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A Quantitative Description of Typing Biomechanics

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One approach to combating work-related upper extremity musculoskeletal disorders (UEMSDs) is to improve understanding of MSD risk factors through quantitative biomechanical characterization of manual tasks, including joint postures, joint dynamics, and force exertion. This paper describes a methodology employed to quantitatively assess professional typing in a workplace setting, and the results of that assessment. Results are compared between different kinds of typing tasks, and between typing and hand-intensive industrial tasks, based on nontask-specific biomechanical terms. Quantitative, biomechanical characterizations of manual tasks will lead to identification of appropriate ranges for joint kinematics and force exertion, which will, in turn, facilitate proper design of manual tasks. Additionally, the methodology could be used to assess manual performance of skilled tasks for proper (healthy) technique, or be used to evaluate progress through a course of rehabilitation (when do an impaired worker's motions begin to resemble motions of healthy workers?).

KEY WORDS: biomechanics; typing; assessment; cumulative trauma disorder; keyboard; hand.

INTRODUCTION

Musculoskeletal disorders (MSDs) are a significant work-related health problem in the United States (1). Though that declaration was made only within the last decade, for years, upper extremity MSDs (UEMSDs), such as tenosynovitis, epicondylitis, forearm muscle strains and sprains, and carpal tunnel syndrome (CTS), have been associated with workplace exposures. Earlier studies associated UEMSDs with employment in hand-intensive tasks in which workers were exposed to repetitive motions, some level of continuous or intermittent mild to moderate levels of force exertion, and intermittent or sustained awkward postures (2–4).

Recently, the occurrence of MSDs in keyboard operators has received considerable attention in the popular press (5). In the 1980s, Australia experienced an

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epidemic of keyboard-related symptom occurrence, termed repetitive strain injury (RSI) in that country (6). With over 45,000,000 computers in workplaces in the U.S., concerns have been raised over the potential for an escalation in the incidence of keyboard-related UEMSDs as dependence on computers increases.

The key to combating work-related UEMSDs in keyboard operators, as well as industrial workers, is an improved understanding of MSD risk factors, so that exposures can be reduced or eliminated. Even though previous studies identified repetitive motion, force, and awkward postures as being related to development of MSDs, knowledge of these risk factors is generally qualitative in nature. Dose–response relationships, which would facilitate exposure management, are lacking. The need exists for quantification of risk factors and responses in studies of these disorders. Additionally, rather than focusing on job-specific factors, such as quantity of parts handled or typing speed, risk factors should be defined and quantified in terms that are common to all hand-intensive tasks, and that reflect the basic biomechanics of the task. Furthermore, the need exists for investigation of intermediate variables, such as carpal tunnel pressure and tendon travel, as a means to improve the understanding of the physical mechanisms by which risk factor exposures and responses are related. Intermediate variables are those that respond to external variables, such as joint posture, and may in turn trigger other responses, from tissue such as nerves and tendons. The multifactorial etiology of MSDs complicates exposure assessment due to interactions and confounding among physical factors, as well as with psychosocial, work organization, and personal factors (7–9). Worker perceptions of peer cohesion, autonomy, work pressure, supervisory control, workload, boredom, job future ambiguity, rest breaks, and frequency of stress have all been shown to be significant, nonphysical, discriminating factors in previous studies of keyboard operators (9–11).

Some quantitative biomechanical research has already been conducted in the specific area of keyboard work. Electromyographic (EMG) studies have recorded elevated muscle activity in forearm and shoulder muscles during keyboarding under various conditions (12, 13). Force exerted during key strike has been shown to be 2–4 times greater than activation requirements (14–16), though these forces are still much lower than forces labeled as excessive in industrial manual work (17–19). Industrial studies also identified associations between upper extremity symptoms and excessive repetition and the interaction of force and repetition. Excessive wrist joint dynamics, specifically flexion-extension velocity and acceleration, have been found to be associated with highly repetitive, hand-intensive industrial jobs with historically elevated incidence rates of MSD occurrence (20). To date, only static wrist posture has been studied in typists. Ulnar deviation has been linked to symptoms in keyboard operators (21–23). In the laboratory, Moore *et al.* (24) identified two intervening variables, dynamic muscle activity and frictional work, which correlated with the results of Silverstein *et al.* (17). Frictional work is the summation over time of the product of tendon force and incremental tendon travel, and is directly influenced by repetition. Wells *et al.* (25) applied the technique of Moore *et al.* (24) to a typing task and was thereby able to compare biomechanical exposures between a typist and a group of industrial workers. Tendon travel was found to be similar between the two types of work, at about 69 m/hr. This suggests that while typing and hand-intensive industrial tasks may appear dissimilar to the eye, some underlying physical factors (intermediate or intervening variables) may be comparable. However, there are, as yet, no benchmarks which allow us to determine what levels of risk may be associated with specific amounts of tendon travel, or most other biomechanical variables.

In summary, concerns exist regarding the occurrence of UEMSDs in workers performing hand-intensive tasks, including typing. Certain physical factors, as well as work organization and psychosocial factors, have been associated with work-related UEMSDs, yet few dose–response relationships or exposure benchmarks have been quantified, in either industrial or typing studies. Recent studies suggest that certain quantitative, biomechanically-based factors may provide important insight into associations between hand-intensive tasks and work-related UEMSDs, as well as lead to the development of exposure control strategies. These factors include wrist joint dynamics and tendon travel. To date, however, wrist joint dynamics have only been studied for industrial tasks, and tendon travel has only been reported in a limited number of typists. As such, a study was designed to quantify these biomechanical factors, and force exertion, in a larger group of professional typists. A number of work organization and psychosocial factors were also examined during the study, however, the focus of this paper will be on the biomechanics of typing. The nonphysical factors are discussed elsewhere (26). The data were collected by a new methodology developed expressly for collecting such information in a workplace setting with minimal disruption to the office routine. The methodology has additional applications, which are discussed later in the text.

Study Objectives

The goals of the study were (1) to quantitatively describe the keying task performed by professional operators on the job in biomechanical terms, including joint postures and joint dynamics, tendon travel, and force; (2) to compare those biomechanical descriptors among groups of typists, categorized by task; and (3) to determine if keyboard operators and industrial workers are exposed to similar levels of biomechanical stressors, given that they develop similar types of UEMSDs.

METHODS

An observational study of keyboard operators was conducted in an effort to improve the understanding of the typing task from a biomechanical perspective. Biomechanical, workstation, and demographic data were collected for each of the subjects.

Subjects

Twenty-five full-time employees from four companies volunteered to participate in the study. Subjects were tested on company time, and received commemo-

Table I. Subject Participation, by Company and Job

Company	Job	Average annual incidence rate[a]	Number of subjects sampled from job	Typing task group[b]
A	Accounting clerk	0.0	2	DE
	Data entry		3	DE
B	Service representative	6.8	10	IE
C	Word processing	3.1	3	WP
	Legal secretary		4	WP
D	Data entry	0.0	3	DE

[a] Average annual rates, based on data from 1991–1993, included any problem involving the upper extremity which met the definition of an OSHA recordable illness item f (due to repetitive trauma). For companies A, B, and D, numerator and denominator data were provided by supervisors or personnel departments. The rate for company C was based on the authors' first-hand review of company OSHA logs and employment data supplied by a corporate ergonomist. Numerator and denominator data were specific to the job group within the department from which subjects were sampled.
[b] DE = data entry; IE = interactive entry; WP = word processing.

rative T-shirts for their participation. In Table I, subjects are described by company, job, and historical job incidence rate of recorded upper extremity illness. Twenty-two of the subjects were female. The three male participants were all from Company B. All subjects were pain-free at the time of testing. Subjects were asked whether, within the past 12 months, they had experienced any upper extremity pain or discomfort which had lasted more than 24 hr. Sixteen responded negatively. Nine responded with remarks about past pain (in years gone by) or intermittent pain (not lasting 24 hr) which seemed to them, to coincide with increased workload.

Although all subjects performed typing tasks, fundamental differences were observed in those tasks between the various groups of subjects. Differences included utilizing different parts of the keyboard, one-handed vs. two-handed typing, and performance assessment. Any or all of these factors might influence typing kinetics. Therefore, subjects were categorized into three groups, based on the keying task they performed: data entry (DE), word processing (WP), or interactive entry (IE). The tasks for both DE and WP typists required transcription of materials from paper sources onto the computer. DE operators primarily used their right hands, entering numerical data with the built-in keypad or using a subset of letter keys which alternated as numeric keys through use of a toggle switch on the keyboard. The output of the DE operators was monitored, and their pay was influenced by their production. WP typed mainly text material, and utilized both hands. The IE typists used one or two hands as needed and both alpha and numeric keys to enter information from paper sources. They also spent a portion of each day entering or accessing information in direct response to telephone inquiries.

Study Design

The study was observational in design. Data from each subject were collected during one 60- to 90-min session. Demographic, biomechanical, and workstation data were collected from each subject.

Demographic Data. A survey containing questions on age, anthropometry, job characteristics (including break schedule, task description, overtime, working hours, and percentage of time spent typing), and work history was administered to each subject.

Biomechanical Data. While subjects performed their normal typing tasks, data describing the following variables were collected simultaneously: key strike force and various joint postures from the right hand (radial-ulnar (RU) and flexion-extension (FE) wrist postures and metacarpophalangeal (MP) and proximal interphalangeal (PIP) flexion postures). Anthropometric and grip strength data were also recorded for each subject.

Workstation Data. Workstation dimensions, including seated eye height, monitor height, and popliteal height, and the presence or absence of features, such as a foot rest and chair adjustability, were documented. Additionally, assessments of activation force requirements were made for each subject's keyboard.

Apparatus and Data Processing

Each data file consisted of four joint position channels and one key force channel of digitized voltage data collected for a six second interval of time, during which the subject typed her own work material. Fifteen to 25 6-sec data collection intervals were recorded for each subject during the 60- to 90-min session. Force and joint position data were collected using a 32-channel, 12-bit analog-to-digital system (Model 2839, Data Translations, Marlboro, MA) and a 486 portable computer. All data channels were sampled at 600 Hz.

Force. Key strike force was measured by two small, mirror-image force plates upon which the keyboard was placed (Fig. 1). The plates contained a matching pair

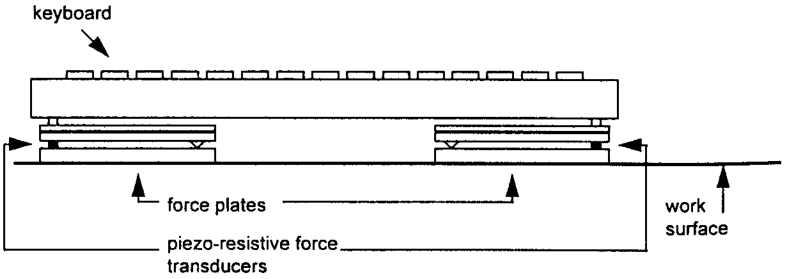

Fig. 1. Keyboard positioned over force plates.

of piezo-resistive miniature force transducers (Model 9211, Kistler Corporation, Amherst, NY). Vertical forces were summed from the two transducers (one mounted in each plate). The signal was amplified by a Kistler 5004 dual mode amplifier.

The force plate system was evaluated by applying static loads to both plates, individually and together, and comparing readings with measurements from an electronic grocery store scale. There was a strong linear relationship between the two sets of measures (coefficient of determination, $r^2 = 0.9992$). Based on residual analysis (27), voltage data from the force plates were filtered through a 13-point Hanning filter, which corresponded to a cutoff frequency of 72.5 Hz.

Wrist and Finger Joint Kinematics. Wrist position was quantified using two independent wrist motion monitors, one for radial-ulnar position and the other for flexion-extension position. These devices were developed in the Biodynamics Lab at The Ohio State University. Each electromechanical device consisted of two pieces of feeler gage connected by a rotary potentiometer. Finger joint position was measured with finger goniometers (Model G-35, Penny + Giles Ltd, Santa Monica, CA). A two-channel amplifier (Model SA-B, Sensotec, Columbus, OH) was modified to power and amplify the signals from the finger goniometers. The signals were amplified a second time with a simple two times, custom-made amplifier.

Joint position, angular velocity, and angular acceleration were calculated via a Laplace transform routine which filtered the voltage data while simultaneously calculating position, velocity, and acceleration for each successive point in time (28).

Tendon Travel Derivation. Armstrong and Chaffin (29) developed regression equations for displacement of the flexor digitorum profundus (FDP) tendons for the wrist, MP, and PIP joints, as functions of joint thickness and joint angle (refer to Eqs. 7 and 5, respectively, in their paper). Tendon travel, standardized to a 1-hr period, was calculated by summing the absolute values of the incremental tendon excursions that occurred between each sampling point. From changes in tendon excursion over time, tendon velocity and acceleration were calculated. Hypothetically, calculated tendon velocity may correspond to muscle velocity, which is known to affect the tension capacity of muscle (30). Average tendon excursion relative to a neutral wrist posture was also calculated for each subject. This variable was indicative of the average FE posture of the subject and of the length of the FDP muscle, either shortened or lengthened relative to resting length.

Data Collection Procedure

Subjects were asked to perform their normal typing functions during the data collection period, and to maintain their typing style. Subjects were not told that key strike force was being measured. They were only told that the plate under the keyboard was a device that identified key strike timing, information that was needed to supplement the joint motion data.

Prior to data collection, all subjects were required to read and sign a consent form which had been approved by the university's human subjects review committee. Once the consent form was signed, anthropometric data were collected, and the survey on work and demographics was completed. Subjects were assured that their responses would remain confidential.

Goniometers were then attached and neutral calibrations were recorded separately for the wrist and finger joints. Subjects were given 10 min to practice typing, in order to acclimate to the equipment. Any adjustments were made during that time. Following the acclimation period, the data collection procedure was explained to the subject.

Subjects were informed that due to the way the plate under the keyboard worked, they would be unable to rest their hands on the plate or on the keyboard while typing. Each was informed that periodically she would receive a request to stop typing and to briefly remove her fingers, just slightly, from the keyboard. This afforded the opportunity to reset the piezo-resistive transducers. Other than not resting the hands while typing and the occasional request to stop typing, the subject was told that her typing should be performed as normally as possible. Subjects were not informed when individual data files were collected.

In light of reports in the literature on associations between key strike force and key activation force (14), several crude activation force samples were collected prior to removal of the force plate from the worker's area. These involved the researcher activating a few alpha and numeric keys with the lightest touch possible. Key displacement was not measured.

Analyses

Data in each file were analyzed only for that portion of the 6-sec interval during which the subject was typing. For example, if typing activity ceased at the 5.2 s mark in a particular data file, only the first 5.2 s of data in that file were analyzed. Statistics for each channel, such as mean and peak values, were averaged across trials within subjects, and then across subjects within typing groups.

RESULTS

Anthropometry and Demographics

Anthropometric data were collected on handedness, height, weight, age, grip strength, and several dimensions of the right and left upper extremities, of which only right hand length is reported. Subject anthropometry is presented in Table II. Work history and demographics are also presented in that table.

Survey Responses

When asked about overtime, most subjects responded with either low estimates (1–2 hr per week) or only seasonal requirements. One IE subject worked 10 hr of overtime per week, another worked 5 hr per week. One WP worked 4 hr of overtime each week. All other reports were below these. Nine subjects reporting

Table II. Subject Anthropometry, Demographics, and Typing History: Group Means, with Standard Deviations in Parentheses

	Typing group		
Variable	Data entry	Word processing	Interactive entry
Height (cm)	160.5 (4.8)	161.6 (5.2)	168.3 (10.5)
Weight (kg)	81.9 (21.6)	67.5 (9.4)	67.5 (18.0)
Age (yr)	40.9 (6.7)	35.7 (11.1)	27.8 (4.0)
Hand strength (cm)	16.9 (0.9)	17.4 (0.8)	17.6 (1.6)
Grip strength (kg)	26.4 (4.3)	30.6 (5.3)	30.8[a] (6.5)[a]
Years of keying for pay	16.2 (7.3)	11.6 (7.2)	6.9 (4.8)
Years on current job	12.6 (7.2)	3.2 (2.5)	2.8 (2.5)
Time spent typing (hr)	6.2 (1.1)	4.9 (1.7)	5.3 (1.7)
Make of keyboard			
Apple	0	0	1
IBM	3	7	9
Nixdorf	3	0	0
Telex	2	0	0

[a] Female subjects only.

Table III. Responses to Questions on Work Characteristics[a]

	Percentage of subjects in each group answering yes			
Questions	DE	WP	IE	Fisher's exact, prob.
Do you have regular, scheduled breaks?[b]	88	0	10	<0.001
Do you take breaks?[c]	100/100	29/14	80/70	<0.002/<0.002
Did subject mention any pain experience?[d]	25	71	20	0.10

[a] Most questions required yes or no responses. Some subjects responded with "sometimes" or "somewhat." The notation below indicates whether the sometimes or somewhat responses were classified as a yes or no response.

[b] No meant free to take breaks as needed.

[c] Yes = responses of "yes," or "somewhat," or "sometimes"/yes = only "yes" responses.

[d] Yes = only "yes" responses.

no overtime were spread across the groups. Responses to additional survey questions are reported in Table III.

Contingency table analyses demonstrated significant differences, based on Fisher's exact test, between typing groups on work break issues. Unlike the regularly scheduled breaks for the DE operators, work breaks for the WP and IE groups were permitted with timing at the discretion of the employees. All of the DE and most of the IE subjects took breaks, however, few of the WP took breaks. Four of the six WP operators who did not regularly take breaks mentioned past or intermittent current experiences of upper extremity pain or discomfort. Thirty-one percent of those who regularly took breaks (four of nine subjects) made mention of pain, compared with 44% of those who did not take regular breaks (five of 16 subjects).

Biomechanical Variables

Descriptions of key strike force, joint position and dynamic variables, and tendon-related variables are presented in this section. Multivariate Analysis of Variance (MANOVA), followed by ANOVA, and then *post hoc* Tukey tests were performed in order to compare differences between typing groups. However, results from these analyses should be interpreted with caution, due to the small number of subjects in each group and unequal variances in some variables. In early investigations, such as this one, wherein new methodologies are developed or applied, descriptive statistics may deserve more attention than comparative ones.

Force. The four statistics used to describe key strike force during typing were average force exerted, average peak force, trial peak force, and cumulative force (normalized to 1 hr). Values are presented in Table IV. Trial peak force refers to the single highest force measurement registered within a 6-sec data file, while average peak is the mean of the individual peak forces registered for each key strike within a data file. Average force exerted refers to the mean of all the force data points within a data file, including time during and between key strikes. The cumulative force statistic describes the sum total of the force applied, normalized to 1 hr of typing. Based on performance monitoring records which were made available for four of the DE operators, it was possible to calculate estimates of cumulative loading per shift for each of those subjects. Those values were 3.7, 7.4, 7.5, and

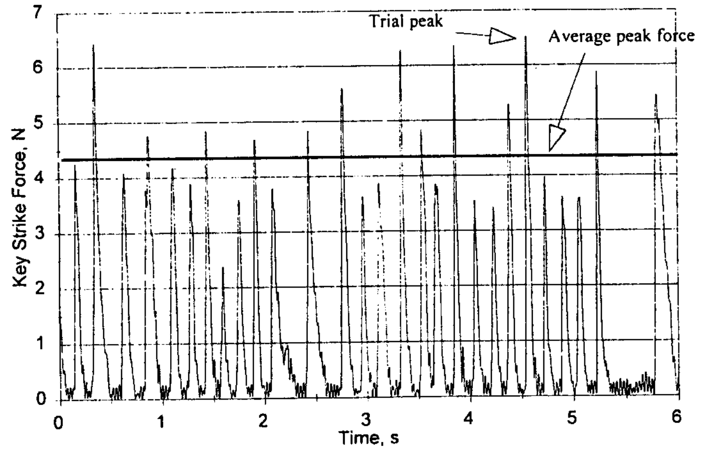

Fig. 2. Sample of key strike force data, and statistics calculated from those data.

Table IV. Key Strike Force Statistics[a]

	Typing group						MANOVA[b]/
Statistic	DE		WP		IE		ANOVA
							W****, P****
Average force	0.7	(0.2)	0.9	(0.2)	0.6	(0.2)	*
Tukey test[c]		AA BB		AA		BB	
Average peak	2.8	(0.9)	1.9	(0.3)	1.9	(0.3)	***
Tukey test		AA		BB		BB	
Trial peak	4.4	(1.7)	3.1	(0.4)	3.2	(0.7)	*
Tukey test		AA		AA		AA	
Cum. force	2.5	(0.8)	3.1	(0.7)	2.2	(0.7)	*
Tukey test		AA BB		AA		BB	

[a] Values averaged over individual subject trials, then averaged within typing groups. Statistics are in N, except for cumulative force, which is in kN·s/hr.

[b] Significance of MANOVA by Wilks' Lambda indicated by W; significance of MANOVA by Pillai's Trace indicated by P.

[c] Group comparisons based on Tukey HSD Test, differences identified at 0.05 level.

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.005$.

****$p < 0.001$.

14.3, in units of kN·s, which serve as a reminder that cumulative force is a product of the level of applied force and the amount of time over which the force is applied. An example of key strike force data, from one of the data entry operators, appears in Fig. 2.

Earlier studies raised questions about the potential effect of key activation force on key strike force (15). As reported in Table II, subjects in the current study worked on a variety of keyboards, though most used the IBM Model M. Based on crude activation force testing, all keyboards appeared to be in compliance with ANSI/HFS (31), which prescribes a key force activation range of 0.25–1.5 N. In the current study, activation force estimates ranged from 0.7 to 1.0 N (avg = 0.8 N, *SD* = 0.1 N). Although the regression model was significant ($p < .002$), activation force was not an accurate predictor of average peak key strike force (coefficient of determination, $r^2 = 0.39$; standard error of estimate = 0.6 N). The ratio of average peak force to activation force ranged from 1.8 to 4.5, with most subjects exerting from 2 to 3.5 times the required force. Individual trial peak key strike forces were 2.5 to almost 7 times higher than activation requirements.

Typing Speed. A two-step heuristic technique was developed for calculating typing speed from force records. The first step employed a computer algorithm to analyze force data from each data file. Based on an examination of several datasets of key strike force, ranges of duration time for single, double, and triple key strikes were used to initially estimate the number of key strikes in a file. Double and triple key strikes sometimes occur when typists strike certain patterns of keys in rapid succession, such as "er" or "the." This does not occur every time these patterns are typed, nor with every typist. When this does occur, however, key strikes no longer appear discrete, as in Fig. 2, and key strike counting becomes more complicated.

In the subsequent step of the heuristic, force data from each file were graphically plotted. Each plot was visually inspected in order to determine whether each key strike had been correctly identified by the computer algorithm. Initial key strike count estimates were adjusted as needed. The adjusted key strike count estimates were then converted to words per minute (wpm) by assuming the standard word equivalent of four letters and one space. A one stroke error in the assessment process would typically affect a typing speed estimate by two wpm. Mean typing speeds, in wpm, were 61.2 (10.2), 74.1 (8.7), and 45.9 (10.2) for the DE, WP, and IE groups, respectively. In comparing these rates, recall that data entry operators used their right hands almost exclusively, while the WP operators typed with both hands. The typing materials of the IE group varied, so hand usage varied for the IE operators.

Joint Position. For both finger and wrist joints, values of mean position and range of motion during typing appear in Table V. An example of joint position data appears in Fig. 3, and corresponds to the force data in Fig. 2. For most subjects, mean MP posture was between 15 and 30 deg of flexion, while mean PIP posture was between 25 and 50 deg of flexion.

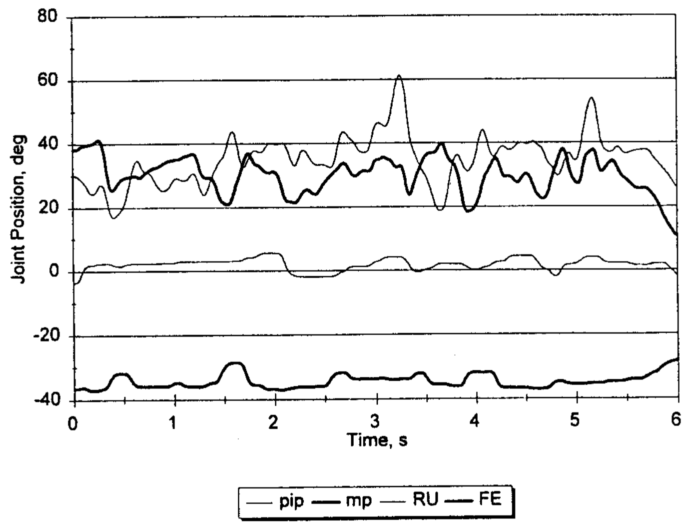

Fig. 3. Sample of wrist and finger joint position data. Upper two lines represent finger joint postures, lower two lines represent wrist joint postures.

Table V. Finger and Wrist Joint Position, in Deg[a]

Statistic	Typing group						MANOVA[b]/ ANOVA
	DE		WP		IE		
PIP							W*, P*
Mean	35.8	(10.7)	39.0	(7.3)	35.7	(5.4)	
Range	34.7	(7.9)	30.2	(2.0)	24.5	(5.6)	***
Tukey test[c]		AA		AA BB		BB	
MP							W***, P***
Mean	28.0	(13.2)	22.0	(3.7)	17.9	(6.3)	
Range	33.6	(5.4)	28.5	(6.4)	21.8	(4.3)	****
Tukey test		AA		AA		BB	
Wrist—RU							W*, P*
Mean	−0.8	(8.7)	−13.5	(4.4)	−7.6	(7.7)	*
Tukey test		AA		BB		AA BB	
Range	8.5	(4.5)	8.7	(3.0)	6.3	(2.6)	
Wrist—FE							W*, P*
Mean	−21.5	(7.9)	−11.6	(6.5)	−11.4	(9.2)	*
Tukey test		AA		AA BB		BB	
Range	14.1	(4.3)	8.9	(5.2)	8.6	(4.3)	*
Tukey test		AA		AA BB		BB	

[a] Positive values indicate flexion or radial deviation.

[b] Significance of MANOVA by Wilks' Lambda indicated by W; significance of MANOVA by Pillai's Trace indicated by P.

[c] Group comparisons based on Tukey HSD Test, differences identified at 0.05 level.

$^{*}p < 0.05$.

$^{**}p < 0.01$.

$^{***}p < 0.005$.

$^{****}p < 0.001$.

The slight mean ulnar deviation in the DE group reflects the usage of the numeric keypad by several subjects. However, there was a substantial spread in mean RU posture, reflected by the standard deviation. The most common posture for subjects was wrist extension combined with ulnar deviation. There was a tendency for ulnar deviation to decrease as extension increased. Joint postures did not appear to be related to hand length.

Joint Velocity. In calculating statistics for joint and tendon velocities and accelerations, absolute values of those derived measurements were utilized. Regarding statistics for MP and PIP joints, there was overlap between the typing groups, but the trends were for higher values to be seen in the DE group and lower values to be seen in the IE group. Velocity statistics for both finger joints are presented in Table VI. The magnitude of the values were similar between the two joints. Finger joint velocity was not highly correlated with typing speed. In part this was due to the data of the WP group. PIP joint velocity did not vary with typing speed in the WP group, though there did appear to be a positive trend between the two variables

Table VI. Joint Velocity Statistics, in Deg/s[a]

Statistic	Typing group						MANOVA[c]/ ANOVA
	DE		WP		IE		
PIP							W****, P****
Mean	64.3	(19.9)	34.8	(5.7)	29.3	(9.4)	****
Tukey test[d]		AA		BB		BB	
Maximum	293.7	(87.9)	235.2	(50.1)	159.9	(40.5)	****
Tukey test		AA		AA BB		BB	
MP							W****, P****
Mean	63.9	(14.6)	41.7	(11.4)	26.5	(7.6)	****
Tukey test		AA		BB		CC	
Maximum	291.3	(66.6)	222.5	(69.2)	139.5	(36.4)	****
Tukey test		AA		AA		BB	
Wrist—RU							W*, P*
Mean [(17/26); (1/0)][b]	8.1	(5.1)	5.4	(3.1)	4.0	(1.7)	
Maximum [(79/116); (4/0)][b]	63.1	(28.9)	55.0	(18.8)	43.8	(20.2)	
Wrist—FE							W*, P*
Mean [(29/42); (2/1)][b]	21.5	(12.6)	5.8	(4.0)	6.1	(3.6)	****
Tukey test		AA		BB		BB	
Maximum [(121/184); (3/1)][b]	134.5	(63.5)	65.2	(27.3)	58.9	(24.7)	***
Tukey test		AA		BB		BB	

[a] Low risk group/high risk group wrist velocity reference values (20) are presented in parentheses in the first column.

[b] Interpretation: Marras and Schoenmarklin (20) identified group means of 17 and 26 deg/s for RU wrist velocity in a group of low risk industrial jobs and a group of high risk industrial jobs, respectively. In the current study, one (1) subject had a mean RU wrist velocity which exceeded that of the low risk industrial group's mean, while no (0) subjects in the current study had mean RU wrist velocities which exceeded that of the high risk industial group's mean.

[c] Significance of MANOVA by Wilks' Lambda indicated by W; significance of MANOVA by Pillai's Trace indicated by P. Model tested included velocity and acceleration statistics for the particular joint of interest.

[d] Group comparisons based on Tukey HSD Test, differences identified at 0.05 level.

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.005$.

****$p < 0.001$.

for the DE and IE groups (the groups with workers predominantly or often typing with only one hand). Hand length was not a predictor of joint velocity.

RU velocity was similar across all three groups, though tended to be higher for the DE group and lower for the IE group. FE velocity was similar in magnitude to RU velocity for the WP and IE groups, but was about double the RU velocity for the DE group. Wrist joint velocity statistics are also presented in Table VI. As a point of reference when examining the values, in studying two groups of highly repetitive, hand-intensive industrial jobs Marras and Schoenmarklin (20) found mean and maximum RU velocities for low risk jobs to be approximately 17 and 79 deg/s, respectively, while values for high risk jobs were 26 and 116 deg/s, respectively. Mean and maximum FE velocities for low risk jobs were approximately 29

Table VII. Joint Acceleration Statistics, in deg/s^2[a]

	Typing group						MANOVA[c]/ ANOVA
Statistic	DE		WP		IE		
PIP							W****, P****
Mean	1455	(501)	717	(163)	593	(231)	****
Tukey test[d]		AA		BB		BB	
Maximum	6670	(2270)	5204	(1428)	3601	(1476)	***
Tukey test		AA		AA BB		BB	
MP							W****, P****
Mean	1487	(334)	881	(292)	537	(158)	****
Tukey test		AA		BB		CC	
Maximum	7172	(1696)	5567	(1960)	3156	(656)	****
Tukey test		AA		BB		CC	
Wrist—RU							W*, P*
Mean [301/494); (1/0)][b]	211	(123)	124	(62)	102	(29)	*
Tukey test		AA		AA BB		BB	
Maximum [(1759/3077); (4/0)][b]	1581	(647)	1131	(356)	1005	(354)	*
Tukey test		AA		AA BB		BB	
Wrist—FE							W*, P*
Mean [(494/824); (3,2)][b]	608	(395)	136	(75)	150	(75)	****
Tukey test		AA		BB		BB	
Maximum [(2788/4927); (3/1)][b]	3408	(1890)	1472	(472)	1360	(546)	***
		AA		BB		BB	

[a] Low risk group/high risk group wrist acceleration reference values (20) are presented in parentheses in the first column.

[b,c,d] Refer to interpretations in Table VI.

*$p < 0.05$

**$p < 0.01$.

***$p < 0.005$.

****$p < 0.001$.

and 121 deg/s, respectively, while values for high risk jobs were 42 and 184 deg/s, respectively. Those values are presented in Table VI along with the number of subjects in the current study displaying velocities which exceeded each of those values. Modest correlations existed between FE velocity and finger joint velocity statistics (ranging, approximately, between 0.5 and 0.7).

Joint Acceleration. As with the finger joint velocity statistics, for both joints there were overlaps in acceleration statistics between the groups, but the trends were for higher values in the DE group and lower values in the IE group. The one exception to that observation was that there were no overlaps in MP statistics between the DE and IE groups. Acceleration statistics for both finger joints are presented in Table VII. Acceleration magnitudes were similar between the two joints. There were only modest correlations between various finger joint acceleration statistics and typing speed (typically about 0.55). Finger joint acceleration did not appear to be related to hand length.

RU acceleration was similar across the three work groups, although slightly higher for the DE group. FE acceleration was similar in magnitude to RU in the WP and IE groups, but was twice the RU magnitude in the DE group. Wrist joint acceleration statistics for typing and reference values from Marras and Schoenmarklin (20) are also listed in Table VII. Statistics for the WP and IE groups were below their low risk reference statistics. Statistics for the DE group exceeded the low risk reference means, but were closer to them than to the high risk reference values.

Key strike force was not found to be highly correlated with FE acceleration statistics, although the correlations were statistically significant. Spearman correlations between FE acceleration statistics and finger joint acceleration statistics ranged from 0.59 to 0.78 (all $p < 0.002$).

Tendon Travel. This variable has been shown to be an indicator of highly repetitive hand-intensive tasks (24). In the current study tendon travel was highly correlated with dynamic finger joint and FE wrist joint variables. In order to assess total tendon travel for a full work shift, the actual amount of typing over the entire shift must be determined. Lacking this information for all but four subjects, FDP tendon travel was examined in normalized format (normalized to 1 hr of continuous typing). The average normalized travel values for the index finger tendon for the DE, WP, and IE groups were 59.0 m/hr (15.9), 38.3 m/hr (8.2), and 30.4 m/hr (10.1), respectively. Based on performance monitoring records for four of the DE opera-

Table VIII. Descriptive Statistics of FDP Tendon Excursion and Dynamics

	Typing group						MANOVA[a]/ ANOVA
Statistic	DE		WP		IE		
							W***, P*
Mean excursion from neutral (mm)	–2.9	(2.2)	–2.5	(1.5)	–3.1	(2.1)	
Velocity (mm/s)							
Mean	15.6	(4.3)	10.2	(2.1)	8.1	(2.8)	****
Tukey test[b]		AA		BB		BB	
Maximum	68.4	(15.1)	53.4	(11.0)	41.6	(14.5)	***
Tukey test		AA		AA BB		BB	
Acceleration (mm/s^2)							
Mean	319	(81)	189	(55)	146	(61)	****
Tukey test		AA		BB		BB	
Maximum	1542	(346)	1542	(301)	856	(505)	**
Tukey test		AA		AA BB		BB	

[a] Significance of MANOVA by Wilks' Lambda indicated by W; significance of MANOVA by Pillai's Trace inidicated by P. Model tested included velocity and acceleration statistics for the particular joint of interest.

[b] Group comparisons based on Tukey HSD Test, differences identified at 0.05 level.

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.005$.

****$p < 0.001$.

tors, average tendon travel per shift was calculated for those subjects. In meters, those values were 86, 124, 149, and 273.

Tendon Excursion and Dynamics. Mean excursion was similar across groups. Negative values are indicative of lengthened positions, relative to resting length estimates. Tendon velocity and acceleration statistics overlapped across groups, yet the trend was toward higher velocities in the DE group and lower values in the IE group. Tendon dynamics were highly correlated with finger joint and FE dynamics, and with normalized tendon travel. Results are summarized in Table VIII.

Workstation Dimensions

Workstation dimensions for the three groups are presented in Table IX. Features, such as a footrest or adjustable chair, are reported as the percentage of subjects within each group possessing the feature. As seen in the group averages, seat pan depth was greatest for the IE group. At 45.9 cm, that group's mean exceeded the ANSI/HFS guideline (31) prescribed range of 38–43 cm. Though seat pan height group means were within compliance, five individuals were seated below the recommended range of 40.6–52 cm. For nine subjects, popliteal height was less than seat pan height. Five of those nine subjects did have footrests. Keyboard support surfaces were near the upper end of the 58.5–71 cm recommended range. Five were above the range and one was below. ANSI/HFS (31) recommends that the top of the VDT screen match seated eye height. Compared with that recommendation, in this sample, two screens were too high and about half were too low.

Table IX. Workstation Dimensions and Features

	Typing group					
	DE		WP		IE	
Dimensions (cm)						
Seat pan depth	40.6	(2.3)	41.0	(2.2)	45.9	(3.5)
Seated eye height	111.9	(6.1)	113.7	(2.6)	114.1	(8.4)
Seat pan height	43.9	(4.2)	47.6	(3.5)	40.6	(4.6)
Popliteal height	43.4	(3.3)	44.8	(1.1)	53.5	(4.5)
Home row height	72.7	(3.0)	69.8	(4.0)	73.7	(7.4)
Screen height	99.5	(2.5)	107.9	(5.8)	102.9	(6.8)
Eye ht–screen ht	12.4	(6.3)	6.4	(5.7)	11.2	(9.6)
Popliteal ht–seat pan ht	–0.5	(2.0)	–2.3	(3.8)	12.9	(6.0)
Features: Percentage of group with feature						
Foot rest	38		71		0	
Adjustable chair	100		86		100	
Chair adjustable while seated	38		100		90	
Height adjustable	100		100		100	
Seat pan angle adjustable	0		50		40	
Backrest angle adjustable	0		50		60	
Document holder	13		86		10	

DISCUSSION

An observational study of professional typing was undertaken in order to accomplish several goals, three of which are discussed in this text. First, typing biomechanics, including key strike force, joint postures and dynamics, and tendon-related variables were successfully quantified for this sample of professional keyboard operators (PKOs). Across all subjects in the current study, the average peak key strike force was 2.2 ± 0.7 N, with minimum and maximum subject averages of 1.3 and 4.2 N, respectively. Average trial peak forces ranged from 1.9 to 6.5 N. These values, measured on the job, are similar to measurements reported from earlier laboratory studies. Rempel *et al.* (16) found average peak forces for four subjects ranged from 1.6 to 5.4 N, though they also mentioned a recording of 7.1 N. In another study, with ten subjects, average maximum force across subjects was 2.0 ± 0.6 N (14).

The significance of these force measurements comes not only in the form of quantification of impact forces and cumulative force exposure, but also in the form of estimates of internal forces. Based on the static optimization model of An *et al.* (32), tension in the extrinsic finger flexors may be twice the level of externally applied force (tip pinch force), while compression in the distal interphalangeal (DIP), PIP, and MP joints may be roughly 2.5, 4.7, and 3.7 times the applied force, respectively.

Finger and wrist joint postures were recorded in this study. Two-thirds of the subjects exhibited mean wrist extension between 10 and 25 deg. Nonneutral wrist postures have been shown to raise the pressure in the carpal tunnel (33). Rempel *et al.* (34) found CTP increased with wrist extension during typing. Based upon that research, 25 deg of extension may be associated with CTP in the range of 10–25 mmHg. In studying the effects of a split keyboard, reductions in CTP have been shown to coincide with reductions in ulnar deviation (35). However, relationships between CTP and ulnar deviation were found to be subject-specific. In the current study, the WP group was the most consistent in the display of ulnar deviation (group mean of 13.5 deg). Hünting *et al.* (22) related ulnar wrist deviation equal to or greater than 20 deg with occurrence of MSD symptoms in PKOs. Only two subjects in the current study exhibited mean ulnar postures exceeding 20 deg. One was a WP who had previously experienced symptoms, however the other was an IE operator, who made no reference to past pain.

Finger posture was recorded in the current study because it provides biomechanically relevant information. Finger posture has been shown to affect carpal tunnel pressure (36), and to be related to differences in finger muscle forces and joint loadings (37). One limitation of the current study is that typing material was not recorded, which makes it difficult to attribute specific key strikes to the instrumented finger. This information would facilitate the use of methods of tendon and joint analysis such as those performed by Harding *et al.* (37), in which posture and force data for an individual subject are combined to determine tendon and joint loads at each joint. In the future, individualized biomechanical analysis may provide vital clues as to why certain workers develop symptoms of UEMSDs while others do not. Quantitative biomechanical analysis methods may also be developed for objective evaluation of manual task performance in order to ensure individuals learning new skills utilize appropriate techniques. Additionally, these analysis methods may be used to evaluate an individual's abilities and task performance technique during rehabilitation.

No relationship between finger joint dynamics and MSD occurrence has yet been reported in the literature. In general, finger joint dynamics are rarely discussed in the literature, though these data are important elements for any truly dynamic biomechanical model of the hand. Index finger joint motion and torque interactions have been studied by Darling and Cole (38). In the current study, finger joint dynamics were found to be highly correlated with estimates of tendon travel and tendon dynamics. Tendon travel may be used to express the repetitiveness of a task. It is also one element in the computation of frictional work. Tendon velocity is assumed to be indicative of muscle velocity, which is inversely related to a muscle's force generating capacity. Compared to an isometric contraction, generating a specific level of tension requires more of the available capacity when the muscle length is changing. Based on rudimentary calculations, typists displaying tendon velocities below 20 mm/s might be working at a capacity decreased by less than 5%, yet when velocities reach 50 mm/s muscle force capacity may be reduced by 15%. All subjects in the current study displayed mean tendon velocities below 20 mm/s. Yet, five subjects exhibited average trial maximum tendon velocities which exceeded 50 mm/s. This means that some typists may be working harder than necessary. For example, one DE subject typed an average of 59 wpm with mean and trial maximum tendon velocity statistics of 7.5 mm/s and 37.8 mm/s, respectively. Another DE subject typed an average of 61 wpm, yet displayed mean and maximum tendon velocity statistics of 16.4 mm/s and 70.2 mm/s, respectively. The second subject would seem to be working less efficiently than the first (same output, greater input).

The second goal of the study was to examine the data by typing group. The study has identified some interesting trends and methodological issues that could facilitate future studies of these differences. Statistical analyses of typing group effect were performed, but the results should be interpreted with caution. Nonetheless, the results tend to indicate that some biomechanical factors differ by typing task. Therefore, future studies should be designed so as not to blindly pool data from operators performing different kinds of typing tasks.

The third goal was to seek out biomechanical similarities between typing and industrial tasks. Based on measurements from this study, limited comparisons may be made between typing and repetitive, hand-intensive industrial tasks. Wrist joint dynamics have been quantified for a number of highly repetitive, hand-intensive industrial tasks (20). Compared to the preliminary benchmarks identified by Marras and Schoenmarklin (20), typing would appear to fit within their low risk job category, although the styles of a couple of the typing subjects more closely resembled their high risk profile.

Industrial tasks and typing appear to differ in terms of some wrist and finger joint kinematics and types of force exertions. However, since UEMSDs are associated with both kinds of work, biomechanical similarities may lie at the level of intervening variables such as tendon travel, cumulative force, or frictional work. If methodologies can be developed to assess these biomechanically-based, nontask-specific exposures for all manual tasks, they may provide vital clues about the pathomechanics of work-related UEMSDs. As discussed previously, developing such a methodology was a fundamental goal of this research.

For the majority of subjects in this study, cumulative force and tendon travel were only calculated on a per hour basis. Totals can only be calculated for typists when either the amount of time actually spent striking keys or the actual number of key strikes is known. Note that this can be very different from the amount of time spent at the computer. Based on the monitored data for four of the DE operators, those subjects were poor judges of the amount of time they spent actually typing. This undoubtedly occurs because individuals have no way to tally the amount of time spent on minor activities such as sorting papers, turning pages, talking to co-workers, stretching, removing staples, looking for paper clips, and the host of other activities which reduce the amount of time actually spent typing. The four subjects overestimated the amount of typing time by 1.7–4.2 times. Cumulative force exposures for these four subjects ranged from 3.7 to 14.3 kN·s per shift. There are, as yet, no values in the literature to which these cumulative force estimates can be compared.

Moore *et al.* (24) examined total tendon travel, but presented results normalized to a particular task. Wells *et al.* (25) presented tendon travel estimates, normalized to 1 hr, for a group of 88 industrial workers and one library data clerk. Those values were 68.2 m/hr (17.9) and 69.5 m/hr, respectively. Group means in the current study were somewhat lower than those values, yet five of the DE operators displayed normalized tendon travel which exceeded 60 m/hr.

In order to provide an additional reference for tendon travel, further analysis was conducted on the original data from Marras and Schoenmarklin (20). Tendon travel was calculated from the wrist motion data of five randomly selected subjects in each of the two risk groups. Results of that analysis are depicted in Fig. 4. While there is some overlap between the risk groups, after visual inspection a case could be made for a low risk upper limit around 55 m/shift and a high risk lower limit around 145 m/shift. In that case, tendon travel for two of the DE operators would classify them between low and high risk, while two would be in the high risk range. From the current study, it would seem that individual style may play a significant role in the biomechanical profile of a given typist. Future studies should seek to determine actual amounts of keying or keying time for subjects in order to calculate operators' daily exposures of tendon travel and cumulative force.

Study Limitations

A number of limitations have been mentioned in conjunction with this study, particularly the small sizes of the groups into which the sample of 25 subjects was divided as a result of differences between typing tasks. As such, emphasis should be on the descriptive statistics, rather than the comparative statistics. Though collection and analysis of quantitative data are time consuming, there is a need for an expanded study of these biomechanical variables in order to examine potential causal connections with upper extremity MSD occurrence in keyboard operators.

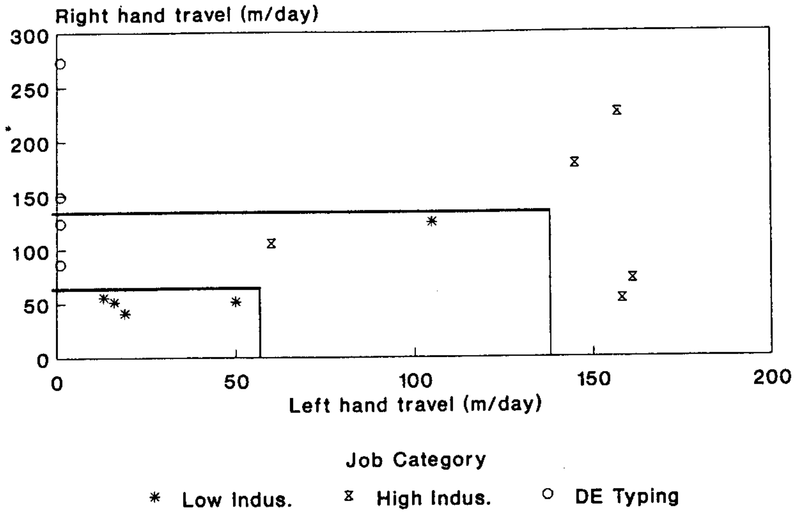

Fig. 4. Comparison of tendon travel of four data entry operators with tendon travel of industrial workers in low and high risk jobs from a study of highly repetitive, hand-intensive industrial jobs by Marras and Schoenmarklin (20). Dark lines mark hypothetical cutoffs for characteristic tendon travel for low and high risk industrial jobs.

Another limitation was the potential for test apparatus to interfere with or influence a subject's typing style, typing speed, or posture. Subjects were instructed to refrain from resting their hands on the keyboard while typing. This was not a change for most two-handed typists, but some of the DE operators who primarily used the numeric keypad normally supported their right hands on the edge of the keyboard. However, a review of videotapes of each subject's testing session did not reveal any overtly unusual postures. Goniometers may also have interfered with typing, though none of the subjects commented on such a problem. Recommendations for future studies include recording subjects typing without goniometers for a brief period of time, in order to collect baseline typing speeds; and briefly collecting data with goniometers, but without the force plate, in order to collect baseline postural data.

Comparisons between tendon travel calculations for typing subjects and for industrial subjects (20) may be controvertible. Calculations for typing subjects were based on finger and wrist joint motions, while calculations for industrial subjects were based only on wrist joint motion. However, it may be argued that for both types of subject, calculations were based on data from the principle joint of motion (finger for typist, wrist for industrial worker).

Last, there were several potentially important variables which this study was not designed to examine, including frictional work, carpal tunnel pressure, and muscle activity. Carpal tunnel pressure measurements are invasive, and therefore not appropriate for an office setting. Muscle activity is measured via electromyographic equipment, which in this circumstance was a nonportable laboratory system. Frictional work calculations are dependent, in part, upon muscle activity estimates. These factors, as they relate to typing, are addressed elsewhere (26).

CONCLUSIONS

The observational study described herein provides new quantitative, biomechanical descriptions of three common keyboard tasks: data entry, word processing, and interactive entry. The paper also describes a new methodology for collecting these data in an office setting. Key strike force was measured with a new, easily portable force plate which was designed to accommodate a variety of keyboards. In addition to wrist posture, which has been reported in past studies, finger joint postures and wrist and finger joint dynamic variables were quantified. Typing task and operator style both appeared to influence the biomechanical characteristics of typing. At 2.8 N, the average peak key strike force for the DE group was almost 50% greater than the 1.9 N averages of the other two groups. At 608 deg/s^2, the mean wrist FE acceleration for the DE group was four times greater than the means of the WP or IE groups. Tendon travel, a correlate of joint dynamics, was calculated for the typists and compared with tendon travel in several repetitive, hand-intensive industrial tasks. For some individuals, typing appears to be biomechanically comparable, in terms of tendon travel and in wrist joint FE acceleration, to industrial tasks which have historically elevated incidence rates of UEMSDs.

Now that a methodology has been devised for collecting kinetic data from typists in a workplace setting, future studies should be designed to collect such data from larger samples of subjects and in conjunction with associated health statistics. This method of quantifying finger and wrist joint biomechanics, in conjunction with force measurements, may be applied to other kinds of manual tasks, as well. This will facilitate identification of quantitative, nontask-specific, biomechanical benchmarks for factors such as tendon travel and wrist joint acceleration, as well as dose–response relationships between biomechanical exposures and UEMSDs, which will lead to development of effective exposure control methods. Such quantitative analysis techniques and benchmarks will also provide methods to assess skilled performance of manual tasks and methods to evaluate progress during rehabilitation. Databases constructed from results from studies such as the current one, could contain quantitative benchmarks that could be used both as targets and training algorithms during the rehabilitation process. In addition, the methodology for assessing hand kinetics may be used to provide biofeedback in order to reinforce appropriate technique during training or return to work, i.e., minimizing keyboard impact or reducing extreme posture. The current study, and previous work by other researchers (14, 20, 24, 29), are initial steps toward achieving these important future goals.

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