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A method for developing biomechanical profiles of hand-intensive tasks

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Abstract

Objective. To develop a methodology for generic, comprehensive biomechanical profiling of hand-intensive tasks.

Design. Based on a multifactorial model of work-related musculoskeletal disorder development, a method was developed for continuous, simultaneous measurement of relevant variables (wrist and finger joint position, force, muscle activity, and carpal tunnel pressure). Joint dynamics and tendon travel were derived.

Background. Few generic dose–response relationships have been identified for work-related musculoskeletal disorders. This may improve if methodologies are developed that quantify multiple factors along several dimensions (means, cumulative exposure, etc.). This requires continuous, simultaneous measurements, and facilitates examination of interactions.

Methods. Five touch-typists were instrumented to quantify their biomechanical profiles using the methodology, and to evaluate the sensitivity of the method to various work organization/design conditions.

Results. The method captured individual and group responses to design conditions and revealed interactions and trade-offs between response variables. Carpal tunnel pressure was found to be sensitive to radial–ulnar wrist posture.

Conclusions. Multi-variable biomechanical profiling can provide insight into effects of work design on workers; however, to achieve statistical significance large numbers of subjects are needed.

Relevance

The etiology of work-related musculoskeletal disorders is complex, and requires an integrated, multidimensional investigative approach that can demonstrate interactions among response variables and individual differences in responses, as well as trade-offs in design features revealed through those responses. Based on individual differences found in internal variables, assessing only external variables may be insufficient for understanding the etiology of these disorders in individuals or individual response to workplace organization/design features.

Keywords: Work-related musculoskeletal disorders; Carpal tunnel pressure; Biomechanics; Ergonomics; Keyboard

1. Introduction

In US workplaces 20 yr ago there were about 675 000 computers. By recent estimates there are now over 90 000 000. Along with increased computer usage has come increased concern for development of work-related musculoskeletal disorders (WMSDs) of the upper limb. Those upper limb soft-tissue disorders, such as tendinitis and carpal tunnel syndrome (CTS), that are generally attributed to chronic tissue stress, are categorized as WMSDs.

Many researchers subscribe to a multifactorial, interaction theory of WMSD etiology, consisting of biomechanical, work organization and design, psychosocial, and personal factors, with the latter three influencing and working through the first [1–3]. Interactions are thought to occur among the various categories of factors, as well as within categories. One version of this theory is depicted in Fig. 1. The research described in this paper focuses on the interactions among the work organization and design factors and the biomechanical response factors in the

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model, as well as interactions among the biomechanical factors.

The model is not limited to a specific category of work. In fact, it is our belief that models and investigative methods that are generic, such as those proposed by Armstrong *et al.* [2] and Moore *et al.* [4] respectively, which can be applied to a range of job categories, may produce the greatest advances in our understanding of WMSD etiology. One example of this is the identification and use of biomarkers in the study of WMSDs [5]. An investigative method that would complement the model presented in Fig. 1 would be generic (and thereby widely applicable), and would assess both internal and external biomechanical responses. Internal responses provide insight into tissue response, while external responses provide direction for workplace design modifications.

To date, epidemiological studies of industrial work have demonstrated more consistent associations between WMSD rates, work design factors, and biomechanical response variables than have studies of office and keyboard work. Associations have been identified between WMSD rates and repetitive work involving high hand forces [6], or high levels of wrist acceleration [7]. High speed tasks and awkward wrist postures, usually in combination with other factors, have also been shown to be associated with WMSDs in industrial populations [8,9]. Awkward wrist postures have also been associated with WMSDs in keyboard operators [10–12].

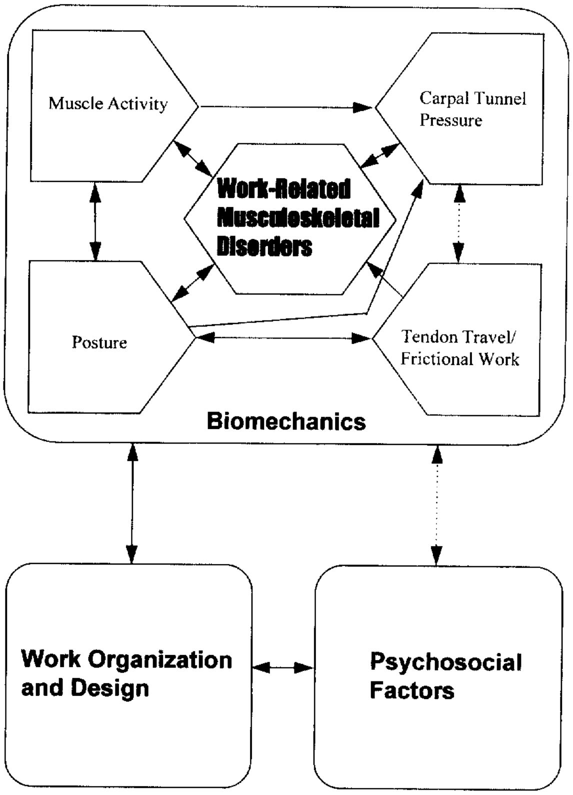

Fig. 1. Interactive, multifactorial model of WMSD etiology. Dotted lines reflect theoretical associations, solid lines reflect demonstrated associations.

Both external response variables (extreme finger and wrist postures), and intervening or internal response variables (sustained low level muscle contraction, elevated carpal tunnel pressure (CTP), and repetitive tendon motion) have been proposed as work-related factors that may contribute to the development of WMSDs. Some of these variables have been studied in typing research, though not all simultaneously. Sustained muscle activity as low as 5% of a maximum voluntary contraction (5%MVC) may be cause for concern [13], yet Onishi *et al.* [14] observed muscle activity ranging from 20–40%MVC in the forearm extensor muscles of female keyboard operators. Continuous or intermittent pressure on a nerve exceeding 20–30 mmHg has been shown to be detrimental to nerve physiology and function [15,16]. Rempel *et al.* [17] found that CTP, in some subjects, exceeded 30 mmHg during typing, and that CTP was directly related to wrist extension. Recently, Werner *et al.* [18] also reported an effect of forearm pronation and supination on CTP, though minimal response to radial–ulnar (RU) position.

Specific finger joint posture combinations have been shown to impact finger joint loading and extrinsic muscle tendon tension during key strike [19], and to raise pressure in the carpal tunnel [18, 20]. Wrist joint postures that deviate from neutral have been associated with operator discomfort [11] and increased CTP [17]. Wrist joint dynamics have been shown to differentiate between high and low risk (risk for recorded upper limb illness or injury) highly repetitive hand-intensive industrial jobs, with lower flexion–extension (FE) dynamics associated with low risk jobs [7]. Cumulative tendon excursion (tendon travel), a direct function of wrist and finger joint motion, has been used to describe task repetitiveness. Tendon travel, a component of frictional work, increases with time on task or increased task rate [4].

Few studies have attempted to assess work design effects through a comprehensive assessment (multiple variables, assessed simultaneously and continuously) of the biomechanical response variables just mentioned [4, 21, 22], even though associations among them are documented in the literature [20, 23]. Benefits to comprehensive assessment include identification of trade-offs in design alternatives (identifying both biomechanical advantages and costs to alternatives) and critical junctures (periods in time when multiple response variables are at critical levels). This paper describes the development and initial testing of a generic, comprehensive methodology for profiling biomechanical response, at group and individual levels, to the effects of work organization and design on hand biomechanics, based upon a multi-factorial model of WMSD development.

2. Method development

A comprehensive methodology, similar in scope to one described by Moore *et al.* [4], was developed to assess several biomechanically relevant variables, simultaneously and continuously during hand-intensive work. Biomechanically relevant variables are those that have been shown, or are theorized, to be associated with WMSD injury mechanisms. The goals for the method included: facilitation of task characterization along multiple dimensions (which facilitates detection of design trade-offs); assessment of cumulative task effects; characterization of individual response differences; and provision of inputs to a dynamic biomechanical model (employed to estimate tendon and joint loadings).

2.1. Measured variables

Wrist joint angular position for both hands are measured in RU and FE planes. Forearm pronation–supination (PS) may also be included. Finger joint posture is measured from the metacarpophalangeal (MP) and proximal interphalangeal (PIP) joints of both index fingers. The index finger was selected for three reasons: the important role of the index finger in most hand functions; subsequent biomechanical modeling; interference with other equipment when goniometers were placed on the middle fingers. External finger tip force is also measured (or hand force, depending on the task). Muscle activity which produced the external finger forces and which positioned the joints is recorded from eight muscles: four primary wrist movers: flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi radialis (ECR), and extensor carpi ulnaris (ECU); the extrinsic index finger movers: index finger subvolumes of the extensor digitorum communis (EDC), flexor digitorum profundus (FDP), and flexor digitorum superficialis (FDS); the first dorsal interosseus (DI1). CTP, an internal or intervening variable and the outcome of the interactions of muscle activity and finger and wrist joint posture, is also measured.

2.2. Derived variables

From the continuously measured variables, joint dynamics and tendon travel are calculated. Joint angular velocity and acceleration, as well as position, are calculated via a Laplace transform routine which filters the joint position data while simultaneously calculating velocity and acceleration for each successive point in time [24]. Tendon travel calculations are based on regression equations developed for displacement of FDP tendons for the wrist, MP, and PIP joints, as functions of joint thickness and angle [25].

2.3. Data acquisition and processing

With few exceptions, equipment and procedures selected to collect the biomechanical data described above are not restricted to a particular work task. Wrist posture is measured with two independent wrist motion monitors, one for RU position and the other for FE. These devices are described elsewhere [7,24]. Finger joint position is measured with finger joint goniometers (Model G-35, Penny+Giles Ltd, Santa Monica, CA, USA).

Electromyographic data are recorded with either fine wire electrodes (0.002 in stainless steel with ML insulation, California Fine Wire Co, Grover City, CA) or pairs of silver chloride surface electrodes. Signals are first amplified 1000 times by preamplifiers, then amplified a second time at subject and muscle specific gains. Amplified signals are conditioned by a 1000 Hz low pass filter and an 80 Hz high pass filter. Signals are then rectified and smoothed, using a 20 ms moving average window. The system has a common ground.

EMG signals are normalized, then smoothed using a 39-point Hanning filter with an equivalent bandwidth of 12 Hz, selected through residual analysis [26]. The normalization formula is presented as eqn (1). In the remainder of the text, reference to EMG implies normalized EMG.

$$\mathrm{NEMG}(i,t) = \frac{\mathrm{EMG}(i,t) - \mathrm{Min\ EMG}(i)}{\mathrm{Max\ EMG(i)} - \mathrm{Min\ EMG(i)}} \qquad (1)$$

where: NEMG(i,t) is normalized EMG for muscle i, at time t; Max EMG(i) is largest voltage recorded for muscle i, during static exertion; Min EMG(i) is the smallest voltage recorded for muscle i, during any resting period; EMG(i,t) is the EMG voltage for muscle i, time t.

CTP is measured by a catheter with a fiber-optic transducer tip (Model 110-4, Camino Laboratories, San Diego, CA, USA), powered by a Camino V420 direct pressure monitor and subsequently amplified via custom-made equipment. Data are smoothed with a 9-point Hanning filter with an equivalent cut-off frequency of 52.4 Hz. Owing to sterilization requirements, catheters are calibrated immediately following testing.

A pair of low profile (1.6 cm thick) force plates, containing a matched pair of piezo-resistive force transducers (Model 9211, Kistler Instrument Corporation, Amherst, NY, USA), is used to estimate finger tip force. The system was specifically constructed to measure force exerted on a keyboard by the fingers during typing. The system is described elsewhere [22].

Data are sampled simultaneously and continuously during intervals of time (such as 6 s, 10 s or 30 s depending on task duration), at 600 Hz, using a 12-bit a–d board (Model 2839, Data Translations, Marlboro MA, USA). Data are stored in digital format.

2.4. *Statistical quantification*

Mean and percentile statistics are used to summarize each variable for a specific task or condition, and changes in those statistics reflect the sensitivity of each measure to changes in conditions. Where biomechanical thresholds are known, comparison statistics are derived. For example, the amount of time during task performance that CTP exceeds 30 mmHg is quantified. Table 1 contains a partial list of potential statistics that could be explored with this method. Correlation and partial correlation analyses are used to investigate interactions among variables.

Table 1
Statistics that can be used to characterize biomechanical variables characterized through the proposed methodology

Variable	Units	Statistic
Finger tip or hand force	N	average (mean) peak force
CTP	mmHg	mean 90th percentile maximum
	%	percentage of task time that CTP exceeds 30 mmHg (benchmark in the literature)
Joint position	deg	mean range of motion (central 90th percentile, calculated as the difference between the 5th and 95th percentile position statistics)
Joint velocity, acceleration	deg/s, deg/s^2	mean 90th percentile
Tendon travel	mm/h	tendon travel per hour
	mm/letter[a]	tendon travel per number of letters typed by hand tendon travel per number of letters typed by index finger
Muscle activity — normalized	unitless	10th percentile mean 90th percentile
Muscle activity — APD	%	percentage of task time muscle activity was below 5%MVC percentage of task time muscle activity was below 10% MVC

[a] Specifically for typing tasks.

3. Method application

The methodology was tested on a small sample of subjects performing a typing task in order to make initial determinations on the consistency, sensitivity, and practicality of the methodology for studying effects of changes in work design and work organization.

3.1. *Subjects*

Five healthy females, with no history of arm pain, gave informed consent to voluntarily participate in the study. Each subject performed a typing test to verify 10-finger touch-typing ability, and achievement of a minimum 40 wpm natural typing rate (the test emphasized accuracy and selection of a typing rate that could be maintained over an extended period of time). Only S5 had professional typing experience. Subjects received compensation. Table 2 contains subjects' anthropometric data and average typing rates.

3.2. *Independent variable*

The study was designed with one independent variable, which was related to the work organization component of the model (Fig. 1). That variable was referred to as typing condition, and it had four levels: Control, Incentive, Split, and Layout. One Apple Adjustable Keyboard was used for all conditions; no wrist support was provided. Using a crossover design,

Table 2
Subject information: anthropometry, average typing rate under natural conditions, and keyboard split angles

Variable	Subject				
	S1	S2	S3	S4	S5
Age (yr)	28	34	28	25	26
Height (cm)	170	163	163	163	163
Weight (kg)	48	47	50	57	51
Dominant hand	L	R	R	R	R
Biacromial distance (cm)	31.5	34.3	28.2	28.0	34.2
Non-dominant hand					
Elbow–index finger tip (cm)	43.0	41.1	40.7	40.6	45.1
Hand length (cm)	17.6	16.8	17.7	17.6	18.6
Wrist thickness (cm)	3.3	3.6	3.6	3.6	3.5
Natural typing speed (wpm)	47.8	63.0	55.0	59.7	76.4
Split angle (deg)	15	22.5	15	15	15

test order was different for each subject. The Control condition simulated natural typing. Subjects typed at normal, self-selected typing speeds, with the keyboard in the closed orientation, with QWERTY key layout. The Incentive condition was similar to Control except that subjects were awarded monetary bonuses for fast, correct typing. Keyboard orientation was the only difference between the Control and Split conditions. Split angle was normalized for each subject, based upon shoulder breadth and forearm–hand length. Split angles appear in Table 2.

The fourth condition, Layout, was a modified version of the ASER alternative letter arrangement system (Avanti Systems, Oak Brook, IL, USA). ASER was designed to enable typists to spend more time on home row and to evenly distribute the typing load between the two hands. Instead of requiring subjects to learn the alternative layout, and switch between QWERTY and the modified ASER layout during testing, letters in the standard sentences that subjects typed under the other three conditions were rearranged for the Layout condition. For example, typing "nun" in the ASER system, required the same motions as typing "juj" in the QWERTY layout. Flannery et al. [27] used a similar technique in their investigation of other alternative key layouts.

Data that were analyzed consisted of subjects typing three standard sentences, three times each, under each condition. Those sentences appear in Table 3. Sentences were designed to produce index finger activity.

3.3. Dependent variables

Key strike force, wrist and finger joint posture, CTP, and muscle activity were measured directly. Invasive measures were taken from the non-dominant arm. Additionally, wrist and finger joint dynamics and tendon travel were derived from joint posture data. Typing speed was derived from force data and word processing documents that recorded subjects' keyboard entries.

Table 3
Test sentences typed by subjects — standard and alternative layout versions

Condition	Sentence number	Sentence
Control, Split, and Incentive	1	many friends betray no sworn vows.
	2	and never again to arms they vowed.
	3	never run beyond the brown fence.
Layout (modified ASER)	1	majy rfldjgs bdkfay jo swofj vows.
	2	ajg jdvdf atalj ko afms khdy vowdg.
	3	jdvdf fuj bdyojg khe bfowj rdjcd.

3.4. Descriptive statistics

Data in each file were analyzed only for that portion of the data collection period during which the subject was typing. Statistics for each channel, from each file were averaged across sentences within a single condition. Sentence means were then averaged together to characterize each of the four conditions for each subject. In calculating mean and percentile statistics for joint velocities and accelerations, absolute values of those derived measurements were utilized.

3.5. Test protocol

Each subject experienced one practice session and one test session. During the practice session, subjects were familiarized with the test apparatus and protocol, and given as much time as they wanted to practice typing under test conditions with the goniometric apparatus in place. Anthropometric measurements were collected during the practice session.

On the test day, the work station was adjusted so that the subject's wrists were placed in a neutral FE orientation when typing. Wrist and finger goniometers were then applied and calibrated. Neutral joint angles (0°) were identified with shoulder abducted 90°, elbow flexed 90°, and forearm and hand resting on a horizontal surface. Zero angles for finger joints were defined with fingers extended, but not hyperextended, on a horizontal surface. Neutral RU wrist position was recorded as the alignment of the third MCP joint, center of wrist rotation, and lateral epicondyle. Neutral FE was recorded with the second metacarpal bone parallel with the forearm. Fine wire electrodes were used on all but the DI1, and were inserted by an experienced physiatrist. A functional check was performed after each insertion. Once second-stage amplifier gains were set for each muscle, static maximum exertions were performed. The pressure catheter was then inserted by a hand surgeon.

Following administration of a local anesthetic (Marcaine), used only to numb the skin in the immediate area of catheter insertion, the surgeon inserted a 14-gage I.V. catheter needle into the carpal tunnel. The insertion was made just proximal to the distal wrist crease and medial to the palmaris longus tendon. After the needle was removed, the sheath remained in place, projecting out of the wrist at a 45° angle with the forearm. The catheter was removed from sterile packaging, zeroed to atmospheric (room) pressure, and inserted through the sheath into the wrist to a distance of 2 cm, based on markings on the catheter. The sheath was then extracted and taped onto the forearm to act as a conduit for the catheter. The catheter was taped in place on the hand in order to fix the transducer's position within the carpal tunnel.

Fig. 2. Subject instrumented with finger and wrist joint goniometers, fine wire electrodes (left arm only), and pressure catheter (left arm only).

A fully instrumented subject appears in Fig. 2. Only the first subject reported feeling any finger tingling or numbness associated with the Marcaine injection, though her typing was not affected (she made no typing errors during the data collection session). Smaller doses of anesthetic were used for the subsequent subjects.

Once completely instrumented, the subject was given 10 min to practice typing with the equipment in place. The subject was then informed of the upcoming typing condition, and was given another 10 min to practice typing for that condition before data collection commenced. Subjects were given rest breaks between typing conditions, but typed almost continuously otherwise. Subject preparation took 2–3 h, and testing required an average of another 2 h.

3.6. *Statistical analysis*

Biomechanical variables were examined with multivariate analysis of variance (MANOVA), followed by ANOVA, and then post hoc Tukey tests. Condition, subject, and condition × subject interactions were examined.

4. Results and discussion

The limited subject sample size restricted the extent of statistical analyses that could be performed on the data. It is sufficient, and not surprising, to summarize those analyses by reporting that, for most variables, subject or subject × condition effects were significant, and precluded the identification of a single profile of natural typing or a specific profile of typing under any other condition for this group of subjects. This also follows from differences in typing ability that were reflected in typing rates, which, for example, ranged from 48–76 wpm across subjects in the Control condition. Results that will be presented and discussed are those that illustrate the important features of the method: the ability to capture group and individual response to workplace organization/design features; sensitivity of measures to changes in workplace features; ability to reveal interactions between responses. These results are the focus of the remainder of the paper, along with a review of the limitations of such an approach.

4.1. *Group response consistency and individual response differences*

Confirmation of the importance of including muscle activity measurements comes from inspection of EDC activity. Consistent with findings from previous studies, each subject in the study exhibited static EMG levels (10th percentile EMG statistic) for the EDC which exceeded 5%MVC. Average values ranged from 5.5–13.1%MVC. This common finding across subjects is in contrast with the findings from the CTP measurements. Only one subject (S2) displayed CTP that exceeded the 30 mmHg threshold. Unique results from such intervening variables, may provide partial explanations as to why some individuals develop WMSDs and co-workers performing similar tasks do not. (Note that elevated CTP may occur more frequently in actual work settings, where wrist extension can occur. In this study, the workstation had been set-up to promote neutral FE posture.)

4.2. *Sensitivity to workplace design changes*

Figures 3 and 4 reveal the sensitivity of CTP in S2 to the split keyboard. Continuous pressure data are presented in Fig. 3 for S2 typing two repetitions of sentence #3 in the Control condition, and in Fig. 4 for S2 typing two repetitions of sentence #3 in the Split condition. Subjects 2, 3, and 4 each demonstrated significant decreases in one or more CTP statistics when using the split keyboard (mean, 90th percentile, maximum, or percentage of time pressure exceeded 30 mmHg); however, only S2 showed significant decreases in each statistic (see Table 4).

Joint position and tendon travel were also shown to be sensitive to condition. Typing condition provided a significant main effect on range of motion (ROM) of the left and right PIP and right MP joints. For each, the ROM for the alternative key layout was significantly less than the other three typing conditions which used the standard QWERTY layout (see Table 5). Tendon travel was also reduced in the Layout condition, especially for the right hand, when compared with the other three conditions. For left and right hands in Layout, FDP/h was $\frac{1}{2}$–$\frac{2}{3}$ that of values for the other three conditions. For the right hand, tendon travel/letter/hand was 2.5 mm/letter for Layout compared with 3.2–3.8 mm/letter for the other three typing conditions, whereas tendon travel/letter/finger was 5.2 mm/letter for Layout and 7.1–7.8 mm/letter for the other three conditions. (Note that this was not due to typing speed differences, since typing speed is not explicitly a factor in the tendon travel/letter statistics.)

4.3. Interactions revealed

Two main types of interaction could potentially be revealed with this type of methodology. The first is the interaction between internal and external variables, and the potential for identifying predictive associations that

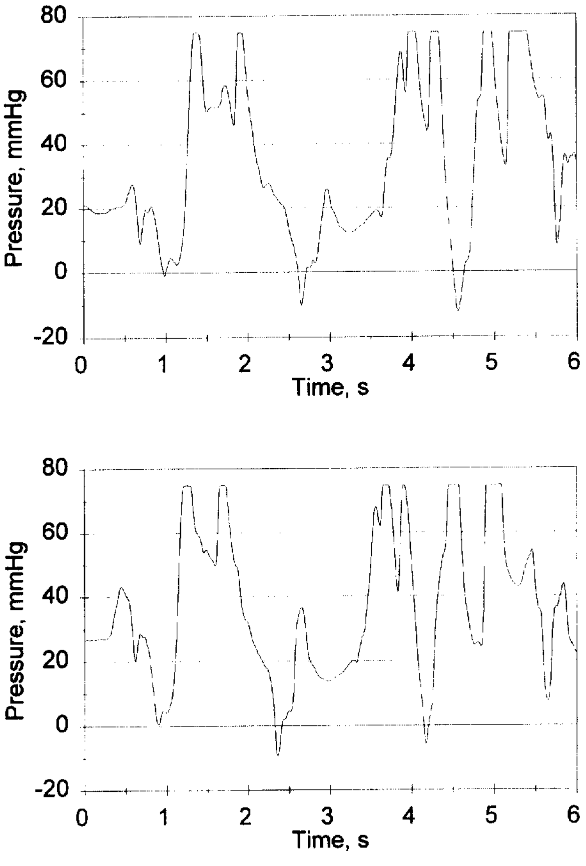

Fig. 3. CTP during two repetitions of sentence #3, Control condition, S2.

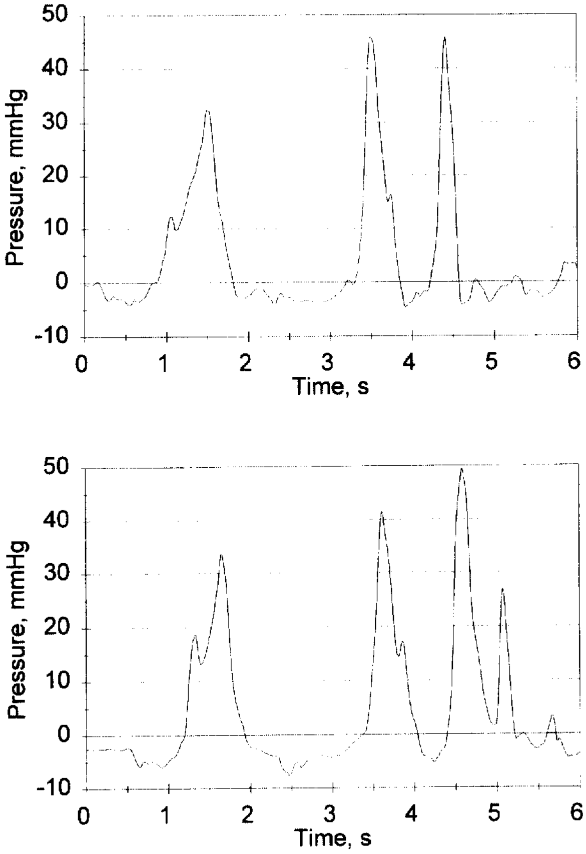

Fig. 4. CTP during two repetitions of sentence #3, Split condition, S2.

Table 4
CTP statistics for the Control and Split conditions. Within the Control condition, Tukey testing separated S2 from the other three subjects

Subject	Control				Split			
	Mean (mmHg)	90th %-ile (mmHg)	Max (mmHg)	T30[a] (%)	Mean (mmHg)	90th %-ile (mmHg)	Max (mmHg)	T30[a] (%)
S2	36.9	> 72.8[b]	> 72.8[b]	56.9	7.4*	29.5*	52.5*	10.1*
S3	−0.2	13.9	34.8	1.0	−1.6	10.8	16.0*	0.0
S4	3.6	10.0	15.5	0.0	0.3	2.0*	4.2*	0.0
S5	2.1	6.8	15.3	0.0	4.5*	12.6*	30.2*	0.7

[a] Percentage of time CTP exceeded 30 mmHg, during typing.

[b] Owing to technical problems during data collection, pressure values exceeding 72.8 mmHg could not be recorded for S2, and pressure could not be recorded for S1 during typing.

*Significantly different from Control, $p \leq 0.01$.

Table 5
Effect of the alternative layout condition on finger joint ROM. Statistics are means across subjects, in degrees

Joint	Alternative layout	QWERTY layout (Control, Incentive, and Split conditions[a])
PIP-left	11.6	15.2–16.9
PIP-right	14.2	21.0–22.4
MP-right	13.0	18.2–18.8

[a] No statistically significant difference between these three conditions.

would preclude the necessity for invasive measurements. For example, where ulnar deviation decreased (as it did for nine of the ten wrists) in the Split condition, CTP also decreased. This correspondence also explains why S5 did not show a decrease in CTP in the Split condition: in response to the split keyboard, she reduced the ulnar deviation in only her right (dominant) wrist.

The response of CTP to changes in wrist posture was also examined through recordings made during reciprocal single plane wrist movements, performed after the typing experiment was completed. S1, S2, and S4 demonstrated strong, second-order relationships between RU posture and CTP (see Fig. 5). Regression models of those associations had adjusted R^2 values ranging from 0.80–0.93. The data for S5 showed a fairly consistent relationship, but not one that could be described by a second-order equation. Two subjects (S1 and S5) demonstrated strong associations ($R^2 = 0.76$ and 0.79) between FE and CTP (Fig. 6). During these supplementary exercises, there were no consistent patterns of change in response to changes in wrist FE for S2 or S4, and none for motion in either plane for S3. Negative pressure values may have been due in part to the speed of the motions. Subjects were asked to complete a cycle (for example, ulnar to radial and back to ulnar) within 10 s. Though slow, these exercises were completed in one-third the time of similar activities reported by Keir *et al.* [28]. The variance in the response curves within a single subject were similar to those reported by Keir *et al.* [28].

Though CTP was shown to be fairly strongly associated with wrist position and also somewhat influenced by typing speed for most subjects, the associations were subject specific, thereby precluding the prediction of CTP from the external (non-invasive) measures used in this methodology. Within-subjects regression analyses of mean CTP during typing showed that for all subjects pressure increased as ulnar deviation increased, for three of four subjects pressure increased with increased typing speed, and for three of four subjects pressure increased with increasing wrist extension. Within-subjects partial correlations between mean pressure and mean RU position while controlling for typing speed and mean FE position ranged from −0.48 to −0.85 for S2–S5.

Trade-offs are the second type of interaction that can be revealed by collecting multiple measures simultaneously. For example, the Split condition was shown to be beneficial to S2, in terms of significant reductions in CTP. However, S2 also showed an increase in

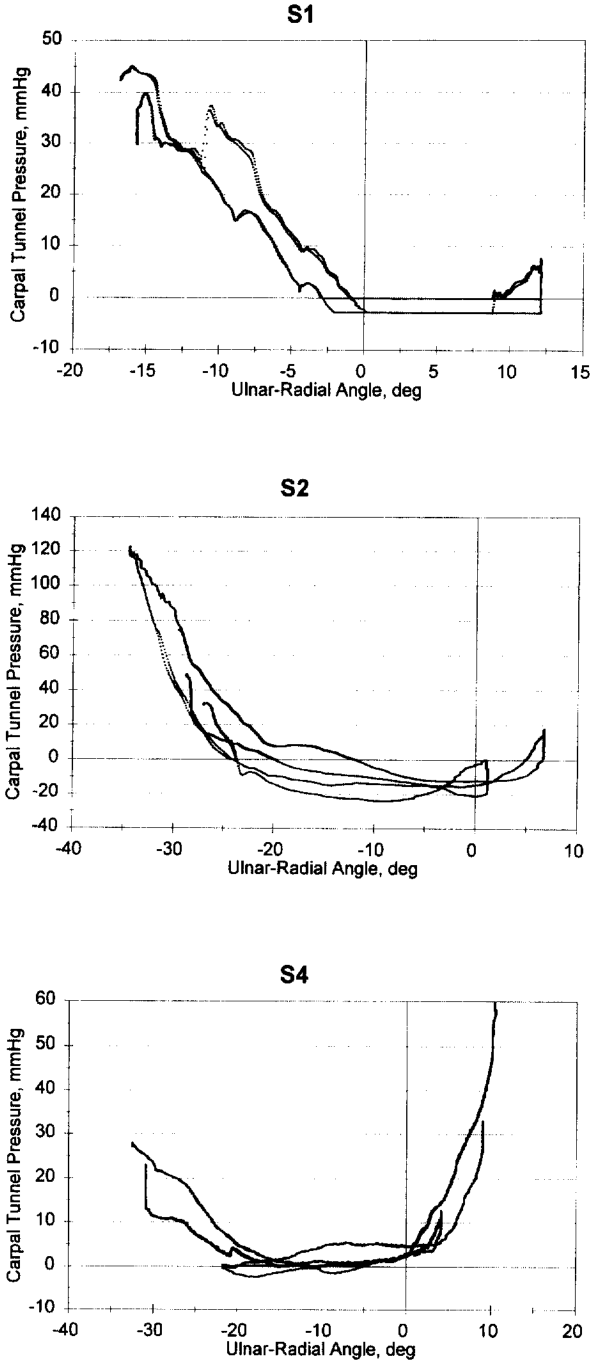

Fig. 5. CTP response to slow, reciprocating RU wrist movement. (Horizontal flat lines seen in S1 graph were due to improper bandwidth settings that were corrected for subsequent subjects.)

tendon travel statistics for the right hand in the Split condition, compared with the Control typing condition. A second example stems from the response of S5 to the Split condition. Although the non-dominant wrist was positioned similarly for Control and Split conditions, there was a statistically significant increase in each CTP statistic in the Split condition (perhaps due to increased activity seen in EDC, FDP, and ECR). These examples demonstrate the ways in which a comprehensive measurement methodology can facilitate capture of a variety of response factors that may be affected by workplace design or organization changes, in order to record both expected and unexpected effects.

4.4. The usefulness of generic, comprehensive methods

There are numerous benefits to be derived from collecting multiple measures continuously and simultaneously from subjects when studying questions in the area of biomechanics. The identification of interactions can provide explanations of results, or may provide information on trade-offs (the benefits and costs) associated with specific designs or conditions. Comprehensive data collection also provides input to biomechanical models, which can explain results of a study from which biomechanical data were obtained, or may explain epidemiological findings.

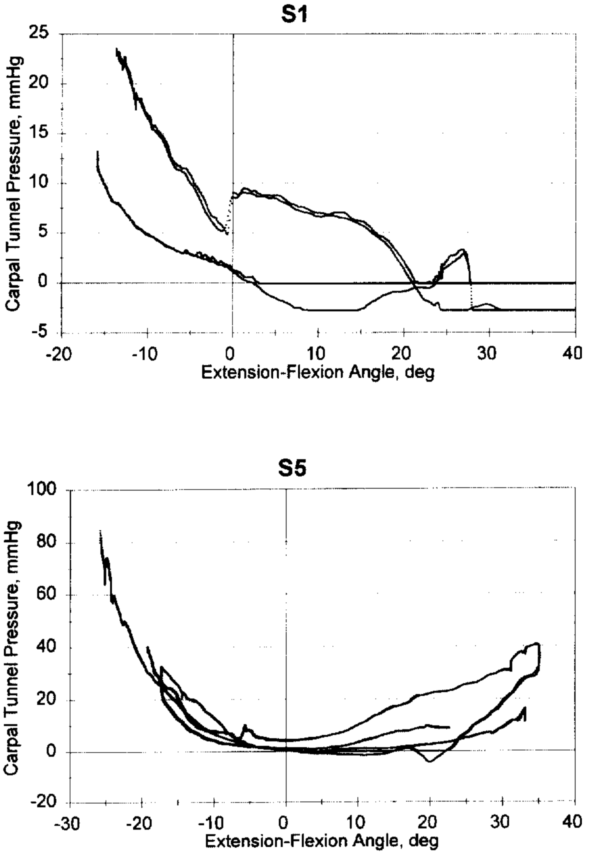

Fig. 6. CTP response to slow, reciprocating FE wrist movement. (Horizontal flat lines seen in S1 graph were due to improper bandwidth settings that were corrected for subsequent subjects.)

Designing a methodology that is biomechanically based and also generic (not task specific) means results can be compared across studies, across types of work, and across researchers. Instead of trying to understand one kind of work (typing, for example), researchers can step back and try to understand hand-intensive work. Though industrial work and typing may at first glance appear to be very different, with generic measurement methods any differences can be quantified, yet similarities can also be identified. This will facilitate the identification of dose–response relationships for WMSD development, in terms that can be applied to many types of hand-intensive work.

4.5. Limitations and recommendations for future research

There are several limitations to the study and the methodology that could be addressed in future work.

4.5.1 Study limitations

First, the study was based on a small number of subjects, which was sufficient to demonstrate the feasibility of the methodology. However, owing to the extent of individual differences, it was not possible to fully characterize natural typing or the effects of changes in natural typing for the group. Expanding the number of subjects may substantiate the study's consistent findings, and trends in the data for the current sample might develop statistical significance. Second, the subjects in the study were homogeneous in terms of anthropometry. A more diverse subject population, both in terms of anthropometry and typing skills, may reveal effects not seen in this study. Studying a larger subject sample would also provide an estimate of the likelihood of elevated CTP induced by keyboard operation in non-symptomatic individuals.

Third, the assessment of alterations in typing biomechanics associated with alternative key layouts deserves an assessment using subjects that are trained on the alternative system. Such a study should utilize text selections that are reflective of letter frequency distributions found in normal text selections.

Fourth, an initial, non-invasive test session, complete except for invasive measures, would be useful to perform in order to know exactly how subjects are affected by the invasive measurements. Not having run such tests, there is no way to know what effect any discomfort the subjects experienced had on their performance.

4.5.2 Methodology limitations

There are several limitations associated with the methodology. The possibility of developing work profiles based on so many variables is likely to be achieved only with large numbers of subjects, based on the extent of individual differences observed. However, the time-intensive nature of the methodology and the necessity for physician assistance, precluded the testing of large numbers of subjects. The invasive nature of some of the measurements also makes subject recruitment and retention challenging and expensive.

Some researchers have discussed methods for dealing with large numbers of variables by combining them into single integrated variables. Tanaka and McGlothlin [29] proposed the development of benchmarks based on combined levels of workload, task repetition, and wrist angle. The benchmarks were an action limit and a maximum permissible limit, theoretically similar to those developed in the 1981 NIOSH Lifting Guide [30]. Moore *et al.* [4] proposed the use of a frictional work factor, the cumulative function of the normal pressure on the sliding tendon. This factor combined tendon exertion (travel), muscle/tendon force, and finger and wrist position. Radwin *et al.* [31] developed frequency-weighted filters, which temper the combined effects of posture and repetitiveness with subjective discomfort. They likened their filter system to a noise dosimeter, in terms of the ability to combine several characteristics into one integrated value. Integrated variables are valuable for understanding risk, whereas individual variables can be more useful when looking for specific ways to reduce risk.

5. Conclusion

A methodology was developed to assess simultaneously several biomechanical variables which are thought to be important in advancing the understanding of the pathophysiology of WMSDs. Those variables included force (assessed as key strike force), finger and wrist joint kinematics, tendon travel, CTP, and muscle activity. The method was used to assess the hand-intensive task of typing on a computer keyboard under four different typing conditions. In addition to identifying advantages or disadvantages to keyboard operators working under particular typing conditions, the more important issue that was explored in this study was the development of a data collection methodology which assessed a number of important external and internal biomechanical variables simultaneously. The methodology is not task specific. Moving beyond task-specific assessments permits researchers to profile tasks strictly along biomechanical dimensions, in order to focus on what is similar about hand-intensive tasks (such as muscle activity or wrist posture), rather than focusing on higher-level task-specific features (such as number of parts handled per hour or typing speed). It is generic biomechanical assessments that will make substantive contributions to our understanding of the pathomechanics of WMSDs.

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