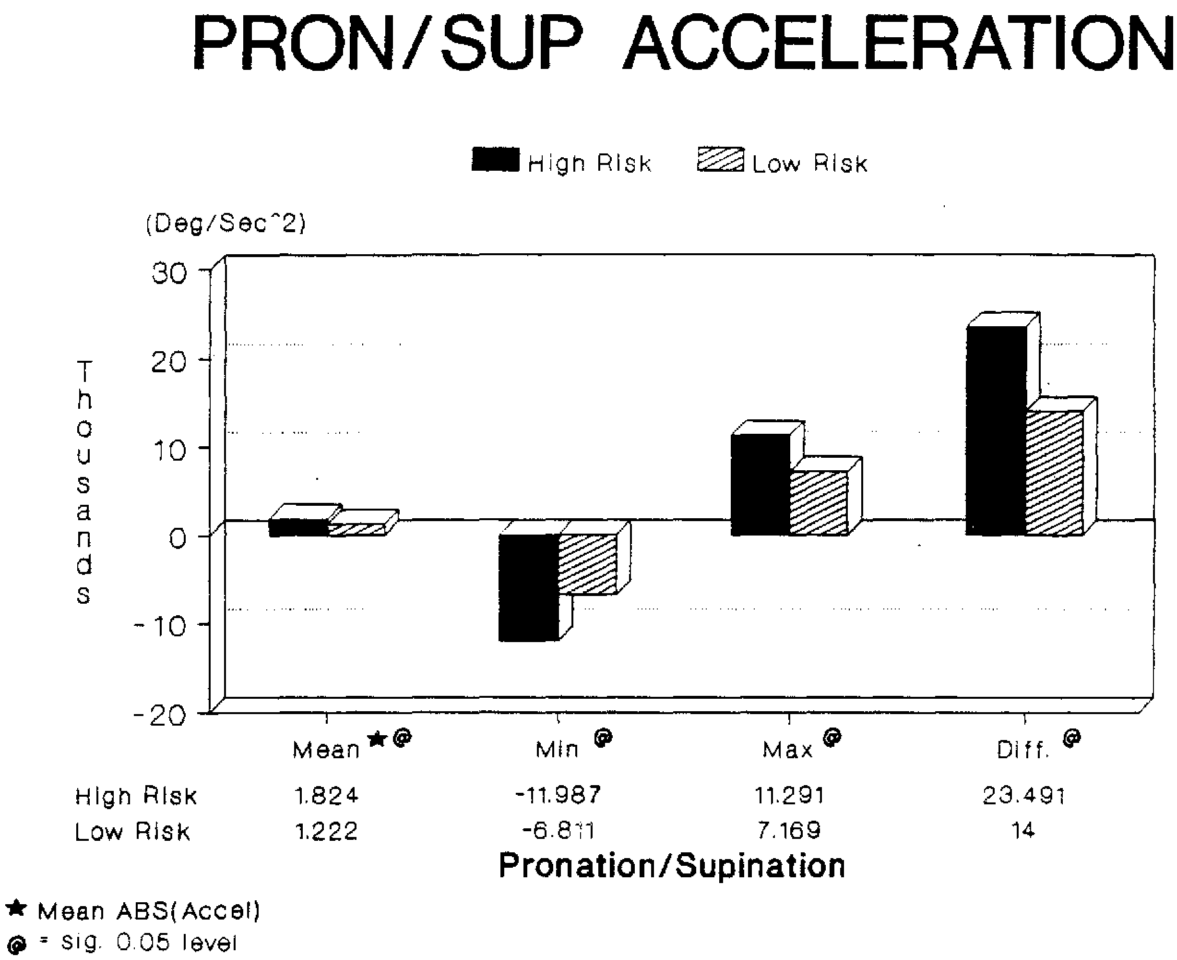


Figure 28. Mean values of wrist acceleration in the pronation/supination plane as a function of CTD risk level.

Table 5. Summary statistics of the kinematic wrist motion data from low and high risk groups of CTD risk.

Position Variables (deg)	**Low Risk Mean**	**Low Risk Std. Dev.**	**High Risk Mean**	**High Risk Std. Dev.**
R/U Pos Avg	-7.62	4.42	-6.73	4.66
R/U Pos Min	-16.51	5.57	-18.96	5.78
R/U Pos Max	1.12	6.17	4.69	4.76
R/U Pos Diff.	17.64	7.53	23.65	6.71
F/E Pos Avg	-10.09	11.88	-12.02	7.16
F/E Pos Min	-23.58	13.12	-29.08	7.32
F/E Pos Max	4.35	12.36	6.56	11.11
F/E Pos Diff.	27.95	9.92	35.63	11.53
P/S Pos Avg	2.47	38.63	8.30	20.50
P/S Pos Min	-31.84	38.76	-38.93	23.40
P/S Pos Max	37.36	38.69	47.70	19.48
P/S Pos Diff.	69.91	29.55	86.63	25.47

Velocity Variables (deg/sec)	**Low Risk Mean**	**Low Risk Std. Dev.**	**High Risk Mean**	**High Risk Std. Dev.**
R/U Vel Avg	17.0	6.7	25.9	6.7
R/U Vel Min	-79.3	34.9	-115.1	36.5
R/U Vel Max	77.3	31.1	115.7	39.5
R/U Vel Diff.	156.6	63.4	230.8	71.9
F/E Vel Avg	28.7	7.6	42.2	11.7
F/E Vel Min	-121.2	42.8	-183.7	76.8
F/E Vel Max	120.3	38.1	174.2	58.4
F/E Vel Diff.	241.5	78.2	358.0	128.5
P/S Vel Avg	67.7	19.5	91.3	23.3
P/S Vel Min	-289.9	112.0	-403.2	149.1
P/S Vel Max	300.2	129.0	449.2	256.2
P/S Vel Diff.	590.5	211.2	852.0	394.6

Table 5 (continued). Summary statistics of the kinematic wrist motion data from low and high risk groups of CTD risk.

Acceleration Variables (deg/sec^2)	**Low Risk Mean**	**Low Risk Std. Dev.**	**High Risk Mean**	**High Risk Std. Dev.**
R/U Acc Avg	301	125	494	142
R/U Acc Min	-1755	818	-2776	913
R/U Acc Max	1759	834	3077	1313
R/U Acc Diff.	3518	1641	5853	2176
F/E Acc Avg	494	156	824	268
F/E Acc Min	-2788	862	-4927	1913
F/E Acc Max	2588	802	4471	1527
F/E Acc Diff.	5377	1630	9398	3388
P/S Acc Avg	1222	384	1824	533
P/S Acc Min	-6811	2571	-11987	6330
P/S Acc Max	7169	2980	11291	4954
P/S Acc Diff.	14000	5545	23490	11483

Table 6. Increase of high risk kinematic values as a percentage of low risk values.

Kinematic Variable	**Plane of Motion R/U**	**F/E**	**P/S**
Pos Avg	NA	NA	NA
Pos Min	14.8%	23.3%	22.3%
Pos Max	318.0%*	50.8%	27.7%
Pos Diff.	34.1%	27.5%	23.9%
Vel Avg	52.4%	47.0%	34.9%
Vel Min	45.1%	51.6%	39.1%
Vel Max	49.7%	44.8%	49.6%
Vel Diff.	47.4%	48.2%	44.3%
Acc Avg	64.1%	66.8%	49.3%
Acc Min	58.2%	76.7%	76.0%
Acc Max	74.9%	72.8%	57.5%
Acc Diff.	66.4%	74.8%	67.8%

* this appears to be an outlier because of the small value in the denominator (1.12 deg)

MANOVA and ANOVAs of Wrist Motion

A multivariate analysis of variance (MANOVA) was performed on all the mean, minimum, and maximum wrist motion data from set D3B (refer to figure 19). The CTD risk effect was significant at the 0.007 level. As a followup, individual analyses of variance (ANOVAs) were performed on the effect of CTD risk on each dependent variable. Since the experimental design was a nested one, the error term for risk level was job nested within risk level (Montgomery, 1984). The statistical results of the ANOVAs are shown in table 7. For each significant t-test, the high risk value was greater than the low risk value.

The overall pattern of table 7 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. The results from the MANOVA and ANOVAs provide statistical evidence for the gestaltic conclusion made from the bar charts in figures 23 through 28 -- velocity and acceleration measures separated CTD risk levels more distinctly than position variables.

Table 7. Probability of type I error from analysis of variance of motion variables. The effect tested was risk of CTDs (DF = 1), and the error term was job nested within risk level (DF = 18).

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

* = significant at the 0.05 level
R/U = radial/ulnar
F/E = flexion/extension
P/S = pronation/supination

Principal Components Analysis

Principal components analysis (PCA) is a statistical technique "applied to a single set of variables where the researcher is interested in discovering which variables in the set form coherent subsets that are relatively independent of one another" (Tabachnik and Fidell, 1989, p. 597). One of the specific goals of PCA is to reduce a large number of variables to a few subsets. Since the dependent variable (risk of CTDs) is not a part of PCA, Tabachnick and Fidell (1989) warn that one of the main problems with PCA is that "there is no criterion beyond interpretability against which to test the solution" (p. 598).

PCA was performed on the following sets of wrist motion variables from dataset D3B, which contained wrist motion from the affected hand (refer to figure 19):

1) all mean, min, and max variables
2) all position variables
3) all velocity variables
4) all acceleration variables
5) all R/U variables
6) all F/E variables
7) all P/S variables

PCAs were also performed on the above sets of variables as a function of CTD risk.

As stated earlier, the risk of CTDs was not involved in these six PCAs. The covariance matrix was used in the PCAs of position, velocity, and acceleration variables because the units of measure were homogenous within each PCA. However, the correlational matrix was used in the PCAs of all variables and in each plane because the units were heterogeneous (deg, deg/sec, and deg/sec^2). Typically in PCA, the variables that have the highest coefficients within the components are those variables with the highest standard deviations.

The results of the PCAs are as follows:

1) As shown in table 9, the results of PCA on all mean, minimum, and maximum variables indicated that the velocity and acceleration variables dominated the first principal

component. Within the first component, the mean and maximum differences (maximum - minimum) in velocity and acceleration accounted for a majority of variance. The second principal component was dominated by the differences between F/E and P/S position variables.

2) Separate PCA of blocks of position, velocity, and acceleration resulted in similar patterns. Table 10 reveals that the maximum difference of P/S acceleration was most highly correlated with the first component, and the P/S variables along with maximum difference of R/U dominated the second component. Differences in patterns of variables within the second component did occur over position, velocity, and acceleration PCAs, but these differences were inconsequential considering the second component comprised only a small percentage of variance (usually less than 10%).

3) PCA of kinematic variables within planes resulted in similar patterns. The dynamic (velocity and acceleration) and static (position) variables were most highly correlated with the first and second components, respectively. As indicated in table 11, the mean and maximum difference of velocity and acceleration dominated the first component, while position variables accounted for the second component.

4) The results from PCA of each risk group were overall similar to the results from risk groups analyzed collectively.

Table 8. Key to coding of wrist motion variables.

First character:	R = radial/ulnar
	F = flexion/extension
	P = pronation/supination
Second character:	P = position
	V = velocity
	A = acceleration
Third through fifth characters:	AVG = average
	MIN = minimum
	MAX = maximum
	RGE = range (range = max - min) Note: range applies to position only
	DIF = difference (difference = max - min)

Examples:

RPAVG = radial/ulnar average position
FVDIF = flexion/extension difference of velocity
PAMAX = pronation/supination maximum acceleration
PPMIN = pronation/supination minimum position

Table 9. Results of principal components analysis (PCA) of the all average, minimum, and maximum variables in the R/U, F/E, and P/S planes. This PCA was performed on a combined set of high and low risk data. The sign preceding each variable represents whether the variable is positively or negatively correlated with the component. Refer to table 8 for key to coding of variables.

Component	Variable	Coefficient	Proportion of Variance	Cumulative Variance
First Component	RPAVG	.00	0.54	0.54
	RPMIN	-.16		
	RPMAX	.14		
	FPAVG	-.07		
	FPMIN	-.15		
	FPMAX	.05		
	PPAVG	.06		
	PPMIN	-.07		
	PPMAX	.12		
	RVAVG	.21		
	RVMIN	-.23		
	RVMAX	.23		
	FVAVG	.22		
	FVMIN	-.21		
	FVMAX	.23		
	PVAVG	.20		
	PVMIN	-.21		
	PVMAX	.22		
	RAAVG	.22		
	RAMIN	-.23		
	RAMAX	.22		
	FAAVG	.22		
	FAMIN	-.24		
	FAMAX	.24		
	PAAVG	.22		
	PAMIN	-.23		
	PAMAX	.24		

(continued)

Table 9 (continued). Results of principal components analysis (PCA) of all average, minimum, and maximum variables in the R/U, F/E, and P/S planes.

Component	Variable	Coefficient	Proportion of Variance	Cumulative Variance
Second Component	RPAVG	.04	0.12	0.66
	RPMIN	.10		
	RPMAX	.06		
	FPAVG	-.42		
	FPMIN	-.31		
	FPMAX	-.44		
	PPAVG	.41		
	PPMIN	.42		
	PPMAX	.35		
	RVAVG	.06		
	RVMIN	.00		
	RVMAX	.00		
	FVAVG	-.01		
	FVMIN	.11		
	FVMAX	-.11		
	PVAVG	.02		
	PVMIN	.06		
	PVMAX	-.03		
	RAAVG	.05		
	RAMIN	-.04		
	RAMAX	.02		
	FAAVG	-.02		
	FAMIN	.05		
	FAMAX	-.10		
	PAAVG	.02		
	PAMIN	.07		
	PAMAX	-.02		

Table 10. Results of principal components analysis (PCA) of the all average, minimum, and maximum **acceleration** variables. This PCA was performed on a combined set of high and low risk data. The sign preceding each variable represents whether the variable is positively or negatively correlated with the component. Refer to table 8 for key to coding of variables.

Component	**Variable**	**Coefficient**	**Proportion of Variance**	**Cumulative Variance**
First Component	RAAVG	-.02	0.93	0.93
	RAMIN	.10		
	RAMAX	-.14		
	FAAVG	-.03		
	FAMIN	.22		
	FAMAX	-.18		
	PAAVG	-.06		
	PAMIN	.73		
	PAMAX	-.60		
Second Component	RAAVG	.05	0.03	0.96
	RAMIN	-.40		
	RAMAX	.38		
	FAAVG	.00		
	FAMIN	.11		
	FAMAX	.00		
	PAAVG	.08		
	PAMIN	.58		
	PAMAX	.58		

Table 11. Results of principal components analysis (PCA) of the all position, velocity, and acceleration variables in the **F/E** plane. This PCA was performed on a combined set of high and low risk data. The sign preceding each variable represents whether the variable is positively or negatively correlated with the component. Refer to table 8 for key to coding of variables.

Component	**Variable**	**Coefficient**	**Proportion of Variance**	**Cumulative Variance**
First Component	FPAVG	-.05	0.64	0.64
	FPMIN	-.20		
	FPMAX	.16		
	FVAVG	.40		
	FVMIN	-.39		
	FVMAX	.39		
	FAAVG	.39		
	FAMIN	-.40		
	FAMAX	.40		
Second Component	FPAVG	.63	0.27	0.91
	FPMIN	.53		
	FPMAX	.57		
	FVAVG	.00		
	FVMIN	-.07		
	FVMAX	.05		
	FAAVG	-.01		
	FAMIN	.00		
	FAMAX	.02		

Discriminant Function Analysis (DFA)

Discriminant function analysis is a statistical technique whose purpose is to predict group membership from a set of predictors (Tabachnik and Fidell, 1989). In this study, group membership was risk of CTDs (low vs. high), and the set of predictors were wrist motion variables. DFA assumes that the covariance matrices within risk groups are homogenous.

The test statistic in DFA is the percentage of subjects correctly classified into CTD risk groups. The normal DFA will produce biased, overclassified results, so a jackknifed DFA is recommended to reduce the bias in classification. A jackknifed DFA from BMDP software (procedure 7M) was used in this analysis to estimate the percentage of correctly classified subjects.

Jackknifed stepwise DFA were performed on the data sets that contained wrist motion from only the affected hand (refer to set D3B in figure 19).

Stepwise DFA on All Variables. A stepwise DFA was performed on all the average and maximum difference wrist motion variables collectively. The maximum difference variables were chosen over the maximum and minimum variables for the sake of parsimony and also to avoid the problem of multicollinearity in DFA. (Since the maximum difference is a linear combination of minimum and maximum, it is perfectly correlated with the minimum and maximum.) The significant predictor variables in this stepwise DFA were R/U range of position, average R/U velocity, and maximum difference of F/E acceleration, which resulted in an overall 78.4% correct classification.

Stepwise DFA on Structured Sets of Variables. Stepwise DFA were performed on permutations (combinations of one, two, and three variables) of five structured sets of predictor variables: range of position, average velocity, velocity difference, average acceleration, and acceleration difference. Tables 12 and 13 reveal the results of DFA on average velocity and acceleration variables.

DFA results suggest the following:

1) velocity and acceleration variables classified risk level better than range of position variables.

2) the sets of average velocity, average acceleration, and acceleration difference predicted group membership about equally well, with an average percentage of correctly classified subjects of approximately 73%. Tables 12 and 13 show the results of average velocity and acceleration analyses.

3) based on F values, the F/E plane tended to predict CTD risk the best.

4) based on conclusions 2) and 3) from DFA, the wrist motion variables that appeared to discriminate most

effectively between CTD risk levels were average velocity and average and difference of acceleration in the F/E plane.

Table 12. Results of stepwise discriminant analysis on structured sets of **average velocity** data from dataset D3B (refer to figure 19). The classification variable was risk with two levels, low and high. The percentages of correct classification were results from jackknifed stepwise discriminant analysis (BMDP, procedure 7M). Refer to table 8 for key to coding of variables.

Signif. Variables*	**F Value**	**% Correct Low Risk**	**% Correct High Risk**	**% Correct Total**
RVAVG*	17.7	70	75	72.5
FVAVG*	18.9	85	60	72.5
PVAVG*	11.1	77.8	73.7	75.7
RVAVG* FVAVG*	3.7 18.9	75	70	72.5
RVAVG* PVAVG	17.8	77.8	73.7	75.7
FVAVG* PVAVG*	20.2 2.0	83.3	63.2	73.0
RVAVG* FVAVG* PVAVG	3.4 20.2	77.8	73.7	75.7

* **F to enter** = 1.05
F to remove = 1.00

Table 13. Results of stepwise discriminant analysis on structured sets of **average acceleration** data from set D3B (refer to figure 19). The classification variable was risk with two levels, low and high. The percentages of correct classification were results from jackknifed stepwise discriminant analysis (BMDP, procedure 7M). Refer to table 8 for key to coding of variables.

Signif. Variables*	**F Value**	**% Correct Low Risk**	**% Correct High Risk**	**% Correct Total**
RAAVG*	20.7	80	65	72.5
FAAVG*	22.8	85	60	72.5
PAAVG*	15.4	72.2	84.2	78.4
RAAVG* FAAVG*	2.9 22.8	75	70	72.5
RAAVG* PAAVG*	19.4 1.9	72.2	63.2	67.6
FAAVG* PAAVG*	24.4 1.1	77.8	57.9	67.6
RAAVG* FAAVG* PAAVG	2.2 24.4	77.8	68.4	73.0

* F to enter = 1.05
F to remove = 1.00

Multiple Logistic Regression (MLR)

Multiple logistic regression is a technique in which two or more continuous variables predict discrete levels of a dependent variable. MLR has less stringent assumptions than DFA in that no parametric assumptions are made on the underlying distributions of the dependent variable. Data from set D3B were analyzed with MLR (refer to figure 19).

A commonly used statistic in MLR is an odds ratio. The odds of an event is the ratio of the probability of an event divided by its complementary probability, as defined in equation (15).

$$\mathbf{odds} = p / q \qquad (15)$$

where:
p = probability of an event occurring
$q = 1 - p$ = probability of an event not occurring

In the domain of this study, the odds ratio was defined as the probability of a high risk of CTDs given a predictor variable at the midpoint of the low and high risk values (one half the distance between the low and high risk values) divided by the probability of a high risk of CTDs given a predictor variable at the mean low risk value. The odds ratio for only one predictor variable assumes all the other predictor variables are held constant. An odds ratio for a group of predictor variables is defined in equations (16), (17), and (18).

$$O.R. = (e^{(B1*D1)})*(e^{(B2*D2)})* \ldots *(e^{(Bn*Dn)}) \quad (16)$$

$$O.R. = e^{(B1*D1 + B2*D2 + \ldots + Bn*Dn)} \quad (17)$$

$$\log(O.R.) = B1*D1 + B2*D2 + \ldots + Bn*Dn \quad (18)$$

where:

O.R. = ratio of the probability of a high risk of CTDs given i = 1..n predictor variables at the midpoints of the low and high risk values (grand mean) divided by the probability of a high risk of CTDs given i = 1..n predictor variables at the low risk values

Bi = coefficient of the ith predictor variable (i = 1..n)

Di = one-half of the difference between the mean high and mean low risk values of predictor variable i

95% confidence intervals were computed for the odds ratio according to equations (19) through (22).

$$\log(O.R.lower) = \log(O.R.) - (1.96)*(D1)*(S.E.) \quad (19)$$
$$\log(O.R.upper) = \log(O.R.) + (1.96)*(D1)*(S.E.) \quad (20)$$

$$O.R.lower = e^{(\log(O.R.) - (1.96)*(D1)*(S.E.))} \quad (21)$$
$$O.R.upper = e^{(\log(O.R.) + (1.96)*(D1)*(S.E.))} \quad (22)$$

where:

O.R. lower = lower bound of 95% confidence interval

O.R. upper = upper bound of " " " "

S.E. = standard error of first predictor variable's coefficient (B1)

D1 = one-half of difference between mean high and low risk values of first predictor variable

Stepwise MLR on Grip Force. A stepwise MLR was performed on left and right hand grip force data. Only right grip force entered and stayed in the model at 0.05 significance level, and the resulting odds ratio was 1.9 (95% confidence interval = 1.18 to 3.06).

Stepwise MLR on All Variables. Similar to DFA, a stepwise MLR was performed on all the average and maximum differences of wrist motion variables collectively. Similar to DFA, the maximum difference variables were chosen over minimum and maximum for parsimony and to avoid problems of multicollinearity. As indicated in table 14, the sole significant variable was F/E acceleration, with an odds ratio of 6.05.

Stepwise MLR on Structured Sets of Variables. Stepwise MLR was performed on permutations of the following five structured sets of predictor variables:

1) range of position (table 15)
2) average velocity (table 16)
3) difference of velocity
4) average acceleration (table 17)
5) difference of acceleration

The statistical results in tables 15 through 17 suggest the following:

1) F/E average acceleration appeared to predict CTD risk better than any other variable, with an odds ratio of 6.05.

2) The second best predictor appeared to be F/E average velocity, with an odds ratio of 3.8.

3) Position variables predicted CTD risk poorly.

Table 14. Results of stepwise multiple logistic regression on all average and range variables from data set D3B (refer to figure 19). The dependent variable is CTD risk with two levels, low and high. Refer to table 8 for key to coding of variables.

Variable*	**Regression Coefficient**	**Model Chi-Square**	**Odds Ratio**	**Odds Ratio 95% Confidence Interval**
FAAVG*	0.01091	21.92	6.05	1.66 - 22.02

* significant at the 0.05 level

Table 15. Results of stepwise multiple logistic regression on structured sets of **range of position** variables from data set D3B (refer to figure 19). The dependent variable is CTD risk with two levels, low and high. Refer to table 8 for key to coding of variables.

Variable*	**Regression Coefficient**	**Model Chi-Square**	**Odds Ratio**	**Odds Ratio 95% Confidence Interval**
RPRGE*	0.1203	6.74	1.443	1.062 - 1.961
FPRGE*	0.06907	5.01	1.305	1.013 - 1.680
PPRGE	0.02439	3.51	1.226	0.9693 - 1.550
RPRGE* FPRGE	0.1203	6.74	1.443	1.062 - 1.961
RPRGE* PPRGE	0.1363	7.48	1.515	1.080 - 2.127
FPRGE* PPRGE	0.07075	5.14	1.312	1.015 - 1.698
RPRGE* FPRGE PPRGE	0.1363	7.48	1.515	1.080 - 2.127

* significant at the 0.05 level

Table 16. Results of stepwise multiple logistic regression on structured sets of **average velocity** variables from data set D3B (refer to figure 19). The dependent variable is CTD risk with two levels, low and high. Refer to table 8 for key to coding of variables.

Variable*	Regression Coefficient	Model Chi-Square	Odds Ratio	Odds Ratio 95% Confidence Interval
RVAVG*	0.2000	14.83	2.435	1.369 - 4.330
FVAVG*	0.1841	17.72	3.465	1.477 - 8.132
PVAVG*	0.0564	10.41	1.952	1.179 - 3.232
RVAVG FVAVG*	 0.1841	17.72	3.465	1.477 - 8.132
RVAVG* PVAVG	0.1985	14.58	2.419	1.359 - 4.308
FVAVG* PVAVG	0.1977	18.46	3.798	1.499 - 9.632
RVAVG FVAVG* PVAVG	 0.1977	18.46	3.798	1.499 - 9.632

* significant at the 0.05 level

Table 17. Results of stepwise multiple logistic regression on structured sets of **average acceleration** variables from data set D3B (refer to figure 19). The dependent variable is CTD risk with two levels, low and high. Refer to table 8 for key to coding of variables.

Variable*	Regression Coefficient	Model Chi-Square	Odds Ratio	Odds Ratio 95% Confidence Interval
RAAVG*	0.01030	16.53	2.690	1.460 - 4.930
FAAVG*	0.009302	20.59	4.640	1.642 - 12.99
PAAVG*	0.003608	14.80	2.962	1.368 - 6.416
RAAVG FAAVG*	 0.009302	20.59	4.640	1.642 - 12.99
RAAVG* PAAVG	0.009908	15.38	2.589	1.422 - 4.711
FAAVG* PAAVG	0.01091	21.92	6.050	1.660 - 22.02
RAAVG FAAVG* PAAVG	 0.01091	21.92	6.050	1.660 - 22.02

* significant at the 0.05 level

Chapter V

DISCUSSION

Job Characteristics

CTD Risk Levels. According to epidemiological criteria, the high risk jobs that were monitored in this study definitely exposed workers to elevated risk of CTDs. The median incidence rate of 18.4 and lost days count of 111.5 per 200,000 hours of exposure corroborate the high risk level of the monitored jobs (refer to table 4). If each worker worked 2000 hours per year (50 weeks * 40 hrs/week = 2000 worker-hours; 200,000 hours per 100 workers) in these high risk jobs, then an alarming 18.4% of all the workers in these jobs reported CTDs.

Based on Wehrle's (1976) epidemiological reports of 25.6 CTS cases per 200,000 hours in some high risk jobs in industry, an incidence rate of 18.4 would definitely be considered high risk. A 18.4% prevalence is similar to Silverstein's et al. (1986) epidemiological findings of 15% to 25% prevalence of CTDs in the most strenuous jobs, which required high repetitions and forces.

Number of Wrist Movements. The jobs that were monitored in both the high and low risk groups were highly repetitious jobs, as demonstrated by the approximately 25,000 wrist movements that were recorded per shift. 25,000 wrist movements translates into a worker completing a fundamental wrist movement almost every second. The number of wrist motions were not significantly different between high and low risk groups.

Force Levels. While the mix of hand grip types was approximately the same in both high and low risk jobs, there were major differences in grip force. As indicated in table 4, the mean grip force in high risk jobs was about 2.5 times as great as in low risk jobs (left hand: 12.8 vs. 4.8 kgf; right hand: 12.0 vs. 4.58 kgf). This difference in grip force was not due to gloves because the Smedley grip strength dynamometer measured only external force (not internal muscular forces) and also because nine out of the ten jobs in each risk group required gloves.

The force values found in this study are similar to the grip forces that Silverstein et al. (1986, 1987) measured in jobs that were classified as high force. In Silverstein's et al. (1986) epidemiological study investigating CTDs, the mean adjusted grip force in the high force group was 12.7 kgf.

Although the difference in grip force between high and low risk jobs in the present study may appear to be a potentially confounding factor, its confounding is mitigated by two factors -- the odds ratio from MLR and the grip force protocol. First, the odds ratio for right hand grip force was 1.9, well below the odds ratio of 6.05 for F/E acceleration (left hand force was not significant). These statistics suggest that wrist motion separated the two levels of CTD risk much more distinctly than grip force. This comparison of odds ratios mitigates the potential confounding due to grip force and supports wrist motion as the primary set of variables that accounted for the difference in CTD incidence rate.

Second, after the monitored task, each subject was asked to squeeze a Smedley dynamometer in either a pulp pinch or power grip with approximately the same force that he/she exerts on the job. The type of grip was determined by the predominant hand configuration in each worker's job. This grip strength protocol had two potential problems that might have caused the difference in grip force between high and low risk jobs. First, each subject might have simulated the peak force required in the job, which would have resulted in an overestimate of the average force. Second, the position of the fingers and thumb on the Smedley might not have been identical to hand configurations on the job.

Partitioning of Variance. The fact that variance between subjects within jobs accounted for a substantial percentage of total variance in wrist motion warranted monitoring two subjects per job in this study (refer to figure 22). If subject variance had been consistently dominated by job variance, then one subject per job would have sufficed.

The large percentage of variance due to subjects could have been due to the following reasons:

1) In this study, the variance between subjects within a job was not purely due to differences between people but included variance due to performing the job in a slightly different orientation or with slightly dissimilar equipment or materials. Differences in orientation and equipment occurred in a minority of the twenty jobs we monitored. For example, the only feasible way to monitor the job that required application of weatherstripping around automobile windows was to measure the wrist motion of two workers. Each subject worked on only one side of the vehicle. The two workers were executing essentially the same motions but with different hands.

2) For some jobs in this study, the workstations were not precisely designed to physically dictate the motion patterns of the workers. The subjects were free to perform the task in a variety of ways -- hence, a large variance due to subjects in these jobs was not surprising. A well-designed ergonomic workstation should have engineering controls built into them in order to physically guide the worker's motion patterns.

3) Lacquaniti and Soechting (1982) found that wrist motion in simple arm movements tended to vary greatly, even though final target performance was accurate and repeatable. The wrist tended to vary its motion pattern across trials of whole arm movements, yet the hand consistently reached its destination with a high degree of accuracy. The large variance due to subjects could have been attributable to differences in motion strategies among workers. Some variation in wrist motion between subjects is expected, even in well-designed ergonomic workstations.

Based on the substantial percentage of variance due to subjects within a job, the protocol of monitoring two subjects per job should be continued in future studies of this kind.

Subject Characteristics

The physical characteristics of subjects between risk levels were comparable in several respects, thereby limiting the number of potential confounding factors. The subjects had identical gender distribution, similar distribution of handedness, similar gross and upper extremity anthropometric measures (except for trunk depth, which shouldn't affect wrist motion), and overall a lack of significant differences in the wrist's biomechanical capabilities. However, the subjects in the low risk group were on the average ten years older and had about ten more years of seniority than their counterparts in the high risk group. The potential confounding due to differences in age between the two risk groups is minimal considering the wrist's biomechanical capabilities (maximum and minimum position, velocity, and acceleration) of both groups were similar overall.

Wrist Motion as a Function of CTD Risk

Analysis of Variance. As indicated in table 7, the the velocity and acceleration measures were overall significantly different between high and low risk jobs while the position measures were not. These results demonstrate the importance of dynamic components in assessing CTD risk.

Wrist posture has been cited often as a risk factor of CTS and CTDs overall in the literature (Alexander and Pulat, 1985; Armstrong, 1983, 1986a, 1986b; Armstrong and Chaffin, 1979a, 1979b; Armstrong et al., 1982; Armstrong et al., 1986; Browne et al., 1984; Eastman Kodak Co., 1986; Fraser, 1989; Greenberg and Chaffin, 1975; Konz, 1983; McCormick and Sanders, 1982; Tichauer, 1966, 1978). Deviated wrist postures appear to have a theoretical base for causing CTDs, as demonstrated by Armstrong's and Chaffin's (1979a) model. In their model, as the wrist was deviated from a neutral position, the resultant reaction force on the tendons increased (refer to figure 4). This increase in resultant reaction force could irritate and inflame the tendons, thereby contributing to tenosynovitis and CTS.

Based on the results from this study, the lack of significant differences in wrist position in all three planes between low and high risk groups suggests that orthogonal wrist posture alone may not be as powerful predictor of CTD risk as the dynamic components of motion. However, wrist posture may play a discriminating role that would otherwise not be revealed by the orthogonal analysis performed in this study. All the kinematic data in this study were analyzed orthogonally, independent of coupled posture. Coupled wrist posture in two or more planes or wrist posture coupled with dynamic components may actually be significant predictors of CTD risk.

Biomechanically, the association between coupled static and dynamic components and CTDs have a theoretical basis, as demonstrated by Schoenmarklin's and Marras' (1991a) model. In their model, the greatest resultant reaction force on the tendons occurred when the hand was deviated and accelerated quickly (refer to figure 5). This resultant reaction force, which resisted the tendon force from deviated posture and hand acceleration, was much greater than the reaction force from a static, deviated posture. A fecund future research project would be analyzing the kinematic data from this study as coupled sets of static and dynamic measures.

Predictive Models. The results from multiple logistic regression (MLR) demonstrated the parsimony and strength of the predictive models. As indicated in the analysis of structured data sets, F/E average acceleration was consistently the best discriminator between risk levels. The odds ratio between high and low risk groups for F/E acceleration was 6.05 (refer to tables 14 and 17). The results from discriminant function analysis (DFA) corroborate the predictive power of F/E acceleration (refer to table 13). F/E acceleration was able to correctly classify approximately 70% of all into their respective risk groups. In both DFA and MLR, all the position variables were poor discriminators of CTD risk levels.

The association between the F/E plane and CTD risk is supported by anatomical and physiological literature. According to Robbins (1963), extreme flexion and extension of the wrist reduced the volume of the carpal tunnel, thereby augmenting compression on the median nerve. Phalen (1966) states that wrist flexion and extension increase pressure within proximal half of the carpal tunnel, whereas only extensor deviations generate higher pressures in the distal half. Phalen (1966) developed a diagnostic test for CTS in which patients push their forearms together in an axial direction while flexing their wrists maximally. In an anatomical study on cadavers, Smith et al. (1977) replaced the median nerve with a water-filled cylindrical balloon and found that pressure on the median nerve increased when the wrist was flexed to an extreme angle and also when the flexor tendons were tensed at various wrist flexion angles. During a flexed posture, the median nerve is squeezed between the flexor retinaculum and the overlying flexor tendons, thereby exposing a worker to CTS.

Armstrong et al. (1984) investigated the histological changes in the flexor tendons as they pass through the carpal tunnel, and they found hyperplasia and increased density in the synovial tissue in the carpal tunnel area. These authors suggested that biomechanical factors, such as repeated exertions with a flexed or extended wrist posture, could partially cause these degenerative changes in tendon tissue. In an investigation of the viscoelastic properties of tendons and their sheaths, Goldstein et al. (1987) found that F/E wrist angle increased the shear traction forces between tendons, their sheaths, and bones and ligaments that form the anatomical pulley. These authors concluded that stresses at the tendon-sheath interface are significant and dependent on F/E wrist angle.

The literature on biomechanical modeling of the wrist also supports the association between F/E acceleration and CTD risk. Armstrong and Chaffin (1979a) modeled the wrist's tendons statically in the F/E plane, and they showed that angular deviations from the neutral position generate large resultant reaction forces on the flexor tendons. Schoenmarklin and Marras (1991a) used the basic structure of Armstrong's and Chaffin's (1979a) model and added the dynamic component of acceleration. When the tendons are accelerated, the resultant reaction force increases dramatically over those forces in static loading (refer to figure 5). The resultant reaction force on the tendons from F/E acceleration could degenerate and inflame the tendons, thereby causing tenosynovitis, or compress the median nerve between the flexor retinaculum and tendons, which could cause CTS. Quick decelerations in the F/E plane could likewise generate high loads on the wrist joint. Compared to static loading on the elbow joint, Amis et al. (1980) predicted a 25-30% increase in elbow joint forces during the deceleration phase of fast elbow flexions.

The association between F/E acceleration and CTD risk can also be explained biomechanically by the concepts of Newtonian mechanics 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 and Wells (1989) and Moore (1988) showed that the frictional work generated in the carpal tunnel supported Silverstein's et al. (1986, 1987) dose-response relationship between repetition and CTD risk.

The deleterious effects of frictional work generated between the tendons and their sheaths is exacerbated by coactivation of the extensor muscles during movements. Varying amounts of extensor muscle force during any static or dynamic movement are required to guide the hand and stabilize the hand so it can generate power or pinch force. In order for the wrist and hand to maintain the same flexor torque or power/pinch force, the flexor muscles have to exert more force to overcome the extensor force. Greater forces in the flexor muscles will generate increased frictional work between the flexor tendons and their adjacent structures, thereby exposing workers to increased risk of CTDs.

Preliminary Motion Benchmarks

The relationship between CTD incidence rate and occupational factors, such as repetition and wrist posture, has been qualitatively established by extensive discussions in the literature (Armstrong, 1983, 1986; Armstrong et al., 1982; Armstrong and Chaffin, 1979a; Birkbeck and Beer, 1975; Jensen et al., 1983; Tichauer, 1966, 1978; Welch, 1972) and epidemiological studies (Armstrong and Chaffin, 1979b; Hymovich and Lindholm, 1966; Silverstein et al., 1985, 1986, 1987; Tanaka et al., 1988). Qualitative links are ineffective tools for industry to use to prevent CTD injuries because they do not relate the magnitude of specific wrist motions to CTD risk.

The objective of this study was to quantify the dose-response relationship between wrist motion parameters and CTD risk and develop preliminary quantitative guidelines on the type and amount of wrist motion that expose workers to CTDs. As stated earlier, the variable that appears to best discriminate between low and high levels of CTD risk is F/E acceleration. Figures 29 and 30 illustrate the mean and maximum difference values of F/E acceleration, respectively, for both risk levels. The values for each risk group in

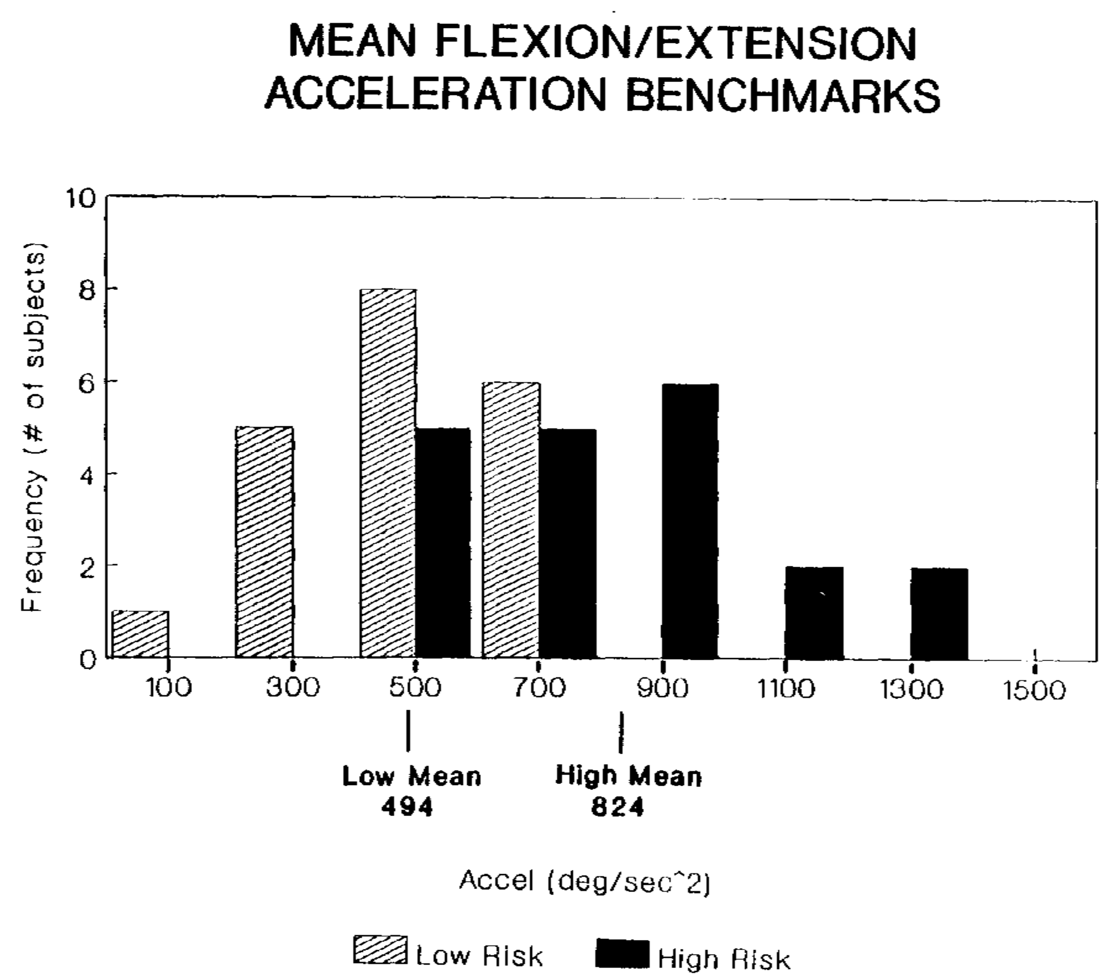


Figure 29. Mean acceleration benchmarks and their distributions in the flexion/extension plane as a function of CTD risk level.

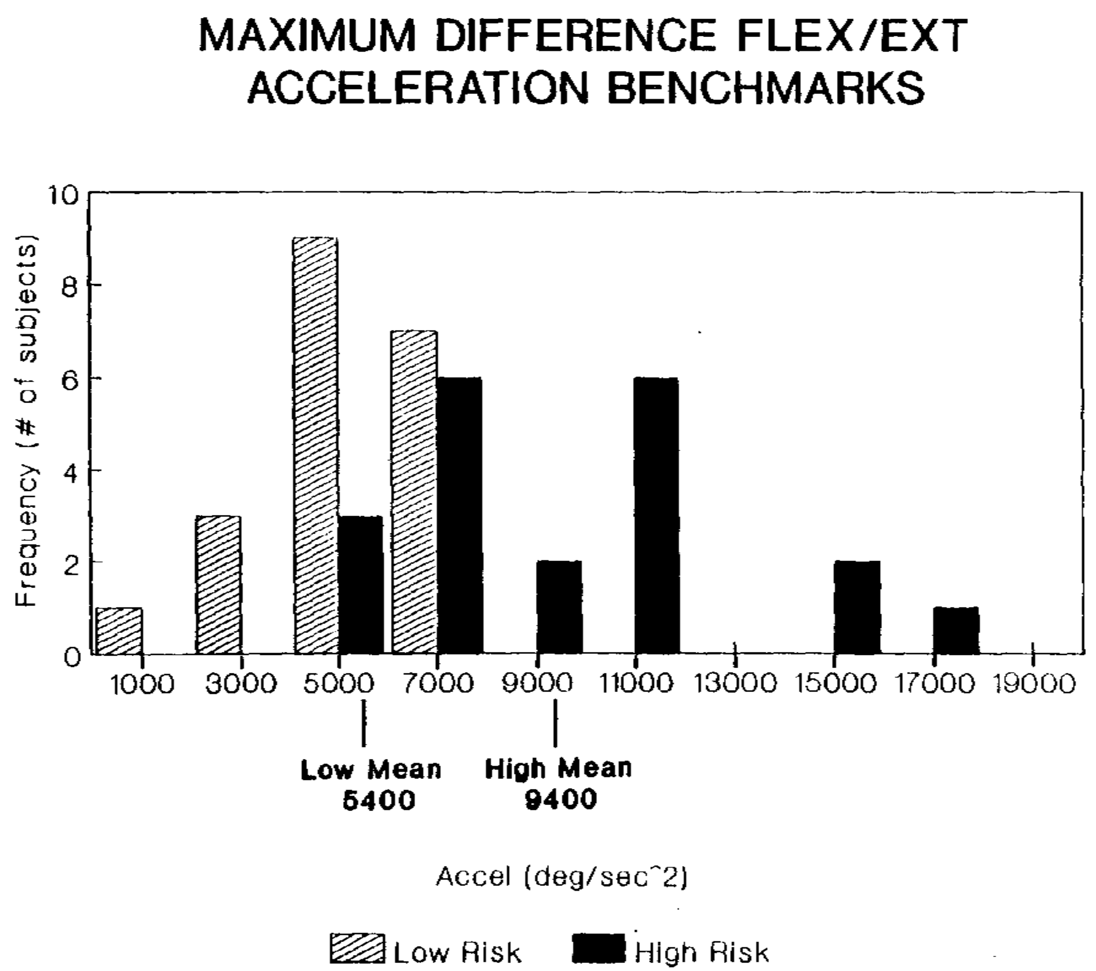


Figure 30. Maximum difference of acceleration benchmarks and their distributions in the flexion/extension plane as a function of CTD risk level. (Maximum difference = maximum - minimum)

figures 29 and 30 should not be taken as discrete cutoffs between risk because of the probabilistic distributions underlying each mean value. However, these benchmarks do provide some insight into approximate levels of injurious and safe levels of F/E acceleration, and they also provide ergonomic practitioners in industry with preliminary quantitative guidelines for risk evaluation of jobs.

Future Research

In order to establish firm quantitative wrist motion guidelines for industry to use to prevent CTDs, the present study needs to be expanded in three ways. First, in the present study, the dose consisted of continuous measures of wrist motion but the response was partitioned into two discrete extremes of CTD risk. The prediction of CTD risk from dosage was limited because of the discrete nature of the response. Ultimately, industry needs CTD risk defined on a continuous scale (incidents per 200,000 hours of exposure) in order to precisely predict risk of CTDs and evaluate jobs. The present study could easily be expanded to include jobs of varying risk level of CTDs.

Second, since only eight manufacturing plants were monitored in the present study, the quantitative wrist motion benchmarks are not generalizable to all industries. In order to make the quantitative prediction of CTD risk from wrist motion more powerful and generalizable, more subjects in more industries will have to be monitored in jobs that vary from low to high incidence rates, inclusive. A larger sample size of subjects is needed to increase predictive power. In addition, more jobs and industries are needed to verify whether the wrist motion benchmarks found in the present study are generalizable to other industries. Considering the established and proven setup of hardware, software, and experimental protocol, the present study could easily be expanded to include more subjects and jobs in industries that were not monitored already.

Third, the motion data from the present and future studies need to be analyzed as coupled data. All the motion data in the present study were analyzed orthogonally, and the orthogonal analysis suggests F/E acceleration is the best predictor of CTD risk. Orthogonal analysis does partially fill the vacuum of quantitative motion data by providing a basis for establishing preliminary motion benchmarks for industry. However, F/E acceleration coupled with a specific loci of oblique or monoplanar wrist posture may actually be a more powerful predictor of CTD risk than F/E acceleration alone. Enlarging the analysis to include coupled sets of static and dynamic parameters would be quite feasible in a continuation of the present study.

Chapter VI

CONCLUSIONS

One of the major research voids in the study of occupational wrist CTDs is the quantification of the relationship between the known kinematic risk factors, such as wrist angle and repetition, and CTD risk. The objective of this research was to determine quantitatively the association between specific wrist motion parameters and the incidence of CTDs as a group.

In order to quantify the link between wrist motion parameters and CTD risk, a quantitative surveillance study was performed in industry in which workers' wrist motion was monitored on the factory floor. A total of forty subjects from eight industrial plants participated in this study (twenty workers in each of two risk groups, low and high). CTD risk level was determined by OSHA 200 logs and medical records. The wrist motion parameters that were monitored on each subject were static (position) and dynamic (velocity and acceleration) measures in each plane of movement (radial/ulnar, flexion/extension, and pronation/supination).

Of all the kinematic parameters measured, orthogonal analysis of the motion data revealed that acceleration in the flexion/extension (F/E) plane discriminated the best between low and high risk groups. F/E velocity was the second best discriminator between risk groups. Contrary to suggestions in the ergonomic literature, static position variables predicted risk level poorly. The epidemiological association between F/E acceleration and CTD risk is compatible with results from empirical studies and theoretical models in the physiologic and biomechanical literature.

The mean acceleration values of high and low CTD risk groups can serve as preliminary, albeit crude, benchmarks to establish injurious and safe levels of wrist motion in industry. Industrial practitioners can use these data as a basis to prevent CTDs in the workplace. These kinematic data can be used to enhance present methods of ergonomic assessments of jobs in that now ergonomic practitioners have a methodology and benchmarks to quantitatively evaluate risk level of jobs and test alternative workplace designs.

In order to make the motion benchmarks more powerful (in a statistical sense) and generalizable to industries not monitored in the present study, this study needs to be continued. In an expanded study, the number of subjects would be increased in order to enhance the predictive power, and the types of industries would be broadened to make the motion benchmarks more generalizable. Furthermore, analysis of the motion data would include coupling of static and dynamic variables in future research.

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REFERENCES

Alexander, D.C. and Pulat, B.M. (1985). Industrial Ergonomics: A Practitioner's Guide. Industrial Engineering and Management Press, Institute of Industrial Engineers.

Amis, A.A., Dowson, D., and Wright, V. (1980). Analysis of elbow forces due to high-speed forearm movemnts. Journal of Biomechanics, 13, 825-831.

An, K.N., Askew, L.J., and Chao, E.Y. (1986). Biomechanics functional assessment of upper extremities. Trends in ergonomics/human factors III, (pp. 573-580). Louisville, KY: Annual International Industrial Ergonomics and Safety Conference.

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

Armstrong, T.J. (1986a). Ergonomics and cumulative trauma disorders. Hand Clinics, 2(3), 553-565.

Armstrong, T.J. (1986b). Upper extremity posture: definition, measurement, and control. Chapter 6 in The Ergonomics of Working Postures. Taylor and Francis.

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, No. 3, 197-201.

Armstrong, T.J. and Chaffin, D.B. (1979a). Some biomechanical aspects of the carpal tunnel. Journal of Biomechanics, 12, 567-570.

Armstrong, T.J. and Chaffin, D.B. (1979b). Carpal tunnel syndrome and selected personal attributes. Journal of Occupational Medicine, 21(7), 481-486.

Armstrong, T.J., Chaffin, D.B., and Foulke, J.A. (1979). A methodology for documenting hand positions and forces during manual work. Journal of Biomechanics, 12, 131-133.

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(2), 103-116.

Armstrong, T.J., Radwin, R.G., Hansen, D.J., and Kennedy, K.W. (1986). Repetitive Trauma Disorders: Job evaluation and design. Human Factors, 28(3), 325-336.

Barnes, R.M. (1981). Motion and Time Study. John Wiley and Sons, Inc.

Birkbeck, M.Q. and Beer, T.C. (1975). Occupation in relation to the carpal tunnel syndrome. Rheumatology and Rehabilitation, 14, 218-221.

Browne, C.D., Nolan, B.M., and Faithful, D.K. (March 17, 1984). Occupational repetitive strain injury. The Medical Journal of Australia, 329-332.

Brumfield, R.H. and Champoux, J.A. (1984). A biomechanical study of normal functional wrist motion. Clinical Orthopaedics and Related Research, 23-25.

Burnett, B. and Bhattacharya, A. (1986). Effect of task design on wrist postures. Trends in ergonomics/human factors III, (pp. 589-595). Louisville, KY: Annual International Industrial Ergonomics and Safety Conference.

Bureau of Labor Statistics Press Release (Nov. 15, 1990). Bureau of Labor reports on survey of occupational injuries and illnesses in 1988. United States Department of Labor, Washington, D.C.

Chaffin, D.B. and Andersson, G.B.J. (1984). Occupational Biomechanics. New York: John Wiley & Sons.

Charash, R.C. (1989). ErgoSPECS: Ergonomic Design Specifications Manual. Minneapolis, MN: ErgoDynamics, Inc. Publishers.

Cunningham, J.W. and Johnston, W.W. (Eds.) (1985). Occupational Medicine and Legal Sourcebook, 2(7), 1-15.

Eastman Kodak Company (1986). Ergonomic Design for People at Work, Volume 2. Van Nostrand Reinhold.

Fraser, T.M. (1989). The Worker at Work. Taylor and Francis.

Garrett, J.W. (March, 1970). Anthropometry of the hands of male Air Force flight personnel (AMRL-TR-69-42). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

Goldstein, S.A., Armstrong, T.J., Chaffin, D.B., and Matthews, L.S. (1987). Analysis of cumulative strain in tendons and tendon sheaths. Journal of Biomechanics, 20, No. 1, 1-6.

Greenberg, L. and Chaffin, D.B. (1975). Workers and their Tools: A Guide to Ergonomic Design of Handtools and Small Presses. Pendell Publishing Co., Midland, MI.

Hymovich, L. and Lindholm, M. (1966). Hand, wrist, and forearm injuries, the result of repetitive motions. Journal of Occupational Medicine, 8, 573-577.

Jensen, R.C., Klein, B.P., and Sanderson, L.M. (September, 1983). Motion-related wrist disorders traced to industries, occupational groups. Monthly Labor Review, 13-16.

Knowlton, R.G. and Gilbert, J.C. (1983). Ulnar deviation and short-term strength reductions as affected by a curve-handled ripping hammer and a conventional claw hammer. Ergonomics, 26(2), 173-179.

Konz, S. (1983). Work Design: Industrial Ergonomics. Second Edition. John Wiley and Sons.

Kroemer, K.H.E. (1989). Cumulative trauma disorders: their recognition and ergonomics measures to avoid them. Applied Ergonomics, 20.4, 274-280.

Lacquaniti, F. and Soechting, J.F. (1982). Coordination of arm and wrist motion during a reaching task. The Journal of Neuroscience, 2, No. 4, 399-408.

Marras, W.S. and Schoenmarklin, R.W. (1991). Quantification of wrist motion in highly repetitive, hand-intensive industrial jobs. Part I: Methodology and Univariate Statistical Analysis. Submitted for publication.

McCormick, E.J. and Sanders, M.S. (1982). Human Factors in Engineering and Design. Fifth edition. McGraw-Hill Book Co.

Montgomery, D.C. (1984). Design and Analysis of Experiments, Second Edition. John Wiley and Sons.

Moore, A.E. (1988). A system to predict internal load factors related to the development of cumulative trauma disorders of the carpal tunnel and extrinsic flexor musculature during grasping. Master's thesis, University of Waterloo, Waterloo, Canada.

Moore, A.E. and Wells, R.P. (June, 1989). Response of biomechanical correlates of cumulative trauma disorders in the carpal tunnel and extrinsix flexor musculature to simulated working conditions. In Proceedings of the XII Congress of the International Society of Biomechanics, Los Angeles, 26-30.

Ortiz, D.J., Kelly, M.J., Courtney, T.K., and Folds, D.J. (Sept., 1989). Design and development of a self study course for apparel supervisors in the practical applications of ergonomic principles; Phase I: Ergonomic considerations in conventional trouser manufacturing. Sponsored by U.S. Defense Logistics Agency. Georgia Institute of Technology Project #A-8311.

Palmer, A.K., Werner, F.W., Murphy, D.M, and Glisson, R.G. (1985). Functional wrist motion: a biomechanical study. The Journal of Hand Surgery, 10A(1), 39-46.

Phalen, G.S. (1966). The carpal tunnel syndrome: seventeen years' experience in diagnosis and treatment of six hundred fifty-four hands. Journal of Bone and Joint Surgery, 48-A(2), 211-228.

Pinkham (August, 1988). CTS impacts thousands and costs are skyrocketing. Occupational Health and Safety.

Putz-Anderson, V., editor (1988). Cumulative Trauma Disorders: A Manual for Musculoskeletal Diseases of the Upper Limbs. Taylor and Francis.

Robbins, H. (1963). Anatomical study of the median nerve in the carpal tunnel and the etiologies of carpal tunnel syndrome. Journal of Bone and Joint Surgery, 45A, 953-966.

Schoenmarklin, R.W. and Marras, W.S. (1987). Measurement of hand and wrist position by a wrist monitor. In Proceedings of the IXth International Conference on Production Research, Cincinnati, OH, 410-416.

Schoenmarklin, R.W. (1988a). An investigation into the effects of hammer angle and orientation on wrist angle and hammering performance. Unpublished master's thesis. The Ohio State University, Columbus, Ohio.

Schoenmarklin, R.W. (1988b). The effect of angled hammers on wrist motion. In Proceedings of the 32nd Meeting of the Human Factors Society, Anaheim, CA, 651-655.

Schoenmarklin, R.W. and Marras, W.S. (1989a). Validation of a hand/wrist electromechanical goniometer. In Proceedings of the 33rd meeting of the Human Factors Society, Denver, CO, 718-722.

Schoenmarklin, R.W. and Marras, W.S. (1989b). Effects of handle angle and work orientation on hammering: Part I. Wrist motion and hammering performance. Human Factors, 31(4), 397-411.

Schoenmarklin, R.W. and Marras, W.S. (1989c). Effects of handle angle and work orientation on hammering: Part II. Muscle fatigue and subjective ratings of body discomfort. Human Factors, 31(4), 397-411.

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.

Schoenmarklin, R.W. and Marras, W.S. (1991a). A dynamic model of flexor tendons in the wrist joint. Submitted to Human Factors for publication.

Schoenmarklin, R.W. and Marras, W.S. (1991b). Maximal kinematic wrist performance in industry. Submitted for publication.

Schoenmarklin, R.W., Marras, W.S., and Leurgans, S.E. (1991). Quantification of wrist motion in highly repetitive, hand-intensive industrial jobs. Part II: Multivariate Statistical Analysis. Submitted for publication.

Silverstein, B.A., Fine, L.J., Armstrong, T.J., Joseph, B., Buchholz, B. and Robertson, M. (1985). Cumulative trauma disorders of the hand and wrist in industry. Chapter 3 in The Ergonomics of Working Postures: Models, Methods, and Cases. Edited by Corlett, N., Wilson, J., and Manenica, I. Taylor and Francis.

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.

Smith, E.M., Sonstegard, D.A., and Anderson, W.H. (1977). Contribution of flexor tendons to the carpal tennel syndrome. Archives of Physical Medicine and Medical Rehabilitation, 58, 379-385.

Tabachnick, B.G. and Fidell, L.S. (1989). Using Multivariate Statistics, Second Edition. Harper & Row, Publishers.

Taleisnik, J. (1985). The Wrist. New York: Churchill Livingstone.

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 Advances in Industrial Ergonomics and Safety I, A. Mital, editor, Taylor and Francis, 419-425.

Tanaka, S., Seligman, P., Halperin, W., Thun, M., Timbrook, C.L., and Wasil, J. (1988). Use of workers' compensation claims data for surveillance of cumulative trauma disorders. Journal of Occupational Medicine, 30(6), 488-492.

Taylor, C.L. and Blaschke, A.C. (1951). A method for kinematic analysis of motions of the shoulder, arm, and hand complex. Annals of New York Academy of Sciences, 51, 1251-1265.

Tichauer, E.R. (1966). Some aspects of stresses on the forearm and hand in industry. Journal of Occupational Medicine, 8, 67-71.

Tichauer, E.R. (1978). The biomechanical basis of ergonomics: anatomy applied to the design of work stations. John Wiley and Sons.

Tobey, S.W., Woolley, C.B., and Armstrong, T.J. (1985). Postural analysis system for the industrial environment. In Proceeding of IXth Annual Meeting of the American Society of Biomechanics (pp. 89-90). Ann Arbor, MI.

Webb Associates, (1978). Anthropometric Source Book; Volume I; Anthropometry for Designers. (NASA Reference Publication 1024).

Wehrle, J. (1976). Chronic wrist injuries associated with repetitive hand motions in industry. Occupational Health and Safety Technical Report, Dept. of Industrial and Operations Engineering. University of Michigan, Ann Arbor, MI.

Welch, R. (1972). The causes of tenosynovitis in industry. Industrial Medicine, 41, No. 10, 16-19.

Winter, D.A. (1979). Biomechanics of Human Movement, Second Edition. John Wiley and Sons.